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Model-based Assessment of Cost-effective Low Impact Development Strategies to Control Water Balance

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Kurzfassung

Der klare Trend zum Leben in der Stadt und die Auswirkungen der Urbanisierung auf die Umwelt sind weitreichend anerkannt. Die Zunahme an versiegelten Flächen führt hierbei zu einer Veränderung der Wasserbilanz: Das Abflussvolumen steigt an, während die Evapotranspiration und die Grundwasseranreicherung abnehmen. Diese Änderungen haben mehrere negative Auswirkungen, wie größere Abflussvolumina, höhere Abflussspitzen, höhere Gefahr von Überflutungen, urbane Hitzeinseln, usw., zur Folge. All diese Entwicklungen stellen eine Herausforderung für die Niederschlagswasserbewirtschaftung lebenswerter Städte dar. Low impact development (LID)-Strategien sind weitreichend bekannte und umgesetzte Konzepte und zielen darauf ab, die hydrologischen Verhältnisse natürlicher Gebiete nachzubilden. Dadurch sollen die negativen Auswirkungen der Urbanisierung abgeschwächt und die hydrologischen Verhältnisse vor der Bebauung wiederhergestellt werden. Für die Bewertung der LID-Leistungsfähigkeit bieten sich hydrologische Simulationen an. Hierfür stehen verschiedene Modellierungstools zur Verfügung. In dieser Arbeit wurde das US EPA Storm Water Management Model (SWMM) verwendet.

Üblicherweise befassen sich Ansätze sowie Richtlinien und Studien zur Bewertung der LID-Leistungsfähigkeit lediglich mit der Abflusskomponente der Wasserbilanz. Der Evapotranspiration und Grundwasseranreicherung wird dabei nur wenig Beachtung geschenkt. Durch den Einsatz von LIDs werden jedoch mehrere Ziele, wie Mikroklima und Grundwasserspiegel, verfolgt. Daher sollte bei der Dimensionierung der LIDs die gesamte Wasserbilanz berücksichtigt werden, um einen nachhaltigen und zielführenden Einsatz zu gewährleisten.

Diese Arbeit präsentiert eine ganzheitliche und modellbasierte Methode zur Bewertung und Auswahl von LID-Strategien. Neben der gesamten Wasserbilanz werden auch ökonomische Aspekte wie Lebenszykluskosten und Flächenverbrauch berücksichtigt. Die Methode basiert auf kontinuierlichen Langzeitsimulationen und der Nutzung gemessener Niederschlagszeitreihen. Damit werden die hydrologischen Verhältnisse am Start eines jeden Regenereignisses berücksichtigt. Die Notwendigkeit einer solchen Vorgehensweise wurde durch eine regenereignisbasierte globale Sensitivitätsanalyse (GSA) bestätigt. Im Zuge der GSA wurden zudem LID-Parameter, welche keinen oder einen hohen Einfluss auf die modellbasierte Wasserbilanz haben, identifiziert. Diese Ergebnisse sind beim Einsatz von SWMM zur Modellierung und Planung von LIDs, unter Berücksichtigung der Wasserbilanz, besonders wertvoll.

Die Effizienz von LID-Strategien (E_{LID}) wurde als Bewertungskennwert mit der Möglichkeit einer Zielgewichtung (Abweichung von Ziel-Wasserbilanz, Lebenszykluskosten, Flächenverbrauch) eingeführt. Die Simulationsergebnisse für drei

verschiedene urbane Flächen zeigen mehrere pareto-optimale LID-Strategien, darunter auch LID-Kaskaden, welche eine fundierte Basis für eine Entscheidungsfindung darstellen.

Abstract

The clear trend to urban living and the impacts of urbanization on the environment are widely acknowledged. The increase of impervious land cover induces an alteration of the water balance: runoff volumes increase, while the evapotranspiration and groundwater recharge decrease. These changes cause several negative impacts, like larger runoff volumes, higher runoff peak rates, higher potential of flooding events, urban heat islands, etc.. All these trends are challenging stormwater management for livable cities. Low impact development (LID) strategies are widely known and implemented concepts that aim to replicate hydrologic characteristics of natural catchments. They mitigate the adverse impacts of urbanization and are applied in order to maintain or restore the predevelopment hydrologic regime. Hydrologic simulations are a reasonable option to evaluate the performance of LID strategies. Several modeling tools facilitate the simulation of hydrologic processes of LIDs. The US EPA Storm Water Management Model (SWMM) was used in this thesis.

Commonly, evaluation approaches as well as guidelines and studies dealing with LID performance focus on the runoff component of the water balance, paying little attention to alterations in evapotranspiration and groundwater recharge. As LIDs are applied pursuing multiple objectives, like micro-climate and groundwater levels, the complete water balance has to be taken into account in terms of an environmentally sustainable and reasonable application and design of LIDs.

This thesis presents a holistic methodology for a model-based assessment and selection of LID strategies. Besides the complete water balance, the method considers economic aspects including life cycle costs and demand for land. The method is based on long-term and continuous simulations using monitored precipitation time series in order to account for hydrologic conditions at the start of a storm event. This is in agreement with results of a storm event-based global sensitivity analysis (GSA). Furthermore, the conducted GSA of model-based water balance to LID parameters identified non-influential and most influential parameters. These results are valuable when using SWMM for planning/modeling LIDs considering the water balance.

The efficiency of LID strategies (E_{LID}) is introduced as an evaluation measure that accounts for emphasizing different objectives (deviation from targeted water balance, life cycle costs, demand for land). The simulation results using three different urban areas show that several pareto-optimal LID strategies including coupled LIDs (LID treatment trains) can be used as a reasonable basis for decision-making.

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List of abbreviations

ET	Evapotranspiration
GR	Groundwater Recharge
GSA	Global Sensitivity Analysis
LID	Low Impact Development
LSA	Local Sensitivity Analysis
P	Precipitation
R	Runoff volume
SWMM	Storm Water Management Model
S_i	First-order index
ST_i	Total effect index
ΔS	Change in System Storage

List of appended papers

This doctoral dissertation consists of a summary and of the following publications which are referred to in the text by their numerals.

Paper I **Leimgruber, Johannes**; Steffelbauer, David; Krebs, Gerald; Tscheikner-Gratl Franz; Muschalla Dirk (2018). Selecting a series of storm events for a model-based assessment of combined sewer overflows. Urban Water Journal 15 (5): 453–460. ISSN 1573-062X. DOI: 10.1080/1573062X.2018.1508601

Paper II **Leimgruber, Johannes**; Krebs, Gerald; Camhy, David; Muschalla, Dirk (2018). Sensitivity of Model-Based Water Balance to Low Impact Development Parameters. Water 10 (12): 1838. ISSN 2073-4441. DOI: 10.3390/w10121838

Paper III **Leimgruber, Johannes**; Krebs, Gerald; Camhy, David; Muschalla, Dirk (2019). Model-Based Selection of Cost-Effective Low Impact Development Strategies to Control Water Balance. Sustainability 11 (8): 2440. ISSN 2073-4441. DOI: 10.3390/su11082440

1 Introduction

1.1 Background

1.1.1 Hydrologic cycle and water balance

The hydrologic cycle is the most essential principle of hydrology (Maidment, 1993) and the dominant among several biogeochemical cycles in nature (Singh, 2017). Water evaporates from land surface and oceans, the occurring water vapor is transported over the earth, inducing precipitation that is intercepted by vegetation or other objects, generates runoff, infiltrates into the soil, recharges groundwater, discharges into streams, and finally, reaches oceans from which it may evaporate once again.

The water balance is based on the principle of conservation of mass. It has to be formulated for a system of specified geometry at a specified time scale (Khedun and Singh, 2017). The water balance can be computed for a part of the hydrologic cycle, e.g. a certain soil profile, or a defined spatial dimension, e.g. a catchment area. Furthermore, any temporal scale can be used for the computation of the water balance.

The literature presents different equations for the water balance, depending on the scope of application. A general and simple expression of the water balance is (e.g., Dyck and Peschke, 1995):

$$P = R + ET + \Delta S \tag{1-1}$$

where P is the precipitation, R is the runoff, ET is the evapotranspiration, and ΔS is the change in system storage.

Precipitation comprises all forms of water that falls from atmosphere, including rainfall, hail, snow, sleet, etc. (Singh, 2017). Precipitation is the central input for the water balance of hydrologic systems and exhibits variability in time and space. The average world-wide annual precipitation is about 505000 km^3 of which about 78% falls over the oceans (Singh, 2017).

Evapotranspiration is a combined term of evaporation and transpiration, describing the transfer of moisture from the surface to the atmosphere. Evaporation occurs from bare soil, impervious surfaces, intercepted water on vegetation, and open water, transpiration from within vegetation (Hobbins and Huntington, 2017). Evapotranspiration is constrained by three limits (Hobbins and Huntington, 2017): the availability of water to evaporate and/or transpirate (hydrologic limit), the availability of energy to drive evapotranspiration (radiative limit), and the ability of the atmosphere to absorb and bear away moisture (advective limit).

Runoff can be classified into different types (Pilgrim and Cordery, 1993). The *Hortonian overland flow* occurs when the rainfall intensity exceeds the infiltration capacity. When the surface horizon of the soil becomes saturated, *saturated overland flow* occurs. Water that infiltrates into the soil and moves laterally in a temporarily saturated zone is called *throughflow*. Processes (losses) preventing runoff are infiltration, retention in depression storage, interception, and to a smaller extent evapotranspiration. A runoff hydrograph can be further separated in surface runoff, rapid subsurface flow or interflow, and groundwater flow or baseflow (Pilgrim and Cordery, 1993). Several methods are in use to estimate runoff (Pilgrim and Cordery, 1993): approaches using a constant loss fraction, a constant loss rate, initial loss and continuing constant loss rate, infiltration curves or equation representing rates of loss varying over time (e.g., equation of Green and Ampt (1911)), and standard rainfall-runoff relation (e.g., curve number of U.S. Soil Conservation Service (1972) or unit hydrograph – first proposed by Sherman (1932)).

The change in system storage accounts for the conservation of mass. It is the difference of water stored in the investigated system between the start and the end of the period under consideration. Depending on the scope of application, groundwater recharge (GR) can also be expressed as a distinct part of the water balance.

1.1.2 Urbanization – Impacts on water balance

The world is experiencing a clear trend to urban living. In 2018, with 55% of the world's population, more people are living in urban than in rural areas (United Nations, 2018). The increase of urban population is 25 percentage points since 1950 and the projections predict 68% percent of the world's population to be urban by 2050 (United Nations, 2018).

The proceeding urbanization implies an increase of impervious land cover as formerly natural surfaces are replaced by buildings, streets, parking lots, etc.. In Austria, a new built-up area of 12.9 ha (41.2% imperviousness) was developed daily between 2015 and 2017 (Umweltbundesamt, 2018). These artificial, impervious areas induce a considerable change in water balance compared to natural areas (Arnold Jr and Gibbons, 1996; Shuster *et al.*, 2005; Haase, 2009; Fletcher *et al.*, 2013). While the runoff increases, evapotranspiration and infiltration/groundwater recharge decrease (Figure 1-1). This results in several negative impacts like higher runoff volumes (Cheng and Wang, 2002; Shuster *et al.*, 2005), higher runoff peak rates (Shuster *et al.*, 2005), increase of runoff/flooding events (Du *et al.*, 2012), reduced base flow (Smakhtin, 2001) due to decreased groundwater recharge, and urban heat islands (UHI) (Chen *et al.*, 2006; Rizwan *et al.*, 2008).

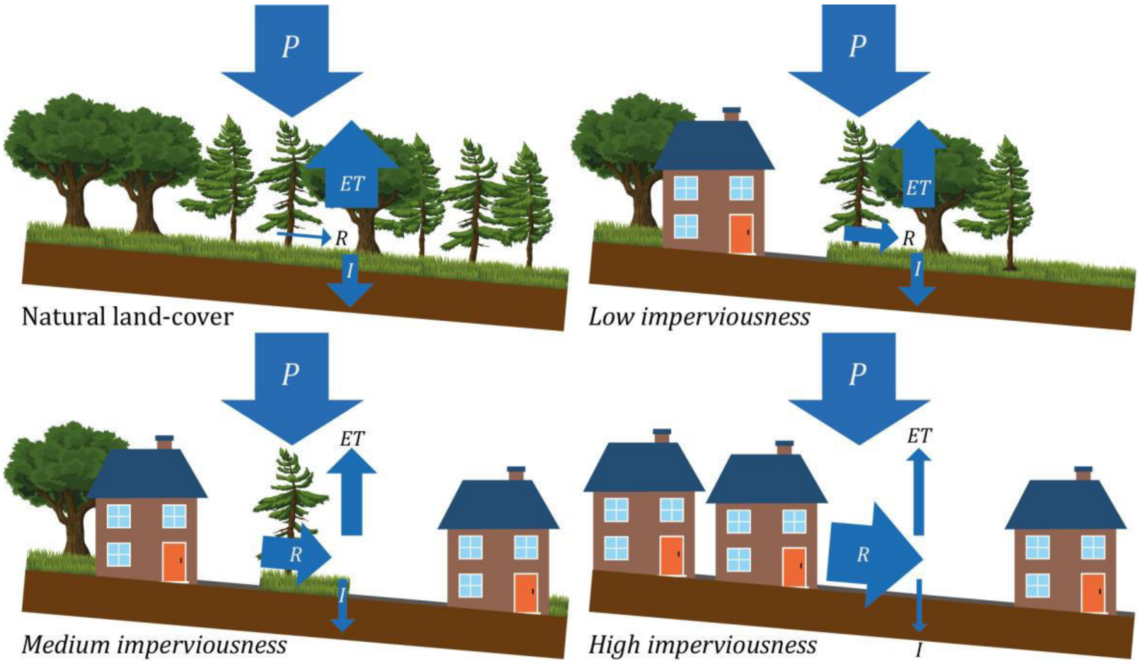

Figure 1-1. Effects of urbanization and increasing imperviousness of land cover on water balance; P – precipitation, ET – Evapotranspiration, I – Infiltration, R – Runoff

1.1.3 Low impact development

The development of settlements and cities induced the need of conveying water away from urban areas through urban drainage. This very old field dates back to at least 3000 BC (Burian and Edwards, 2002) and includes wastewater and stormwater. Due to the increase of urbanization, the management of urban drainage has become a challenging issue (Chocat *et al.*, 2001; Fletcher *et al.*, 2013).

Stormwater management has seen significant changes over the past decades. Conventional stormwater management aimed to convey stormwater from urban areas in order to protect structures and prevent flooding. More recent approaches are more holistic and include multiple objectives like the restoration of the natural water balance, the improvement of the microclimate, the increase of biodiversity, etc. (compare, e.g., US EPA, 2000; Ahiablame *et al.*, 2012; Ashley *et al.*, 2013; Matzinger *et al.*, 2017). Urban drainage is no longer seen only as a problem, the opportunities are more and more recognized. As a consequence, a new terminology has developed for this more integrated approaches that emerged in the 1980s and 1990s (for details compare Fletcher *et al.*, 2015): SUDS (Sustainable urban drainage systems), BMPs (Best management practices), LID (Low impact development), WSUD (Water sensitive urban design), etc.. These terms differ in their specificity and their primary focus, but show significant overlap. All terms are based on two common principles (Fletcher *et al.*, 2015): (i) mitigation of adverse changes to hydrology and approximation of natural conditions, (ii) reduction of pollutants and improvement of water quality.

The term LID has been most commonly used in North America and New Zealand, appearing first in a report by Barlow *et al.* (1977) on land use planning in Vermont, USA (Fletcher *et al.*, 2015). It has been most influential adopted in Prince George's County, Maryland, USA in the early 1990s (e.g., in Prince George's County Department of Environmental and Resources, 1993; Coffman, 2000). In Germany, the change towards technologies like rainwater harvesting and green roofs started in the early 1980s. During the 1990s, several decentralized techniques for stormwater management were developed (e.g., Geiger and Dreiseitl, 1995). A variety of terms can be found in the German language too, e.g., *naturnahe Regenwasserbewirtschaftung* (nature-like stormwater management) (e.g., Sieker *et al.*, 1996), *naturnahe Konzepte* (nature-based concepts), and *dezentrale Regenwasserbewirtschaftung* (decentralized stormwater management) (e.g., Sieker *et al.*, 2006). The use of such approaches is highlighted by German national guidelines (DWA, 2006), defining the water balance as a target of stormwater management (DWA, 2016), as well as several studies dealing with such stormwater management measures (e.g., Bente, 2001). Similarly, the Austrian guideline (OEWAV, 2003) also recommends to avoid, infiltrate, use or detain stormwater runoff on-site whenever possible.

All these stormwater management principles that aim to reduce runoff volume at the source and to mimic natural water cycles are referred to as "low impact development" (LID) in this thesis. LID strategies are a widely known and implemented stormwater management concept, comprising both structural and non-structural practices (e.g., Ahiablame *et al.*, 2012). Structural practices include green roofs, rain barrels, bio-retention cells, infiltration trenches, infiltration swales, and more. They can be applied as stand-alone solution using a single LID type as well as coupled in series (LID treatment train). Nonstructural practices refer to planning strategies that reduce and disconnect impervious surfaces, and conservate existing natural sites.

LIDs aim to mitigate the adverse impacts of urbanization by replicating or at least approximating hydrologic characteristics of natural catchments, using hydrologic functions provided by nature like infiltration, evapotranspiration, and retention (US EPA, 2000; Ahiablame *et al.*, 2012).

Numerous field and laboratory studies as well as evaluations based on hydrologic simulation document the effects of LID application like runoff volume reduction (e.g., Dietz and Clausen, 2008; Wilson C. E. *et al.*, 2015) and reduction of water pollution (e.g., Lenhart Hayes A. and Hunt William F., 2011; Jia *et al.*, 2015). Ahiablame et al. (2012) and Eckart et al. (2017) provide substantial overviews on studies dealing with the evaluation of LID practices.

1.1.4 Urban stormwater modelling

Stormwater is subjected to several processes between falling on the earth surface and, e.g., reaching a receiving water body. Rainfall-runoff modelling deals with these processes and is based on hydrologic and hydraulic relationships that go back to scientists of the 17th and 18th century, e.g. de Saint Venant, Darcy, and Manning.

The modelling literature shows different ways of classifying models. Grayson and Blöschl (2000) focus on three features to distinguish modelling approaches in catchment hydrology: (i) stochastic or deterministic approach for parameter specification, (ii) nature of the algorithms (empirical, conceptual, process(physically)-based), and (iii) lumped or distributed spatial representation. A deterministic model always produces identical results for the same input parameters, while stochastic models show one or more inputs/parameters that are selected at random from defined distributions, generating different results. Empirical models are only based on calibrated relationships between inputs and outputs without attempting to describe the behavior caused by individual processes. Conceptual models comprise basic hydrologic processes like infiltration, evaporation, runoff, etc., but the algorithms used to describe the processes are basically calibrated input-output relationships. Models based mainly on the fundamental physics of hydrologic processes are often called 'physically-based'. They were developed in order to reduce the need of calibration as the parameters are measurable physical quantities. Dividing the study area into elements and considering spatial parameter variation results in distributed models, while lumped models are not spatially explicit and average the effects of variability of processes in space.

First rainfall-runoff models emerged more than 150 years ago. The empirical rational method (Mulvany, 1851) is frequently acknowledged as one of the first models capable of estimating peak flow rates. One of the first computer-based modelling approaches is the Stanford Watershed Model (Crawford and Linsley, 1966) which is a classic example for a conceptual model (Grayson and Blöschl, 2000). Urban catchments are dominated by processes on impervious areas compared to natural catchments (Boyd *et al.*, 1993). Consequently, models that were developed specifically for urban areas show a particular focus. Urban stormwater models comprise two basic components (Zoppou, 2001): (i) rainfall-runoff modelling (runoff generation and concentration due to precipitation considering initial and continuous losses), (ii) transport modelling (routing of runoff through the urban drainage system).

Modelling tools that are able to simulate the stormwater runoff quantity and quality emerged in the earlier 1970s and were primarily developed by US government agencies (Zoppou, 2001). Reviews of urban stormwater models (e.g., Zoppou, 2001) show a large number and diversity of available models. Some popular examples are the Hydrologic Simulation Program-Fortran (HSPF) (e.g. (Bicknell *et al.*, 1993)), the Storm Water Management Model (SWMM) (Huber and Dickinson, 1988; Rossman, 2015) and its proprietary platforms (e.g., PCSWMM, XP-SWMM), the Hydrologic Modeling System HEC-HMS (Charley *et al.*, 1995), MIKE-SWMM (combining MIKE (DHI, 2003) and SWMM), and MIKE-SHE (combining MIKE and SHE (Abbott *et al.*, 1986)).

After LID strategies started to appear and were considered as a reasonable method of managing stormwater, modelling tools were updated in order to evaluate the LID performance. These tools primarily aimed to assess the performance of LIDs in managing urban stormwater runoff quantity and quality (Jayasooriya and Ng, 2014). At present, a wide range of models is available to simulate LIDs and to evaluate their effects within stormwater models. Reviews on models applicable to simulate LIDs can be found in (Elliott and Trowsdale, 2007; Jayasooriya and Ng, 2014; Haris *et al.*, 2016; Eckart *et al.*, 2017; Kaykhosravi *et al.*, 2018). There are models addressing (i) stormwater quality and quantity, (ii) economic analysis, or (iii) both stormwater management and economic aspects together (Jayasooriya and Ng, 2014). Examples for the different types of models are:

(i) RECARGA (Severson and Atchinson, 2004), SWMM (Rossman, 2015),
(ii) WERF BMP and LID Whole Life Cycle Cost Modeling Tools (Water Environment Research Foundation, 2016), Green Infrastructure Valuation Toolkit (The Mersey Forest *et al.*, 2010),
(iii) EPA System for Urban Stormwater Treatment and Analysis Integration Model (SUSTAIN) (Lai *et al.*, 2007), Low-Impact Development Rapid Assessment (LIDRA) (Yu Ziwen *et al.*, 2010).

1.2 Research gap

LID strategies aim to mitigate the adverse impacts of urbanization like the increase of runoff volume and decrease of evapotranspiration. Hydrologic simulation is a reasonable option to evaluate the performance of LID strategies with respect to the water balance. Simulations allow analyzing the pre- and post-development hydrologic conditions.

Usually, evaluation approaches (e.g., Coffman, 2000) and studies dealing with LID performance (compare review papers by Ahiablame *et al.*, 2012; Eckart *et al.*, 2017) focus on the runoff component of the water balance. Little attention is paid to alterations in evapotranspiration and groundwater recharge, although they have great influence on the micro-climate (heat island effect) or increase of groundwater levels due to artificial groundwater recharge (e.g., Goebel *et al.*, 2007; Fletcher *et al.*, 2013). Unfortunately, also planning guidelines (e.g., MDE, 2000; DWA, 2005; ON, 2013, for an overview of international approaches compare Ballard *et al.*, 2016) do not pursue a holistic approach considering the complete water balance. In terms of an environmentally sustainable and reasonable application and design of LIDs, the complete water balance has to be taken into account. Such holistic approaches (e.g., complete water balance considered in Feng *et al.*, 2016; Henrichs *et al.*, 2016; Eger *et al.*, 2017) provide a suitable basis for planning purposes. Furthermore, the LID performance should be assessed at the site scale, as suggested by Burns et al. (2012), in order to account for micro-climatic aspects, to restore the pre-development water balance at small scales, and to restore the natural flow regimes at larger scales downstream.

Commonly, the design of LIDs implies the calculation of the required retention volume, which is basically the difference between the stormwater volume collected by the LID and the stormwater volume that infiltrates through the LID into the native soil beneath. For this purpose, several planning guidelines and design manuals propose to use design storm events of a certain duration and return period. Design approaches of this kind do not consider the actually occurring storm characteristics nor the hydrologic conditions at the start of a storm event, e.g. retention volume available due to antecedent dry periods and storm events. Consequently, the assessment of LID performance can diverge from monitoring in the field. For this reason, monitored precipitation time series including storm events as well as dry periods and long-term simulations are to prefer.

Several LID design approaches aim to design a certain LID type, e.g. an infiltration swale or trench. Recommendations for the selection of the proper LID type are rare. A reasonable LID strategy can also combine different LID types in series to a LID treatment train (compare, e.g., Kim *et al.*, 2015; She Nian *et al.*, 2015; Xu *et al.*, 2017; Auger Steve *et al.*, 2018). This option is usually not covered in design approaches neither. The selection of LID strategies is also controlled by economic considerations (compare, e.g., MacMullan and Reich, 2007; Montalto *et al.*, 2007; Liao *et al.*, 2015; Chui *et al.*, 2016), primarily based on the estimation of life cycle costs. Several cost estimating tools have been developed for this purpose (e.g., Houdeshel *et al.*, 2010; Yu Ziwen *et al.*, 2010).

The assessment of LID strategies has to be holistic in terms of considering the complete water balance, the option of LID treatment trains, and the cost-effectiveness (life cycle costs, demand for land). However, to the author's knowledge, no studies or approaches are available that address all these combined assessment criteria.

1.3 Objectives

According to the research gap described in Section 1.2, the main objective of this thesis was to develop a holistic methodology for a model-based assessment of LID strategies. The assessment method considers the complete water balance, economic aspects including life cycle costs and demand for land, and the option of applying LID treatment trains. The methodology can be applied for the selection of a proper LID strategy as well as for the design of the LID.

The proposed methodology is based on long-term and continuous simulations using a monitored precipitation time series in order to account for hydrologic conditions at the start of a storm event. First, a model-based sensitivity analysis was conducted in order to identify influential and non-influential LID parameters on the particular water balance component (Paper **II**). Water balance and sensitivity evaluations were conducted for the long-term as well as for single storm events. A method for the separation of storm events was developed in the first paper (Paper **I**). The third paper (Paper **III**) introduces the methodology for the model-based selection and design of cost-effective LID strategies in order to control the water balance. The method was applied to three catchments, representing typical urban areas (two residential areas, one commercial area).

The specific objectives of this thesis were to

(i) develop a method of little computational effort for the separation of storm events,

(ii) conduct a model-based global sensitivity analysis in order to identify influential and non-influential LID parameters on the water balance components; evaluate the water balance and sensitivities for the long-term as well as based on storm events in order to identify the influence of storm event characteristics, e.g. antecedent dry period; emphasize the need for long-term simulations for the evaluation of LID performance,

(iii) develop a holistic methodology for a model-based assessment/selection/design of LID strategies that considers the complete water balance, life cycle costs, and demand for land; introduce an evaluation measure for the efficiency of LID strategies that also accounts for emphasizing different planning objectives.

2 Methods and materials

The Storm Water Management Model (SWMM, compare Section 2.4) was used in this thesis as it is currently one of the most sophisticated modeling tools for hydrologic simulation of LID strategies (Jayasooriya and Ng, 2014).

All results are based on long-term simulations of a 10-year period (description of precipitation time series in Section 2.7). The evaporation rates were computed using a daily min-max temperature series (compare Section 2.7) and the Hargreaves method (Hargreaves and Samani, 1985) that is implemented in SWMM.

The simulation results were used to compute the water balance:

$$\Delta S = P - ET - R - GR \qquad (2\text{-}1)$$

where P is the precipitation (mm), R is the runoff volume (mm), ET is the evapotranspiration (mm), GR is the groundwater recharge (mm), and ΔS is the change in system storage (mm).

Commonly, the water balance components are expressed as fraction of the precipitation:

$$1 = \frac{\Delta S + ET + R + GR}{P} \qquad (2\text{-}2)$$

2.1 Sensitivity analysis of model-based water balance to LID parameters

A model-based sensitivity analysis of the water balance to LID parameters was conducted in order to identify non-influential parameters (parameter fixing) and parameters that affect particular water balance components (parameter prioritization) (Paper **II**). The investigated LIDs were: extensive green roof, bio-retention cell, and infiltration trench (compare Section 2.3).

Saltelli et al. (2004) provides the following definition of sensitivity analysis: *„The study of how uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input."* Investigating the model-based sensitivity of the water balance to LID parameters, the model is SWMM, the output is the water balance and the model input are the LID parameters (parameter ranges in Table 2-2, Table 2-3, Table 2-4,).

Local sensitivity analysis (LSA) methods investigate the influence of a small perturbation near a certain input space value (parameter value) on the model output. In contrast, global sensitivity analysis (GSA) methods aim to assess the model output variation over the whole parameter range. Consequently, GSA methods do not only account for the influence of one parameter, but also for the influence of parameter interactions on the model output. As a typical approach of LSA – the one-at-time (OAT) sensitivity analysis – was demonstrated to be inadequate for environmental models (Saltelli and Annoni, 2010) and as the influence of interactions between LID parameters on the water balance is of high interest, a GSA was conducted (Paper **II**).

In the field of sensitivity analysis, a variety of GSA methods is available (compare, e.g., Saltelli *et al.*, 2007). The boundary conditions affecting the choice of a proper GSA method are the number of parameters and the computation time per simulation run. According to Saltelli *et al.* (2005), with a maximum of 13 parameters (green roof, Table 2-2) and a short computation time of 1-2 min. per simulation run, the variance-based method of Sobol (1993) was used. The first-order sensitivity index S_i and the total effect index ST_i were calculated:

$$S_i = \frac{V_{X_i}(E_{X\sim i}(Y|X_i))}{V(Y)} \tag{2-3}$$

$$ST_i = \frac{E(V(Y|X_{\sim i}))}{V(Y)} \tag{2-4}$$

where S_i is the first-order index, ST_i is the total effect index, Y is the variable (model output), X is the parameter, V is the variance, $X_{\sim i}$ are all parameters but X_i, and E denotes the average.

On the one hand, the first-order index S_i accounts for the main contribution of each parameter X_i to the variance of the output. It is obtained by the variation of the average Y when fixing X_i at different values while varying the other parameters. It indicates the potential reduction of output variance, on average, if X_i could be fixed. Consequently, it is used to find the most influential parameters that should be determined first in order to reduce the output variance (parameter prioritization). On the other hand, the total effect index ST_i represents the total contribution of a parameter X_i to the output variance. It summarizes the first-order effects and all higher-order effects due to parameter interactions. A ST_i of zero indicates that the parameter has no influence on the output variance and that it does not affect the output when fixing it at an arbitrary value in its parameter range. Consequently, ST_i is used to identify non-influential parameters (parameter fixing). Further information about the GSA method used can be found in Paper **II**, Sobol (1993), and Saltelli *et al.* (2007). The open-source Python library for Sensitivity Analysis SALib (Herman and Usher, 2017) was used for the implementation. It uses an extended Sobol sequence of quasi-random numbers (Sobol, 1976) in order to substantially reduce computation time. The sampling scheme was proposed by Saltelli (2002).

The water balance and correspondent sensitivities were calculated based on long-term and continuous simulations (Section 2.7). The sensitivity evaluations were conducted for these long-term results, but also for storm events within these long-term simulations. The separation of storm events was based on an event gap (G_e) of 4 hours and a threshold (T_v) of 1 mm precipitation depth in 1 hour (T_t) (description of method in Section 2.5 and in Paper **I**). The storm event-based water balance was assessed from the start of a storm event to the start of the subsequent storm event. The effects of the storm event characteristics precipitation depth and antecedent dry period on the sensitivity of the water balance to LID parameters were investigated.

2.2 Model-based assessment and selection of LID strategies

Several LID strategies (compare Section 2.3) with varying size and combination of LID types were investigated with respect to their performance regarding the water balance, the life cycle costs, and the demand for land (Paper **III**).

2.2.1 Case studies and design of LID strategies

Three case studies representing characteristic urban areas were used for the study (Figure 2-1): one commercial area and two residential areas. The entire impervious commercial area has a size of 16000 m² including a roofage of 6000 m². The residential areas cover 1100 m² each, but differ in the degree of development (dod), which is the proportion between built-up area and building site area. The low-developed residential area has a roofage of 200 m² (dod = 0.18) whereas the high-developed residential area has a roofage of 600 m² (dod = 0.55). A driveway of 40 m² exists in both residential areas, the remaining area is covered by lawn.

The investigated LIDs (Section 2.3) were similarly parameterized to provide comparable retention volumes and hydrologic behavior (Table 2-2, Table 2-3, Table 2-4, Table 2-5). The parameters are in agreement with literature parameter ranges (FLL, 2008; Rossman and Huber, 2016a, 2016b). The blind drain was simulated with a storage node that allows for infiltration to the native soil and prevents evapotranspiration. The surface above the blind drain was simulated as well (Figure 2-3e). The blind drain storage depth was defined to 30 cm. The other LID strategies were simulated using the soil moisture model of SWMM (Figure 2-3).

A main goal of the study was the reasonable design of LIDs. For this purpose, a potential total LID area (A_{pot}) was assigned to each case study due to space restrictions: 2500 m² for the commercial area, 60 m² for the low-developed residential area, and 120 m² for the high-developed residential area. A_{pot} was divided into 50 sections. The sections were incrementally used for the application of a LID type (e.g. infiltration trench applied to 1, 2, 3…, 50 sections) and each state was simulated. In order to investigate LIDs coupled in series (LID treatment trains), two different LID types were applied to the sections, directing the runoff from the first LID to the second one (Figure 2-2). The application of LIDs to the sections was again executed incrementally.

$$A_{LID1} = \frac{A_{pot}}{50} \cdot n_{LID1}$$
$$A_{LID2} = \frac{A_{pot}}{50} \cdot n_{LID2} \quad (2\text{-}5)$$
$$max(n_{LID1} + n_{LID2}) = 50$$
$$for\ single\ LID\ strategies: n_{LID2} = 0$$

where A_{LID1} is the area of LID1 in m², A_{LID2} is the area of LID2 in m², A_{pot} is the potential LID area for the respective case study, n_{LID1} is the number of sections occupied by LID1, and n_{LID2} is the number of sections occupied by LID2.

The green roof was not applied incrementally. Only the two options 'green roof' or 'tiled roof' covering the complete roofage were considered (Figure 2-2).

The simulation results using the grid of 50 sections were used as supporting points for a linear interpolation.

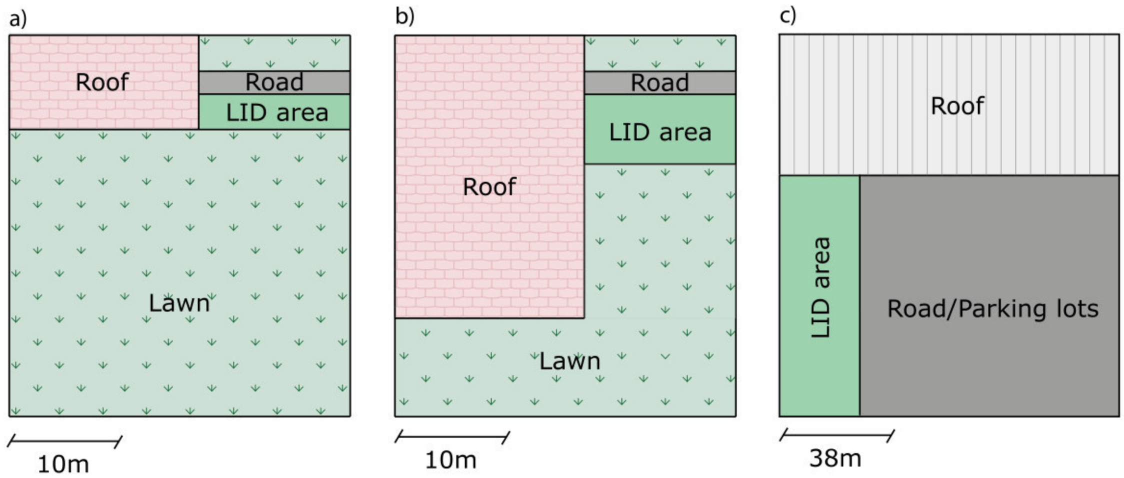

Figure 2-1. Schematic setting of investigated case studies; a) low-developed residential area, b) high-developed residential area, c) commercial area.

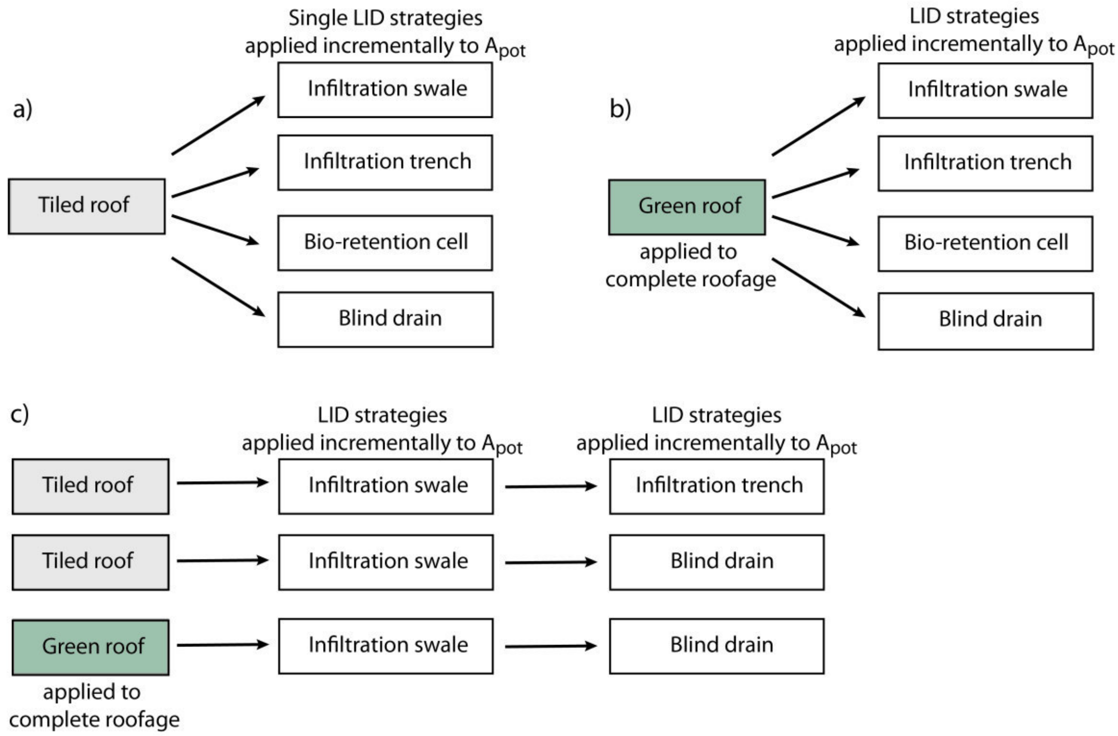

Figure 2-2. Investigated LID strategies. a) Single LIDs; b) LID treatment trains with green roof; c) two-part and three-part LID treatment trains.

2.2.2 Water balance, costs, demand for land

The water balance was computed based on the long-term simulation results (see Equation 2-1). Life cycle costs were calculated for every investigated LID strategy applying a dynamic cost comparison calculation (compare Section 2.6). The calculations were based on the assumption of an interest rate of 3%, a life span (interest period) of 30 years (Leimbach *et al.*, 2018), and maintenance costs of 5% of construction costs (according to references in

Table 2-1). The reference point was defined at the start of the LID life span. The one-time construction costs were converted into uniformly distributed annual costs (compare Section 2.6) and added to the annual maintenance costs:

$$TC_a = C_o \cdot \frac{i \cdot (1+i)^n}{(1+i)^n - 1} + C_o \cdot \mathrm{p} \qquad (2\text{-}6)$$

where TC_a are the total annual costs per unit (€/year), C_0 are the construction costs per unit (€), n is the life span (years), i is the interest rate (%), p is the proportion of maintenance to construction costs (%).

Table 2-1. Construction costs and maintenance costs for investigated LIDs; [1](Matzinger *et al.*, 2017), [2](Sieker, 2018), [3](Muschalla *et al.*, 2014), [4](Leimbach *et al.*, 2018)

	Construction costs		Maintenance Costs		Total costs		Reference (adapted)
LID							
Green roof	35	€/m²	1.75	€/(m²·year)	3.54	€/(m²·year)	1,2,3
Infiltration swale	30	€/m²	1.5	€/(m²·year)	3.03	€/(m²·year)	1,2,3,4
Infiltration trench	105	€/m³	5.25	€/(m³·year)	10.61	€/(m³·year)	1,2,3,4
Bio-retention cell	135	€/m³	6.75	€/(m³·year)	13.64	€/(m³·year)	1,2,3,4
Blind drain	105	€/m³	5.25	€/(m³·year)	10.61	€/(m³·year)	1,2,3,4

The demand for land was used as an additional factor for the evaluation of LID strategies. Especially in highly urbanized areas, land can be rare and/or very expensive. Thus, the demand for land (d_{land}) was used as a further indicator of LID performance besides the water balance and life cycle costs.

For bio-retention cell, infiltration swale, and infiltration trench:

$$d_{land} = A_{LID} \tag{2-7}$$

For blind drain:

$$d_{land} = 0$$

where d_{land} is the demand for land and A_{LID} is the area of the LID (see also Equation 2-5).

2.2.3 Assessment and efficiency of LID strategies

LID strategies are applied in order to achieve or at least to approximate a certain targeted water balance. Boundary conditions affecting the design and selection of reasonable LID strategies are the life cycle costs and/or demand for land. The goal is to identify the LID strategy that either minimizes (i) the deviation from the targeted water balance, (ii) the costs, and (iii) the demand for land. This multi-objective task usually does not have one optimal solution that equally satisfies the mentioned requirements. Consequently, the simulation results and the requirement of minimizing the three objectives were used in order to identify non-dominated (pareto-optimal) LID strategies. The approach of gridding methods (compare, e.g., Schuetze *et al.*, 2002) was used for this task as the evaluations were conducted for a defined number of points (grid of 50 sections).

The simulation results were used to calculate the deviation from the targeted water balance:

$$D_{WB} = \overline{R_{sim} - R_t} + \overline{ET_{sim} - ET_t} + \overline{GR_{sim} - GR_t} \quad (2\text{-}8)$$

where D_{WB} is the deviation from a targeted water balance (in percentage points), R is the runoff volume (in % of precipitation depth), ET is the evapotranspiration (in % of precipitation depth), GR is the groundwater recharge (in % of precipitation depth), sim denotes the simulated value, and t denotes the value of target state.

The targeted water balance can be defined by stakeholders or in order to aim for natural (pre-development) conditions based on hydrologic simulation (e.g., Henrichs *et al.*, 2019). For demonstration purposes, an arbitrary defined targeted water balance with a runoff volume of 5%, an evapotranspiration of 45%, and a groundwater recharge of 50% was used.

For the decision process, the efficiency of LID strategies (E_{LID}) was introduced as a function of costs in order to evaluate the effect of invested money. It is computed as the difference between one and the sum of the normalized deviation from the targeted water balance and the normalized demand for land. Weighting factors are used in order to emphasize a certain objective:

$$E_{LID}(C) = 1 - \left(w_{land} * \frac{d_{land}}{\max(d_{land})} + w_{WB} * \frac{D_{WB}}{\max(D_{WB})}\right) \quad (2\text{-}9)$$

with: $w_{land} + w_{WB} = 1$

where E_{LID} is the efficiency of LID strategies, C are the costs, d_{land} is the demand for land, D_{WB} is the deviation from the targeted water balance, w_{land} is the weighting factor for the demand for land, and w_{WB} is the weighting factor for the deviation from targeted water balance.

2.3 Investigated low impact development types

Among the variety of LID types, some of the most implemented in stormwater management projects, were investigated: Green roof, infiltration swale, infiltration trench, bio-retention cell, and blind drain.

Green roofs consist of an engineered soil mixture (substrate) that is partially or completely covered with vegetation. An underlying waterproof drainage mat conveys the stormwater off the roof. Commonly, green roofs are categorized as “extensive” (substrate ≤ 150 mm) or “intensive” (substrate > 150 mm) (Mentens *et al.*, 2006; FLL, 2008). The required level of maintenance is an additional factor for the categorization (Ahiablame *et al.*, 2012). Extensive green roofs are generally planted with dense, low growing, and drought-resistant vegetation, needing little maintenance. In contrast, intensive green roof vegetation can include grasses, flowers, shrubs, and even trees, potentially needing drainage and irrigation systems. In addition to the reduction of stormwater runoff, the implementation of green roofs provides various other benefits, such as reducing energy costs, extending life of roof, and conserving land that would otherwise be needed for stormwater management (US EPA, 2000). Green roofs are applicable to new developments as well as to existing rooftops considering structural design requirements.

Infiltration swales are partially or completely vegetated depressions that account for retention and infiltration of stormwater. They can also be used as shallow open channels with mild side slops in order to convey, control and improve stormwater through infiltration, sedimentation, and filtration, primarily along streets instead of traditional curbs and gutters (US EPA, 2000; Ahiablame *et al.*, 2012). The top soil can be amended with engineered infiltration soil mixtures (Eckart *et al.*, 2017).

Infiltration trenches consist of ditches usually filled with gravel. They intercept runoff from impervious areas, provide retention volume in the gravel pore spaces as well as additional time for stormwater to infiltrate into the native soil below (Rossman and Huber, 2016a).

Bio-retention cells combine the characteristics of an infiltration swale and an underlying infiltration trench. The swale contains vegetation grown in an engineered soil mixture that is placed above a gravel storage bed (Rossman and Huber, 2016a). Thus, retention volume is provided through the surface depression (swale) as well as the soil mixture and the gravel layer that accounts for infiltration into the native soil below. Bio-retention systems aim to act similar to natural and undeveloped catchments as they capture runoff, allow for infiltration and groundwater recharge, promote evapotranspiration and reduce peak flows as well as pollutant loads (Dietz, 2007; Ahiablame *et al.*, 2012). They can be used in commercial and residential areas and are usually planted with shrubs, perennials, and/or trees, and covered with shredded hardwood bark mulch (Dietz, 2007).

A blind drain is an underground infiltration body filled with gravel or other filling materials, capturing surface runoff that is directed to it through an underground inlet pipe. It provides retention volume in the pore space of the filling material and accounts for infiltration into the native soil below. Due to the underground implementation, blind drains do not require space on the surface.

Table 2-2. Green roof parameter ranges for the sensitivity analysis and parameter values used for the assessment of LID performance in Section 2.2. [1](Rossman and Huber, 2016a), [2](Rossman and Huber, 2016b), [3](FLL, 2008), [4](Sieker *et al.*, 1996)

Parameter	min	max	Value used in Section 2.2	Unit	Reference
Berm height	0	80	10	mm	1
Vegetation volume	0	0.2	0.2	%	1
Surface roughness	0.04	0.35	0.1	$s/m^{1/3}$	2
Surface slope	2	100	1.0	%	
Soil thickness *(for extensive green roof)*	40	200	100	mm	1
Porosity	0.36	0.65	0.55	-	3, 1, adapted
Field capacity	0.1	0.35	0.4	-	3, 1, adapted
Wilting point	0		0.1		
Conductivity	18	100	50	mm/h	3, adapted
Conductivity slope	30	55	30	-	1
Suction head	50	100	65	mm	1
Drainage mat thickness	13	50	30	mm	1
Drainage mat void fraction	0.2	0.4	0.4	-	1
Drainage mat roughness	0.01	0.03	0.02	$s/m^{1/3}$	1

Table 2-3. Bio-retention cell parameter ranges for the sensitivity analysis and parameter values used for the assessment of LID performance in Section 2.2. [1](Rossman and Huber, 2016a), [2](Rossman and Huber, 2016b), [4](Sieker *et al.*, 1996)

Parameter	min	max	Value used in Section 2.2	Unit	Reference
Berm height	150	300	300	mm	1
Vegetation volume	0	0.2	0.1	fraction	1
Surface roughness	0.04	0.35	0.16	$s/m^{1/3}$	2
Surface slope	0	10	1	%	
Soil thickness	300	2000	300	mm	2
Porosity	0.3	0.55	0.5	-	2
Field capacity	0.01	0.2	0.2	-	2
Wilting point	0		0.1	-	
Conductivity	50	140	120	mm/h	2
Conductivity slope	30	55	40	-	2
Suction head	50	100	50	mm	2
Storage thickness	150	1500	100	mm	2
Storage void fraction	0.2	0.4	0.3	-	2
Storage seepage rate	7.2	72	10	mm/h	4

Table 2-4. Infiltration trench parameter ranges for the sensitivity analysis and parameter values used for the assessment of LID performance in Section 2.2. [1](Rossman and Huber, 2016a), [4](Sieker *et al.*, 1996)

Parameter	min	max	Value used in Section 2.2	Unit	Reference
Berm height	0	300	300	mm	1
Vegetation volume	0		0.0		
Surface roughness	0.012	0.03	0.02	s/m$^{1/3}$	1
Surface slope	0	10	1.0	%	
Storage thickness	900	3650	1000	mm	1
Storage void ratio	0.2	0.4	0.3	-	1
Storage seepage rate	7.2	72	10	mm/h	4

Table 2-5. Infiltration swale parameter values used for the assessment of LID performance in Section 2.2. [1](Rossman and Huber, 2016a), [2](Rossman and Huber, 2016b)

Parameter	Value used in Section 2.2	Unit
Berm height	300	mm
Vegetation volume	0.1	fraction
Surface roughness	0.16	s/m$^{1/3}$
Surface slope	1.0	%
Soil thickness	300	mm
Porosity	0.5	-
Field capacity	0.2	-
Wilting point	0.1	-
Conductivity	120	mm/h
Conductivity slope	40	-
Suction head	*50*	*mm*

2.4 Storm Water Management Model

The United States Environmental Protection Agency Storm Water Management Model (SWMM) is a dynamic rainfall-runoff simulation model (Rossman, 2015). It is one of the most popular modelling tools among water resource researchers and professionals and can be used at wide range of spatial scales varying from site to catchment scale (Jayasooriya and Ng, 2014). It can be used for single event or continuous long-term simulation of runoff quantity and quality. SWMM has its beginning in 1971 (Metcalf *et al.*, 1971) and was upgraded several times since then. The edition used for this work was SWMM 5.1.010.

SWMM simulates hydrologic processes on the surface as well as routing of runoff in the sewer system. It accounts for a variety of hydrologic processes like time-varying precipitation, interception from depression storage, evaporation of standing surface water, evapotranspiration out of the soil and/or LIDs, infiltration of stormwater into the soil, percolation of infiltrated water into groundwater, and nonlinear reservoir routing of overland flow. SWMM provides the consideration of spatial variability of these processes by dividing the study area into homogeneous subcatchments that comprise fractions of impervious and pervious areas.

SWMM was discussed in several reviews about tools for modeling stormwater management and particularly LIDs (e.g., Zoppou, 2001; Elliott and Trowsdale, 2007; Jayasooriya and Ng, 2014). SWMM can be applied for the evaluation of different LID types such as bio-retention cells, rain barrels, infiltration trenches, or green roofs. As SWMM has undergone upgrades, the approaches to model LID hydrology have been upgraded as well (Rossman and Huber, 2016a). A first simple approach used the void volume available in the LID (Davis and McCuen, 2005) in order to determine how much precipitation depth will be captured. Unfortunately, effects of varying precipitation intensity and storm event frequency on the surface infiltration, soil moisture retention, and storage capacity, were ignored. However, high sophisticated soil physics models are too computationally intensive for implementation in SWMM, considering its field of application. The use of conventional elements and features in SWMM, as suggested by Huber et al. (2006), can result in very complex arrangements (e.g., Lucas, 2010). Consequently, to allow for a reasonable computational effort and level of accuracy for the simulation of storm events, SWMM 5 uses an additional type of element for LIDs (Rossman, 2010).

SWMM provides a soil moisture model comprising different horizontal layers for the simulation of LIDs. Depending on the investigated LID type, a different number and combination of layers is used (Figure 2-3). The layers account for the simulation of the different hydrologic processes within the LID (Figure 2-3). The surface layer captures precipitation as well as runoff from other areas, optionally provides a surface retention volume, accounts for the runoff generation from the LID unit, allows for the infiltration into the soil or storage layer below as well as for evapotranspiration of any ponded surface water. The soil layer represents an engineered soil mixture supporting vegetative growth. The storage layer consists of gravel or other filling materials with a certain fraction of pore spaces. The drainage mat at the bottom of a green roof structure conveys percolated stormwater off the roof. Each layer is defined by a certain number of parameters that affect the hydrologic behavior (overview and parameter ranges in Table 2-2, Table 2-3, Table 2-4, Table 2-5).

The LID unit is simulated by solving a set of flow continuity equations that describe the change in water content in the respective layer over time as the difference between inflow and outflow water flux rates (Rossman and Huber, 2016a). Inflows are the precipitation rate and inflow to the surface layer from runoff captured from other areas. Outflows are the evapotranspiration rate and exfiltration rate into the native soil. Infiltration and percolation are either inflow or outflow, depending on the examined layer. The infiltration of surface water into the soil layer is modeled with the Green-Ampt approach (Green and Ampt, 1911), evapotranspiration is computed from the user-supplied time series of daily potential evapotranspiration, percolation is simulated using Darcy's Law, and the bottom exfiltration (groundwater recharge) rate is assumed to be the saturated hydraulic conductivity of the native soil underneath the LID unit.

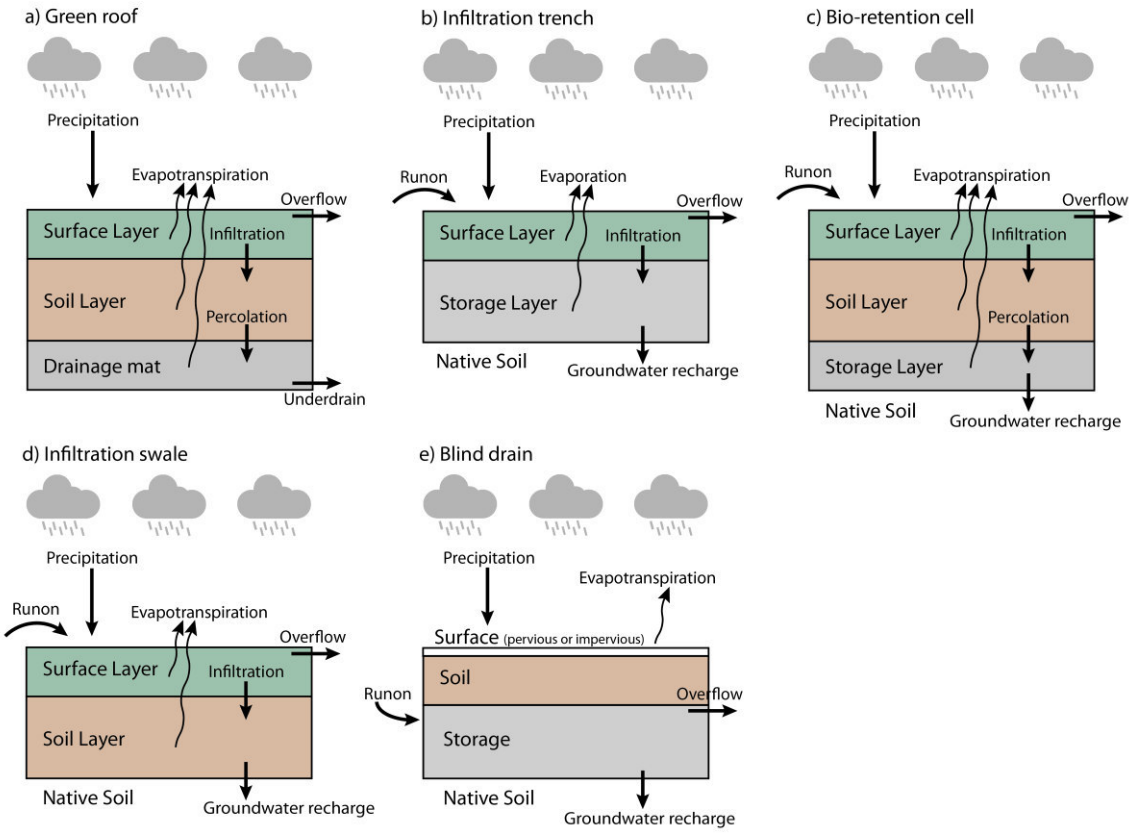

Figure 2-3. Layer concept and simulated hydrologic processes for different types of LIDs: a) green roof, b) infiltration trench, c) bio-retention cell, d) infiltration swale, e) blind drain.

2.5 Storm event separation

A method for the separation of storm events within the precipitation continuum was developed (Paper **I**). It is primarily based on a minimum inter-event time (MIT) (event gap, G_e) that is the most used criterion to separate storm events (Dunkerley, 2008; Molina-Sanchis *et al.*, 2016). Additionally, a threshold for the precipitation depth (threshold-value, T_v) within a certain time period (threshold-time, T_t) is defined to consider the storm period for the separation of storm events. The method works as follows (exemplary scheme in Figure 2-4):

(i) Calculation of precipitation sum (PS) over T_t and every time step of the precipitation continuum as a rolling sum.

(ii) Comparison of PS(t) with T_v. Only if PS(t) > T_v, the respective time period (t – T_t) is considered as a storm period.

(iii) Comparison of time intervals (TI) between obtained storm periods with G_e. If TI > G_e, storm periods are separated to single storm events.

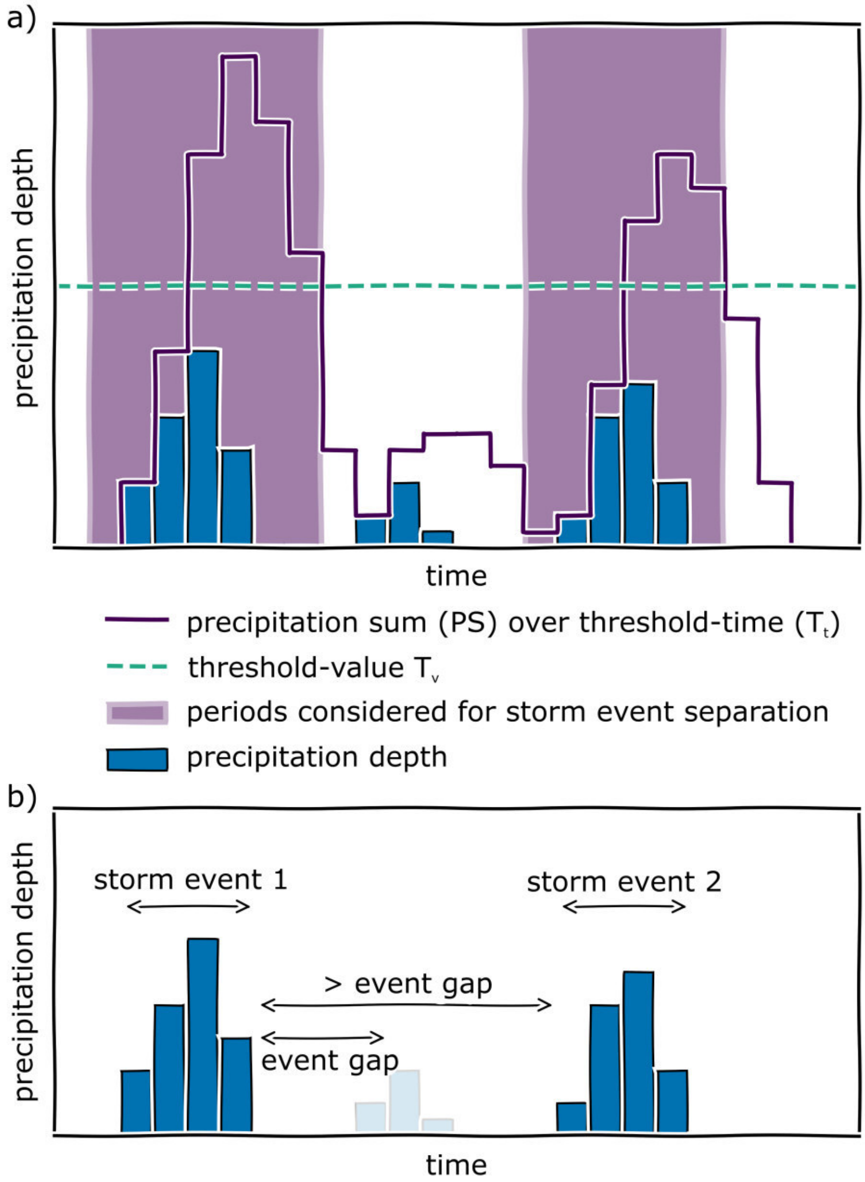

Figure 2-4. Scheme of the method for storm event separation (modified from (Leimgruber *et al.*, 2018)). a) PS(t) with T_t = 4 time intervals is illustrated by the purple continuous line. Periods where PS(t) > T_v (turquoise dashed line) are indicated by the purple-shaded area. b) Periods considered for storm event separation are separated as TI > G_e.

2.6 Dynamic cost comparison calculation

Life cycle costs including construction and maintenance costs can be calculated following a dynamic cost comparison calculation (DWA, 2012). The construction costs and running maintenance costs have to be estimated for each planning alternative. Costs can accrue at different points in time. Simply summing up the costs at different points in time would result in serious miscalculations with respect to the longevity of LIDs. Consequently, in order to facilitate a fair cost comparison, costs have to be time-adjusted using conversion factors based on the period of analysis (life span) and interest rate. Costs have to be converted to one common point in time (reference date) in a dynamic validation procedure. The so-called “present value at the reference date” or “project cost present value” is the time-adjusted value of a cost. Costs arising prior to the reference date are accumulated adding unaccrued interest, costs arising after the reference date are discounted deducting it. The application of conversion factors for a time-based weighting of costs accounts for two major issues: on the one hand, the impact of under- or overestimated past or future cost effects versus those at the present time or point reference, expressed by the interest rate. On the other hand, in order to determine the level of deviation from the nominal costs and resultant present values, the time period between actual cost outflow and reference point is crucial. Thus, the period for discounting and accumulating (interest period) has to be defined by a reference point.

The investigated alternatives can be compared using either the present value of costs or annual costs. For the temporal weighting of costs applying mathematical formula, a distinction is made between (i) individual costs (one-time or single costs), (ii) annually recurring costs (uniform cost series), and (iii) progressively rising cost series (series increasing annually by the same percentage). In this work, the Capital Recovery Factor (CRFAC, also known as annuity factor) was used to convert the individual cost (construction cost) into a uniform cost series:

$$CRFAC(i;n) = \frac{i\ \cdot (1+i)^n}{(1+i)^n - 1} \tag{2-10}$$

where i is the interest rate in % and n is the interest period in years (life span).

2.7 Hydro-meteorological data

The precipitation time series used for the simulations has a length of 10 years comprising the period between the start of 1996 and the end of 2005 (Figure 2-5). It was provided by the Austrian Water and Waste Management Association (OEWAV) (OEWAV, 2007) and was measured in Graz/Austria. It has a recording time interval of 5min, a maximum intensity of 11.4 mm/5min, and an annual average precipitation depth of 783 mm.

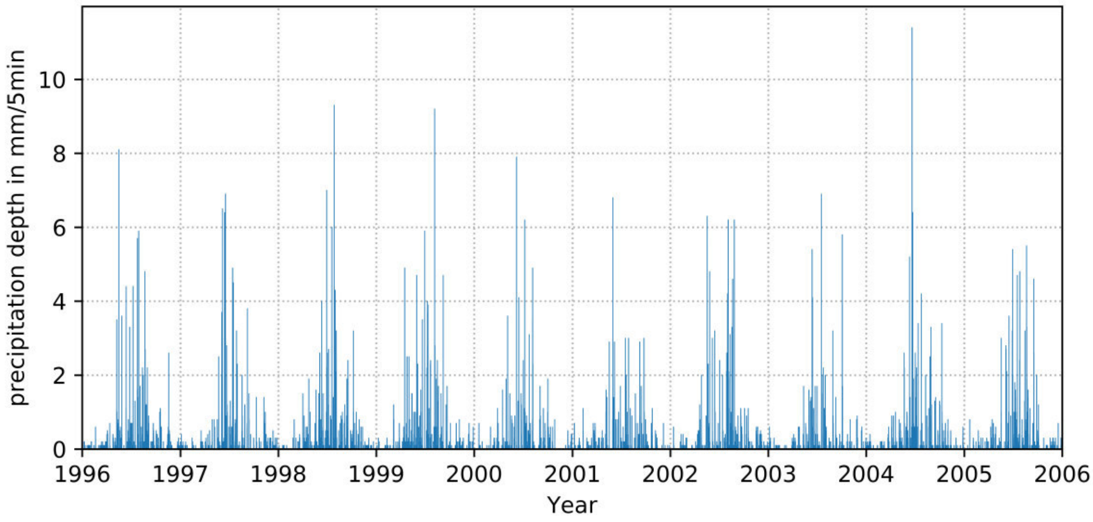

Figure 2-5. Precipitation time series of 10 years (1996-2006) used for the simulations; measurement station: Graz/Austria.

The temperature series for the computation of the evaporation rates is provided by the Central Institute for Meteorology and Geodynamics (ZAMG) (ZAMG, 2017). It provides daily min-max temperatures with an overall minimum of -21.2 °C, mean of 10.6 °C, and maximum of 37.2 °C (Figure 2-6).

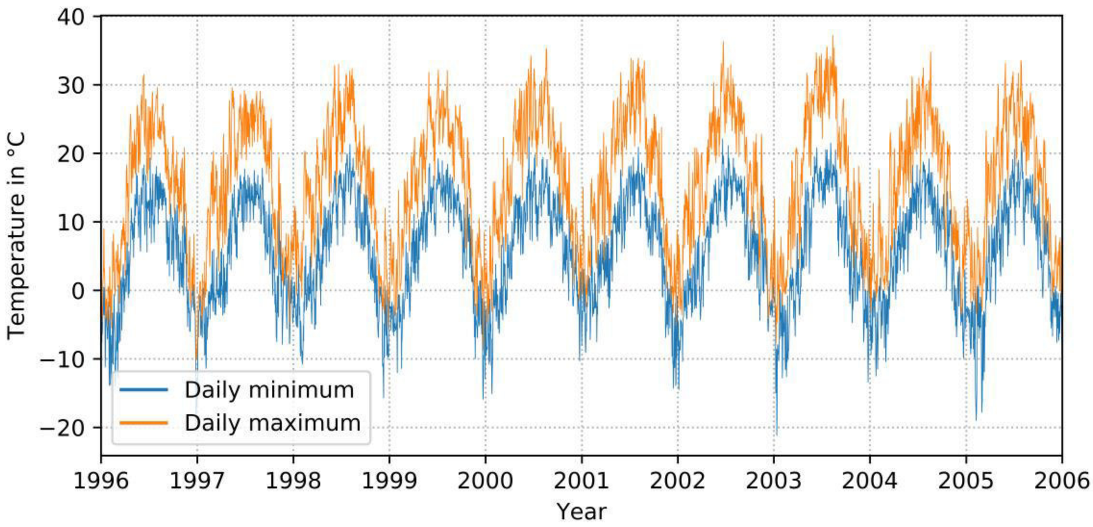

Figure 2-6. Time series of daily min-max temperatures measured in Graz/Austria between 1996 and 2006.

3 Results

3.1 Global sensitivity analysis

The results for the long-term and storm event-based GSA are illustrated below. For further results and details, please refer to Paper **II**.

3.1.1 Long-term evaluation

The change in system storage for the long-term simulations is almost zero and negligibly small compared to the other components. Consequently, it is not further considered for the illustrated results.

The conducted long-term simulations revealed a runoff volume for the green roof ranging between 10.2-54.3% of precipitation depth, whereas the evapotranspiration ranges between 54.8-89.3% (Figure 3-1).

The first-order index S_i as well as the total effect index ST_i is zero (or <0.01) for nine green roof parameters (Table 3-1). The highest S_i results for the *soil thickness*, followed by the *porosity*.

Table 3-1. Result of the long-term sensitivity analysis for the green roof. Non-influential parameters (ST_i < 0.01, blue-shaded); most influential parameters (highest S_i, green-shaded).

	Runoff volume		Evapo-transpiration	
Parameter	S_i	ST_i	S_i	ST_i
Berm height	0.000	0.000	0.000	0.000
Vegetation volume	0.000	0.000	0.000	0.000
Surface roughness	0.000	0.000	0.000	0.000
Surface slope	0.000	0.000	0.000	0.000
Soil thickness	0.795	0.804	0.798	0.807
Porosity	0.168	0.188	0.166	0.186
Field capacity	0.003	0.030	0.003	0.030
Conductivity	0.001	0.004	0.001	0.004
Conductivity slope	0.022	0.024	0.021	0.023
Suction head	0.000	0.000	0.000	0.000
Drainage mat thickness	0.000	0.000	0.000	0.000
Drainage mat void fraction	0.000	0.000	0.000	0.000
Drainage mat roughness	0.000	0.000	0.000	0.000

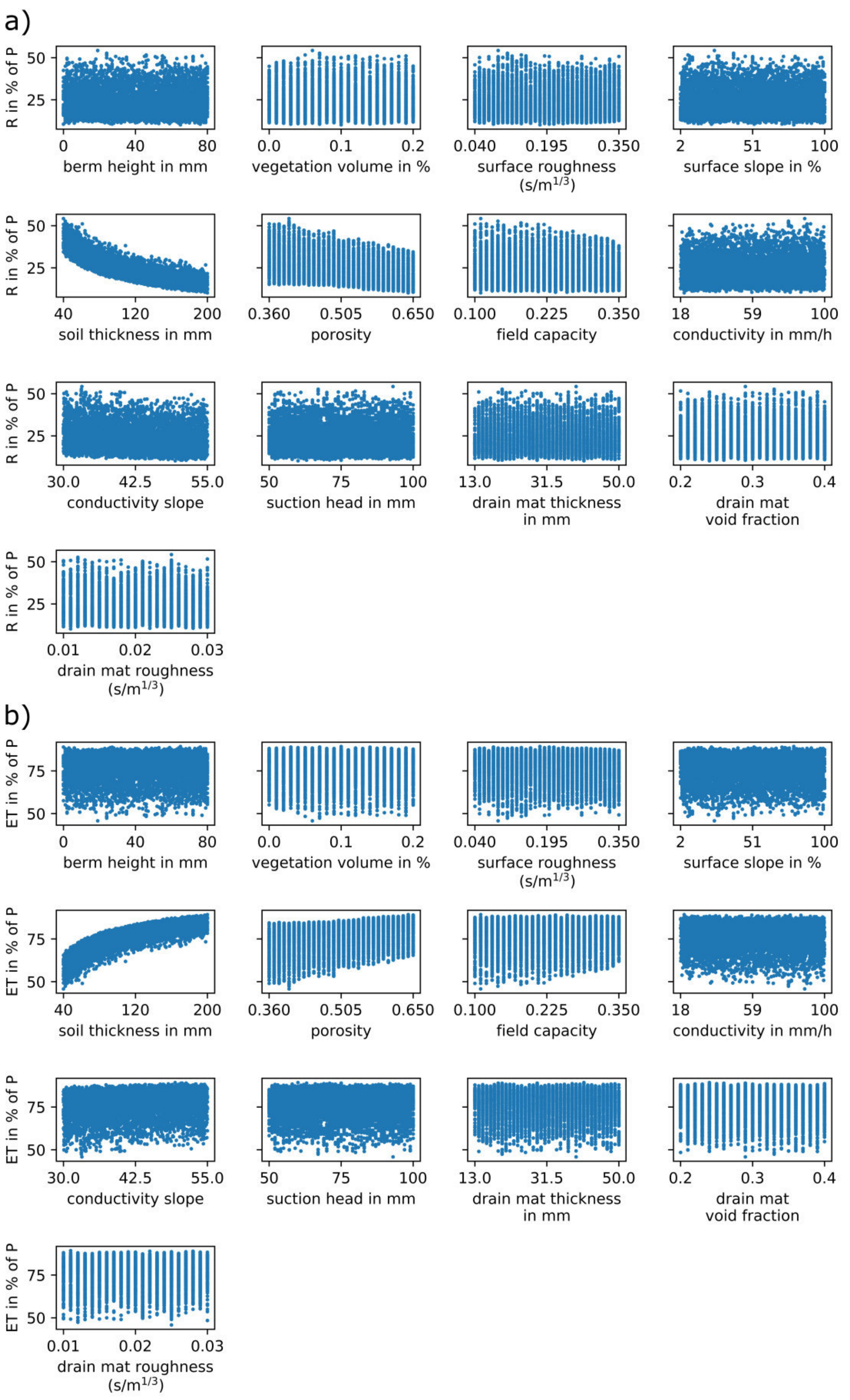

Figure 3-1. Long-term simulation results for the green roof. Each dot illustrates the result of a particular parameter sample. a) Runoff volume (R); b) Evapotranspiration (ET).

The long-term runoff volume for the infiltration trench ranges between 0.0-6.7% of precipitation depth, the evapotranspiration between 8.3-9.3%, and the groundwater recharge between 84.2-91.7% (Figure 3-2).

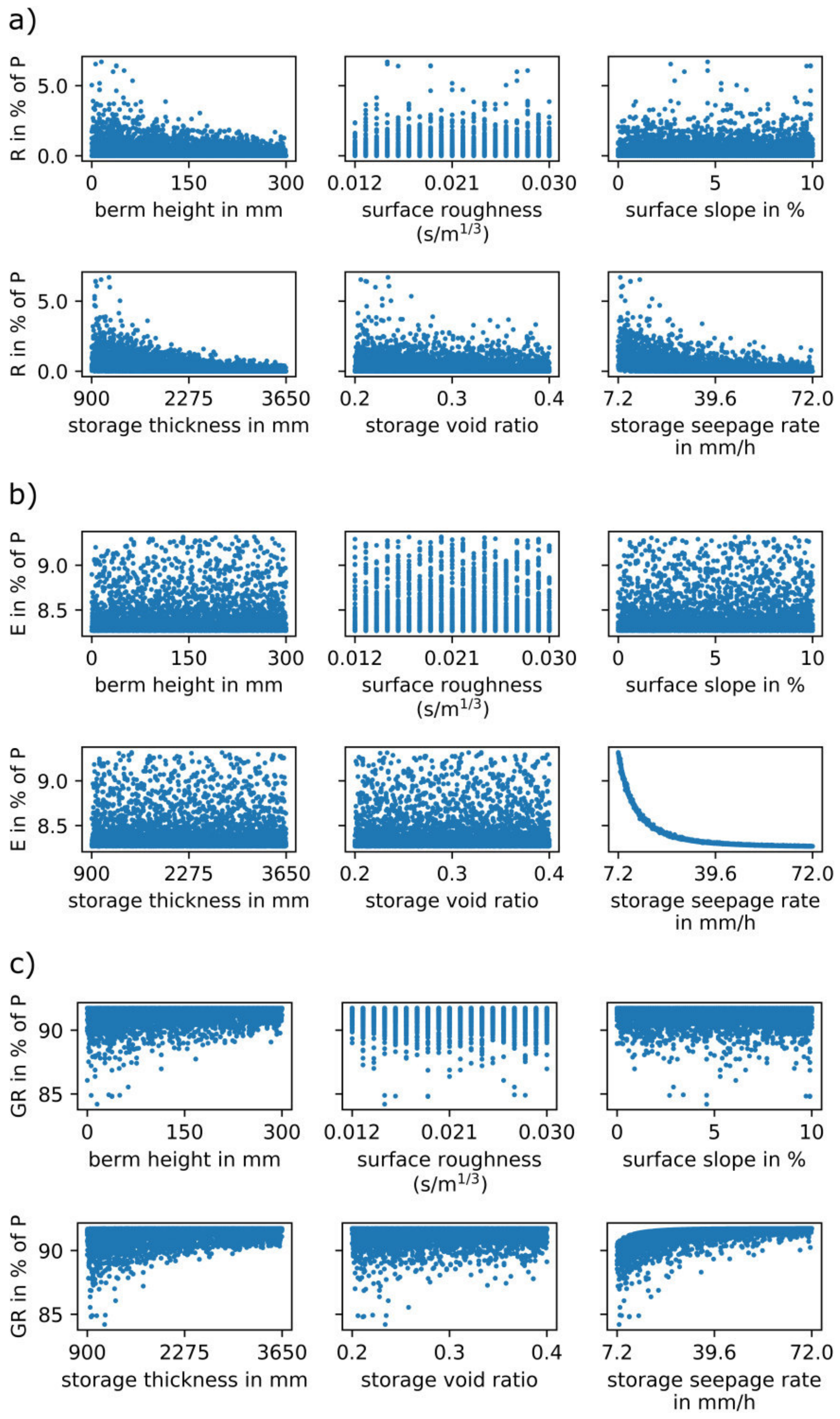

Figure 3-2. Long-term simulation results for the infiltration trench depending on the value of the six green roof parameters. Each dot illustrates the result of a particular parameter sample. a) Runoff volume (R); b) Evapotranspiration (ET); c) Groundwater recharge (GR).

The *storage seepage rate* has the highest S_i for all three water balance components (Table 3-2). The sensitivity indices are zero (or < 0.01) for all other parameters with respect to the evapotranspiration. With respect to the runoff volume and groundwater recharge, the ST_i is zero for the *surface roughness* and *surface slope*.

Table 3-2. Result of the long-term sensitivity analysis for the infiltration trench. Non-influential parameters (ST_i < 0.01, blue-shaded); most influential parameters (highest S_i, green-shaded).

	Runoff volume		Evaporation		Groundwater recharge	
Parameter	S_i	ST_i	S_i	ST_i	S_i	ST_i
Berm height	0.039	0.248	0.001	0.000	0.015	0.161
Surface roughness	0.000	0.000	0.000	0.000	0.000	0.000
Surface slope	0.000	0.000	0.000	0.000	0.000	0.000
Storage thickness	0.216	0.552	0.001	0.000	0.137	0.369
Storage void ratio	0.022	0.094	0.000	0.000	0.013	0.063
Storage seepage rate	0.285	0.465	0.999	1.000	0.533	0.642

3.1.2 Storm event-based evaluation

The separation of storm events revealed 775 individual events. The precipitation depth per storm event ranges between 1.1-124.0 mm with a mean of 8.7 mm. The duration of storm events ranges between 10 min and 25 h with a mean of 3.6 h.

The LID parameters with the highest S_i were used to illustrate the investigations on single storm events. In contrast to the long-term evaluation, the change in system storage may not be zero or negligibly small. It was investigated combined with the groundwater recharge ($\Delta S + GR$). The storm event characteristics ‘precipitation depth’ and ‘antecedent dry period’ were used for the investigations regarding the runoff volume and storage change/groundwater recharge. The length of water balance period (start of storm event to start of next storm event) and the precipitation depth per water balance period were used for the investigations regarding the evapotranspiration.

The storm event-based sensitivity of the runoff volume to the green roof parameter *soil thickness* is clearly affected by the storm event characteristics precipitation depth and antecedent dry period (Figure 3-3a). Higher sensitivity indices were revealed for storm events with high precipitation depth and short antecedent dry period. The results for the storm event-based sensitivity of the evapotranspiration to the *soil thickness* show an influence of the investigated water balance period and the appropriate precipitation depth as well (Figure 3-3b). A long water balance period and/or a small precipitation depth per water balance period results in a higher S_i.

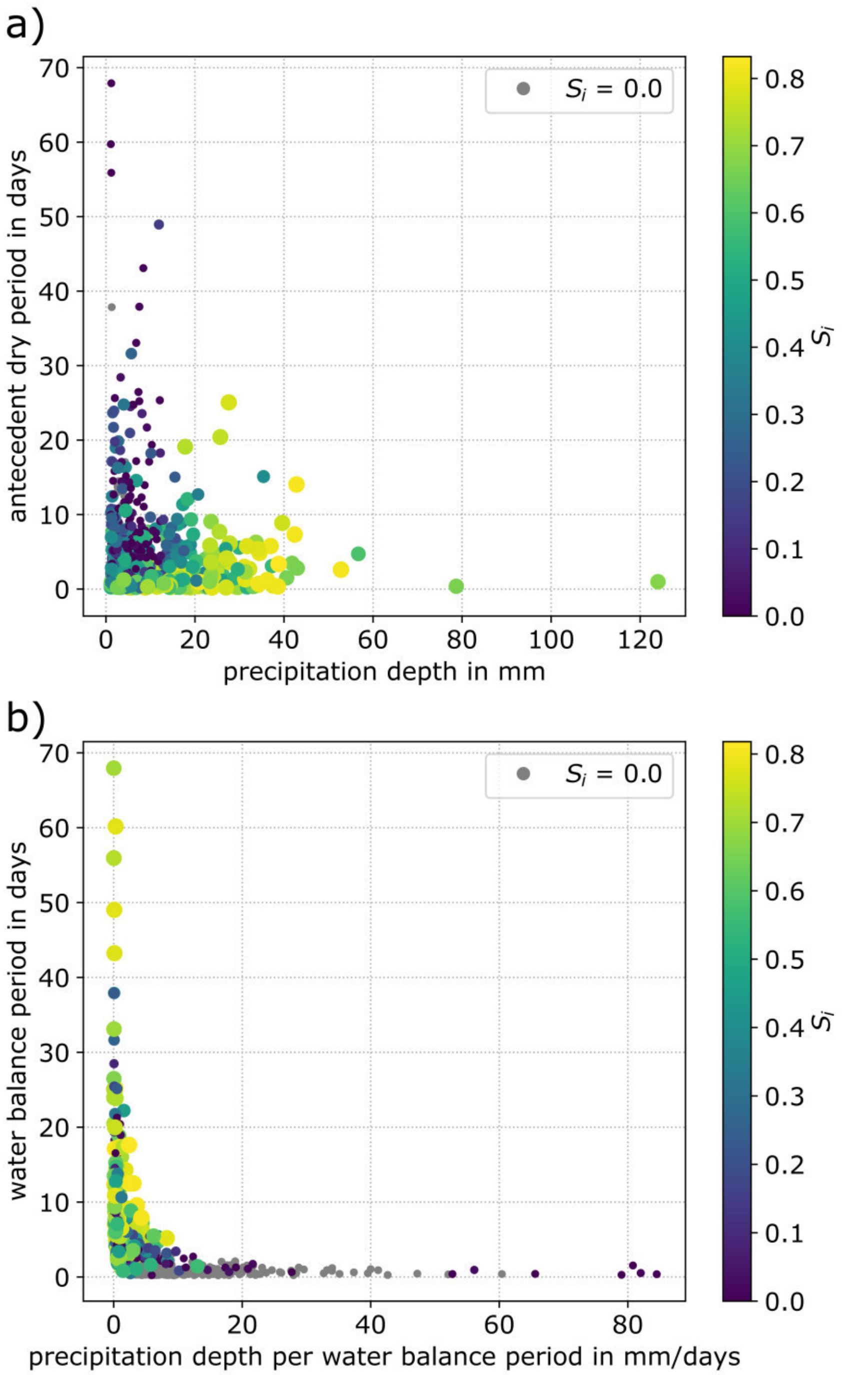

Figure 3-3. Result of storm event-based sensitivity analysis for the green roof parameter *soil thickness*. a) S_i for runoff volume, depending on precipitation depth and antecedent dry period; b) S_i for evapotranspiration, depending on precipitation depth per water balance period and water balance period.

The infiltration trench parameter *storage seepage rate* influences the runoff volume only for storm events with a high precipitation depth and/or short antecedent dry period (Figure 3-4a). In contrast, the storage change/groundwater recharge is highly sensitive to the *storage seepage rate* for the predominant part of the storm events (Figure 3-4b). Only storm events with high precipitation depth and/or small antecedent dry period tend to show a smaller S_i.

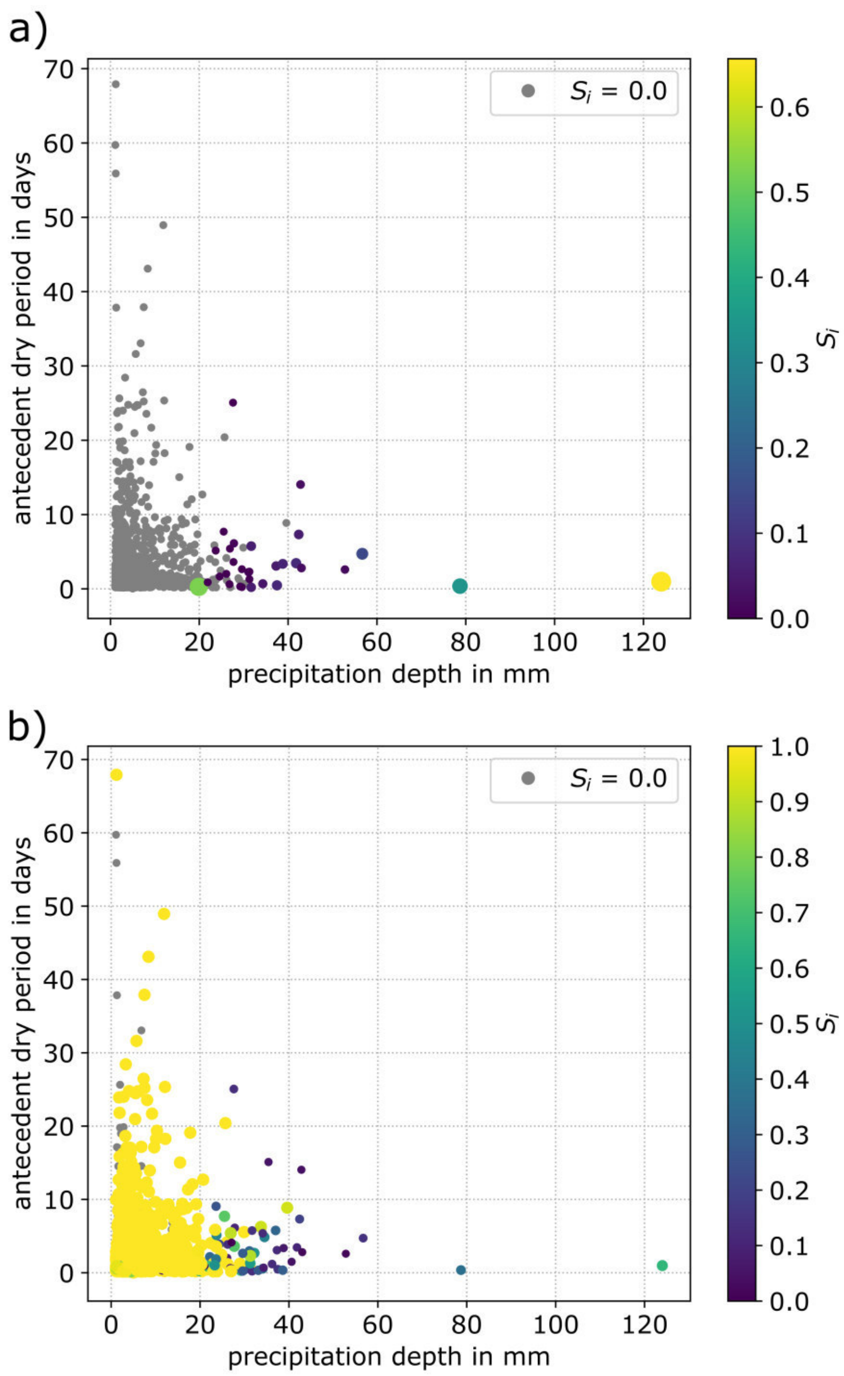

Figure 3-4. Result of storm event-based sensitivity analysis for the infiltration trench parameter *storage seepage rate*, illustrated depending on precipitation depth and antecedent dry period. a) S_i for runoff volume; b) S_i for storage change/groundwater recharge.

3.2 Assessment and selection of LID strategies

The change in system storage is not taken into consideration, as it is almost zero or at least negligibly small compared to the other water balance components for long-term evaluations. The results illustrated below represent only a selection of the complete results and were selected in order to describe the main outcome of the investigations. Further results can be found in Paper **III**.

3.2.1 Water balance, costs, demand for land

The results for the runoff volume are qualitatively similar for all three investigated areas (Figure 3-5, Figure 3-6, Figure 3-7). Differences were revealed for the absolute values. The runoff volume decreases with an increasing size of the applied LID and an associated increase in costs (Figure 3-5a, Figure 3-6a, Figure 3-7a). The evapotranspiration is constant for the blind drain (Figure 3-5b+e, Figure 3-6b+e, Figure 3-7b+e) and the infiltration trench applied to the residential areas (Figure 3-5b+e, Figure 3-6b+e). All other LID strategies show a linear increase of evapotranspiration (Figure 3-5b+e, Figure 3-6b+e, Figure 3-7b+e). The groundwater recharge for the application of the blind drain (Figure 3-5c+f, Figure 3-6c+f, Figure 3-7c+f) and the infiltration trench applied to residential areas (Figure 3-5c+f, Figure 3-6c+f) mirrors the runoff volume. The groundwater recharge results for the infiltration trench applied to the commercial area (Figure 3-7c+f), the infiltration swale and bio-retention cell (Figure 3-5c+f, Figure 3-6c+f, Figure 3-7c+f), are similar except a small decrease of groundwater recharge for larger LIDs.

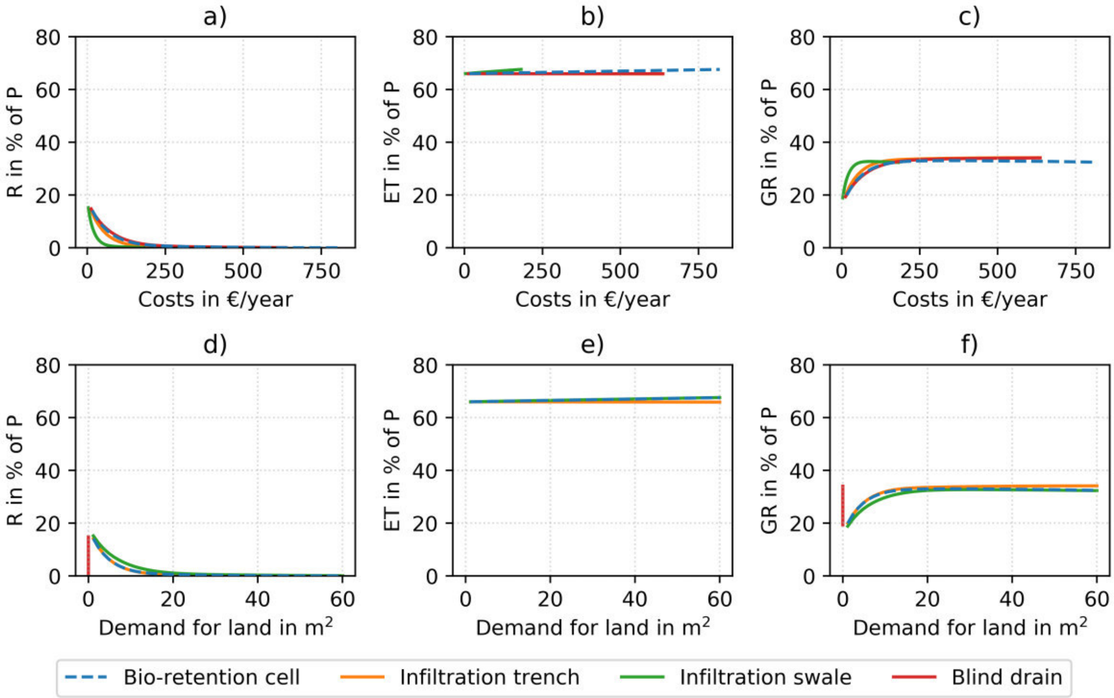

Figure 3-5. Simulated long-term water balance for the low-developed residential area applying single LID strategies of increasing size. Relation between costs (a-c), respectively demand for land (d-f), and runoff volume (a, d), evapotranspiration (b, e), groundwater recharge (c, f).

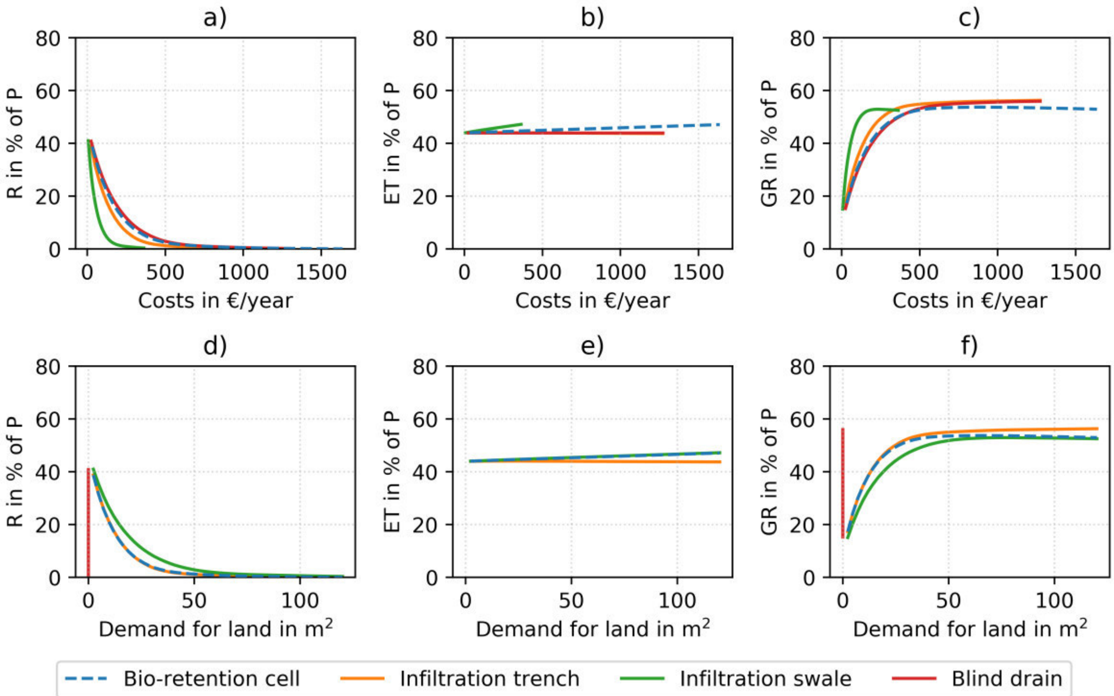

Figure 3-6. Simulated long-term water balance for the high-developed residential area applying single LID strategies of increasing size. Relation between costs (a-c), respectively demand for land (d-f), and runoff volume (a, d), evapotranspiration (b, e), groundwater recharge (c, f).

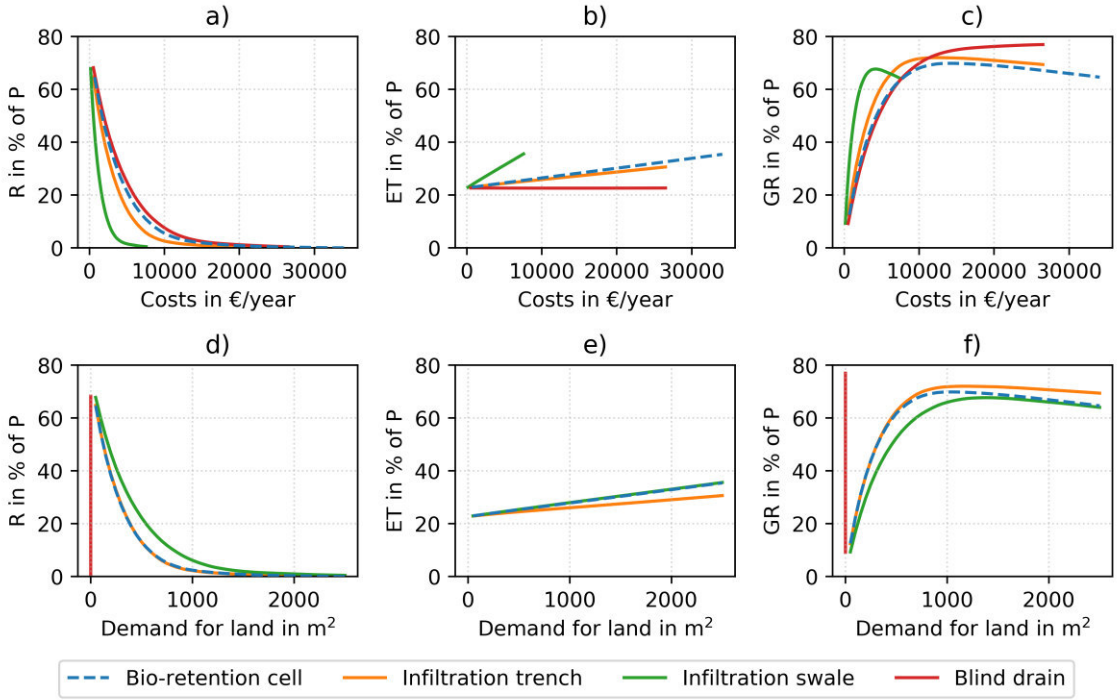

Figure 3-7. Simulated long-term water balance for the commercial area applying single LID strategies of increasing size. Relation between costs (a-c), respectively demand for land (d-f), and runoff volume (a, d), evapotranspiration (b, e), groundwater recharge (c, f).

The effect of applying a green roof and downstream LIDs (LID treatment train) is exemplary illustrated for the commercial area (Figure 3-8). The runoff volume and groundwater recharge obviously decrease whereas the evapotranspiration increases when applying a green roof (Figure 3-8) instead of a tiled roof (Figure 3-7). The qualitative trend for the application of an increasing downstream LID size does not change compared to the scenarios with tiled roof.

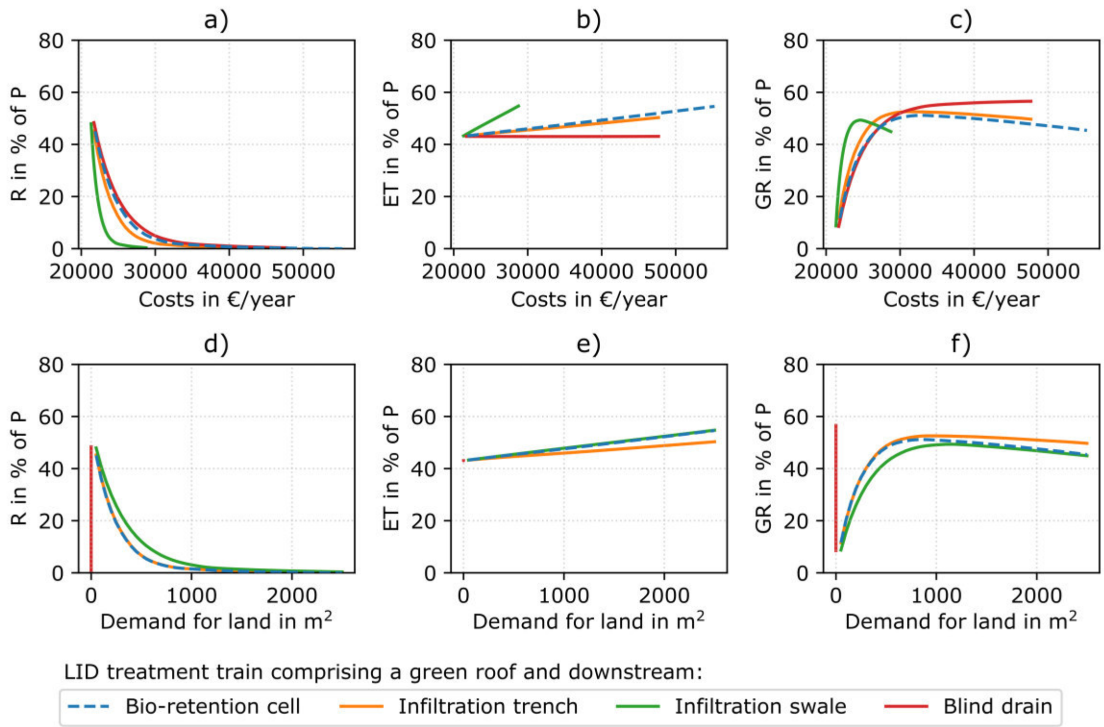

Figure 3-8. Simulated long-term water balance for the commercial area applying a green roof and different downstream LIDs of increasing size (LID treatment train). Relation between costs (a-c), respectively demand for land (d-f), and runoff volume (a, d), evapotranspiration (b, e), groundwater recharge (c, f).

An example for a two-part LID treatment train is an infiltration swale coupled with a downstream blind drain (Figure 3-9). Increasing the proportion of the infiltration swale on the total potential LID area (A_{pot}) results in a decreasing runoff volume and an increasing evapotranspiration. Similar to the single LID result (Figure 3-7) the groundwater recharge increases with an increasing infiltration swale size except for a small decrease for the largest infiltration swales. Applying a downstream blind drain of increasing size decreases the runoff volume, increases the groundwater recharge, but does not affect the evapotranspiration.

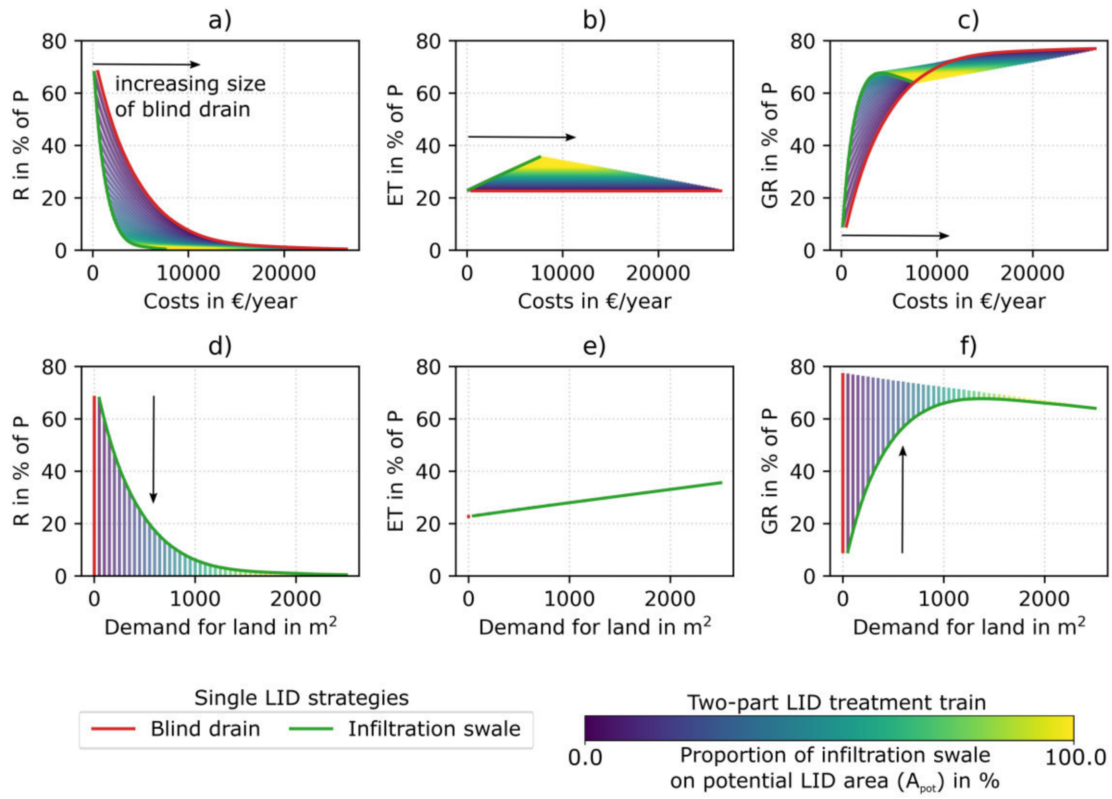

Figure 3-9. Simulated long-term water balance for the commercial area applying a LID treatment train comprising an infiltration swale with altering proportion on potential LID area (A_{pot}) and a downstream blind drain of increasing size. Each colored line of the LID treatment train illustrates the simulation results for a constant proportion of infiltration swale on A_{pot} and an increasing size of the blind drain (indicated by the arrow). Relation between costs and a) runoff volume, b) evapotranspiration, c) groundwater recharge. Relation between demand for land and d) runoff volume, e) evapotranspiration, f) groundwater recharge.

3.2.2 Assessment and efficiency of LID strategies

The deviation from the targeted water balance decreases with an increasing size of a single LID applied but it increases at a certain point (Figure 3-10). A deviation of almost zero is achieved when applying an infiltration swale or a bioretention cell to the high-developed residential area. All single LID strategies show a range of non-dominated options (pareto-optimal).

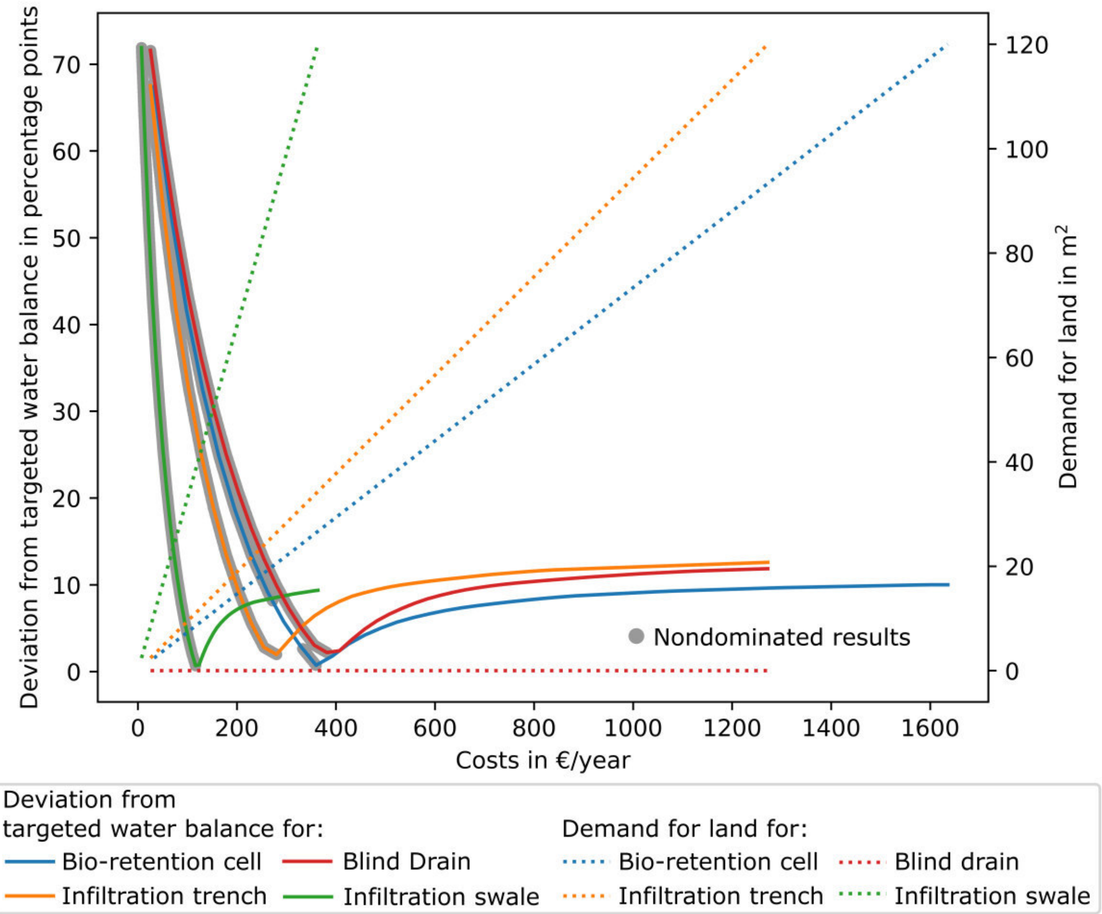

Figure 3-10. Assessment of applying single LID strategies to the high-developed residential area with respect to a targeted water balance and demand for land. The non-dominated results (grey-bold) are only illustrated for the relation costs-deviation from targeted water balance.

The efficiency of LID strategies is illustrated for the single LIDs and a LID treatment train comprising an infiltration swale and a downstream blind drain (Figure 3-11). The results differ when emphasizing different objectives by varying the weighting factors for the deviation from targeted water balance and demand for land (w_{WB}, w_{land}). Non-dominated results are identified for single LID strategies as well as for the LID treatment train.

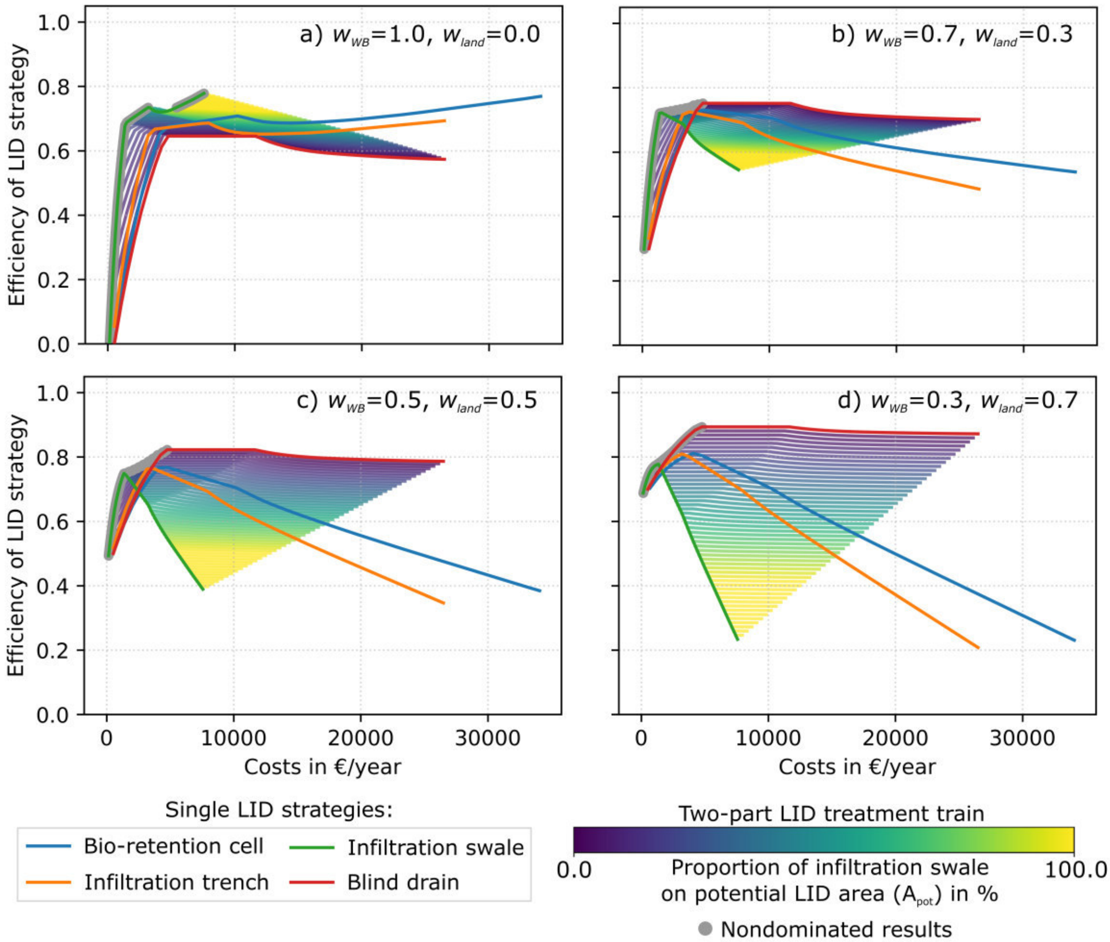

Figure 3-11. Assessment of applying different single LID strategies of increasing size and a LID treatment train consisting of an infiltration swale with altering proportion on total LID area (A_{pot}) and a downstream blind drain of increasing size to the commercial area. Calculation of LID efficiency (E_{LID}) with varying weights deviation from targeted water balance (w_{WB}) and demand for land (w_{land}). Each colored line of the LID treatment train illustrates ELID for a constant proportion of infiltration swale on A_{pot} and an increasing size of the blind drain. The non-dominated results are illustrated in grey-bold.

4 Discussion

LID strategies provide several ecosystem services (for an overview compare, e.g., Tzoulas *et al.*, 2007). Amongst others, they facilitate an increase of biodiversity and habitats in urban areas (Oberndorfer *et al.*, 2007; MacIvor and Lundholm, 2011; Cook-Patton and Bauerle, 2012; Andersson *et al.*, 2014; Braaker *et al.*, 2014), prevent urban heat islands (Santamouris, 2014; Norton *et al.*, 2015), and improve the air quality (Pugh *et al.*, 2012). Green roofs also account for building energy savings (Castleton *et al.*, 2010; Sadineni *et al.*, 2011; Jaffal *et al.*, 2012). In terms of stormwater management, LID strategies are primarily applied to retain stormwater and reduce surface runoff.

However, in order to pursue a holistic approach considering other aspects like micro-climate, the evapotranspiration and groundwater recharge have to be taken into consideration as well. Hydrologic simulations are a reasonable option to evaluate the LID performance with respect to the water balance. The conducted simulations clearly showed the influence of LID parameters and the effect of applying LID strategies on the individual water balance components.

4.1 Sensitivity analysis of model-based water balance to LID parameters

4.1.1 Long-term evaluation

Scatter-plots are a simple and informative way to evaluate the results of a sensitivity analysis. The identification of a pattern indicates that the investigated model output (water balance component) is sensitive to the LID parameter. The clearer the pattern in the plot, the higher might be the potential influence of the LID parameter. The scatter-plots of the simulated water balance components against each LID parameter showed some more or less clear patterns (Figure 3-1, Figure 3-2). The obtained sensitivity indices confirmed the visually derived results (Table 3-1, Table 3-2). On the one hand, several LID parameters were identified that do not affect the model-based water balance. Consequently, they can be fixed anywhere in their range and do not have to be considered further. On the other hand, LID parameters were identified that affect a certain water balance component. Practitioners can focus on those when dealing with the simulation of LIDs and the impact on the water balance for planning purposes.

The scatter-plots for the green roof runoff volume show the most distinct pattern for the *soil thickness* (Figure 3-1a). The scatter-plots for the *porosity* and *field capacity* indicate a similar influence of the parameters on the runoff volume, but to a much smaller extent. The *soil thickness* is the most influential parameter, followed by the *porosity* (Table 3-1). This finding is in agreement with the study of Krebs *et al.* (2016) that revealed the *porosity* as a highly influential parameter for green roof runoff without investigating the *soil thickness*. The total effect index ST_i is zero or close to zero for nine of the parameters (Table 3-1). That implies that the water balance is not affected by these parameters. The results for the evapotranspiration are similar to those of the runoff volume, but inverted with respect to the effect of higher parameter values (Figure 3-1b). The identification of most influential and non-influential parameters is the same as for the runoff volume as well (compare similar values for sensitivity indices in Table 3-1).

The green roof performance with respect to the water balance is expectably affected by the retention volume, which is primarily defined by the *soil thickness* and *porosity*. The available retention volume affects both runoff volume and evapotranspiration. The more stormwater can be retained in the green roof system, the less runoff will occur and the more water is available for evapotranspiration.

The scatter-plots for the infiltration trench runoff volume (Figure 3-2a) and groundwater recharge (Figure 3-2b) show a pattern for parameters that are related to the retention volume (*berm height, storage thickness, storage void ratio*) and the restoration of retention volume (*storage seepage rate*). The larger the retention volume and the faster it is restored, the fewer surcharged conditions and overflow events will occur. The *storage seepage rate* and *storage thickness* are the most influential parameters for the runoff volume and groundwater recharge (highest S_i, Table 3-2). The evapotranspiration is only influenced by the *storage seepage rate* (pattern in Figure 3-2b, $S_i > 0$ in Table 3-2). However, this finding is hydrologically not that relevant as the range for the evapotranspiration is very small (only 1.0 percentage point between minimum and maximum). This small range can be explained by the dominant infiltration due to the small evaporation rates of 6.4 mm/day compared to the minimal seepage rate of 7.2 mm/h (up to 72 mm/h). Additionally, SWMM does not account for the response of evapotranspiration to the soil moisture variation (Youcan and Steven, 2016), which also restricts variations for the simulated evapotranspiration values. The *surface roughness* and *surface slope* are non-influential for the complete water balance ($ST_i = 0$, Table 3-2).

The *storage thickness*, *storage void ratio*, and *storage seepage rate* were identified as influential parameters for the infiltration (groundwater recharge) by the study of Song *et al.* (2018) as well, but not the *berm height*. Differences in results to Song *et al.* (2018) might be based on some different approaches: one-at-a-time sensitivity analysis instead of a GSA, different parameter range for the berm height, application of a single and small storm event instead of a precipitation continuum for the sensitivity analysis. Song *et al.* (2018) did not reveal the runoff volume to be sensitive to any infiltration trench parameters. The reason for this result is the precipitation data used (only a single and small storm event) which does not cause runoff.

4.1.2 Storm event-based evaluation

The storm event-based GSA clearly revealed differences in the sensitivity indices obtained for different storm events. It showed that the sensitivity of water balance components to LID parameters depends on storm event characteristics.

With respect to the green roof, storm events with a small precipitation depth tend to result in small sensitivity indices as it is more likely that stormwater is retained in the green roof and no or little runoff occurs (Figure 3-3a). The probability that no runoff occurs increases with longer antecedent dry periods as well, resulting again in lower sensitivity indices (Figure 3-3a). A longer antecedent dry period implies a higher restoration of green roof retention volume due to evapotranspiration. Thus, evapotranspiration is a key process that controls the green roof retention capacity (in agreement with Palla *et al.*, 2008; Kasmin *et al.*, 2010; Stovin *et al.*, 2013). The precipitation depth of a storm event and the inter-event time influence the availability of water in green roof systems as they affect the occurrence of dry conditions. On the one hand, a longer investigation period for water balance (storm event + inter-event time) tends to result in higher sensitivity indices as the soil falls dry more likely (Figure 3-3b). On the other hand, the probability of dry conditions decreases with higher precipitation depths, resulting in very small sensitivity indices (Figure 3-3b).

In contrast to the green roof, an infiltration trench should not show a runoff or at least only with a certain recurrence time according to planning guidelines (for an overview of international approaches compare Ballard *et al.*, 2016). Consequently, the runoff volume should only be sensitive to infiltration trench parameters for storm events that cause surcharged conditions. Such surcharged conditions are encouraged by a high precipitation depth and/or a short antecedent dry period, which accounts for the restoration of retention volume. These assumptions are confirmed by the storm event-based sensitivity analysis results. The runoff volume is only sensitive to the *storage seepage rate* for storm events with high precipitation depth and/or short antecedent dry period (Figure 3-4a). The occurrence of surcharged conditions and runoff also affects the results for the storage change/groundwater recharge (Figure 3-4b) as overflowing water is not available for infiltration anymore. Therefore, smaller sensitivity indices for some storm events with higher precipitation depth and shorter antecedent dry period were computed. The predominant fraction of the storm events shows a high influence of the *storage seepage rate* on the storage change/groundwater recharge (Figure 3-4b). The stormwater volume that infiltrates into the native soil below is affected by this parameter especially for short-term investigations.

The inter-event time (antecedent dry period) affects the hydrologic conditions at the start of a storm event and consequently the LID performance. Furthermore, it is crucial for the evapotranspiration as it might limit the water availability. Consequently, long-term and continuous simulations and evaluations are needed for a reasonable assessment of LID performance. According to this, long-term simulations have to be used even for single storm event evaluations.

The influence of storm event characteristics also indicates that the GSA results are related to the precipitation time series used. Using another precipitation time series with e.g. less annual precipitation depth may not result in any runoff for a particular LID. That would also imply that no sensitivity of runoff volume would be identified to the respective LID parameters. Using other temperature time series could also change the GSA results. The temperature controls the evapotranspiration and consequently also the drying time, e.g., of the green roof soil. If dry conditions never appear, no sensitivity of evapotranspiration to a LID parameter would be identified.

4.2 Assessment and selection of LID strategies

4.2.1 Water balance, costs, demand for land

The results for the application of LIDs with respect to the water balance are in agreement with many field and laboratory studies as well as evaluations based on hydrologic simulations (for an overview compare Ahiablame *et al.*, 2012; Eckart *et al.*, 2017): All LID strategies are capable to reduce the runoff volume due to their retention volume. The green roof, bio-retention cell, and infiltration swale induce an increase of evapotranspiration as stormwater is retained in the soil layer. The increase is linear as SWMM does not account for the response of evapotranspiration to the soil moisture variation (Youcan and Steven, 2016). The underground blind drain does naturally not affect the evapotranspiration, but it increases the groundwater recharge substantially, just as well as the infiltration trench does.

The investigations were on the level of a single site. For a holistic approach, the challenge is to find a LID strategy that addresses all water balance components regarding the deviation from a target state. For assessments at a larger scale, some compensations between sites can also be taken into consideration. LID strategies that exceed a certain targeted water balance component can be reasonable to counterbalance another site where this component is achievable or only with very high costs or demand for land or even not at all. However, an assessment at the site scale should be preferred, as suggested also by Burns *et al.* (2012), in order to restore natural hydrologic processes at small scales. That is reasonable to consequently restore natural flow regimes at larger scales downstream and when thinking of micro-climate issues.

The decrease curves of runoff volume when applying LID strategies of increasing size start steep and flatten converging to a runoff volume of zero (Figure 3-5a, Figure 3-6a, Figure 3-7a). Thus, the additional benefit of financial investment decreases with an increasing LID size with respect to the runoff volume. The costs-runoff-curve is the steepest for the infiltration swale due to the lowest costs per LID unit. Considering only the costs, the infiltration trench performance is better compared to the bio-retention cell and blind drain due to lower costs per LID unit and a larger retention volume (surface storage), respectively. With respect to the demand for land, the infiltration trench and bio-retention cell provide a better and similar performance as they have a larger and similar retention volume per LID unit compared to the infiltration swale (Figure 3-5d, Figure 3-6d, Figure 3-7d). The underground blind drain does not require land (Figure 3-5d-f, Figure 3-6d-f, Figure 3-7d-f). Consequently, it is a reasonable option when land is rare/expensive.

However, the underground arrangement of the blind drain implicates that no increase of evapotranspiration is achieved when increasing the blind drain size (Figure 3-5b+e, Figure 3-6b+e, Figure 3-7b+e). Hence, it is not a reasonable option for micro-climate issues as no cooling effect due to evapotranspiration is provided (compare, e.g., Bowler *et al.*, 2010; Santamouris, 2014). The kind of surface above the blind drain (pervious lawn for the residential areas, impervious road/parking lot for the commercial area) and the ratio of impervious to pervious surface in the area (different dod for residential areas) control the value of the constant evapotranspiration. The different kind of surface also accounts for different results between the residential and commercial area with respect to the infiltration trench and evapotranspiration (Figure 3-5b+e, Figure 3-6b+e, Figure 3-7b+e). The infiltration trench performance regarding the evapotranspiration is not substantially better than those of the lawn.

The increase of evapotranspiration for the increasing size of infiltration swale and bio-retention cell is equal and linear as SWMM does not account for the response of evapotranspiration to the soil moisture variation (Youcan and Steven, 2016) (Figure 3-5b+e, Figure 3-6b+e, Figure 3-7b+e).

The groundwater recharge shows the proper opposite of the runoff volume (Figure 3-5c+f, Figure 3-6c+f, Figure 3-7c+f). An exception is a small decrease of groundwater recharge for the largest LIDs for strategies that result in a linearly increasing evapotranspiration (infiltration swale, bio-retention cell, infiltration trench applied to commercial area) (Figure 3-5c+f, Figure 3-6c+f, Figure 3-7c+f).

The extent of the mentioned effects on the water balance when applying single LID strategies is obviously different for the investigated areas. The effects increase with an increasing degree of imperviousness. The reason is the initial state of the respective area without LIDs. The residential areas already have a lawn area that limits the runoff volume and accounts for evapotranspiration compared to the commercial area. Thus, the commercial area has the highest potential for applying LIDs. Nevertheless, LID strategies are able to improve the water balance for both residential and commercial areas (in agreement with Dietz, 2007).

The hydrologic performance of the green roof is different compared to the tiled roof (Figure 3-7, Figure 3-8). The soil layer retains stormwater, reduces runoff volume and accounts for evapotranspiration. Consequently, also the runoff to a downstream LID is reduced when applying a green roof. Increasing the size of the downstream LID reveals the same effects as the investigations on single LID strategies.

The application of a LID treatment train is suitable to mitigate some shortcomings of single LID strategies. An example is the combination of an infiltration swale that accounts for an increase of evapotranspiration and a downstream blind drain that provides a good infiltration performance and does not require additional land (Figure 3-9). Thus, such a LID treatment train is reasonable to control/improve the complete water balance, especially when land is rare and/or expensive. The size of the infiltration swale can be limited by the maximal land available whereas the size of the blind drain is either limited by a cost budget or it is chosen to achieve a certain runoff volume.

4.2.2 Assessment and efficiency of LID strategies

Both the bio-retention cell and infiltration swale achieve a deviation of almost zero from the targeted water balance when applying them with a certain size to the high-developed residential area (Figure 3-10). The respective costs are higher but the demand for land is smaller for the bio-retention cell (360 €/year, 26.4 m²) than for the infiltration swale (116 €/year, 38.4 m²). It is up to the stakeholders and the particular boundary conditions, e.g. land available, cost limit, etc., to decide which LID to apply. The decision process is driven by the deviation from targeted water balance, the costs, and demand for land. All three values should be minimized. The resulting non-dominated (pareto-optimal) results can be seen as a trade-off between the decision values (deviation from targeted water balance, costs, demand for land).

The calculated efficiency of LID strategies (E_{LID}) combines the impact of invested money on the water balance and the emerging demand for land. In addition, weighting factors can be used in order to emphasize a certain objective. Non-dominated results are identified targeting minimal costs and a maximal E_{LID} (Figure 3-11). With respect to the exemplary investigations, the infiltration swale provides the best results when only the deviation from targeted water balance is considered (Figure 3-11a). E_{LID} increases for LID strategies comprising a blind drain when the weighting factor for the demand for land is increased, as the blind drain does not require land (Figure 3-11b-d). This is valid not only for applying the blind drain as single LID but also in the scope of a treatment train with an infiltration swale. Thus, in highly urbanized areas where land is rare and/or expensive the application of a blind drain provides a reasonable option. However, the inexistent evapotranspiration of a blind drain is a serious shortcoming (Figure 3-11a). The combination with an infiltration swale is consequently especially valuable. The infiltration swale is cost-saving (lowest costs per unit of investigated LIDs) and accounts for an increase of evapotranspiration. The downstream blind drain collects the runoff that cannot infiltrate in the infiltration swale while causing no further demand for land.

The results show impressively that the effect/efficiency of invested money with respect to the water balance is far from proportional (Figure 3-11a). The benefit of an additional investment is stronger for the range of lower investments (e.g. up to 4000 €/year for the infiltration trench and bio-retention cell). The improvement of E_{LID} is small for higher investments as the deviation from targeted water balance is only reduced slightly while the costs increase linearly. It is even possible that E_{LID} decreases at a certain point. That is the case for example for the blind drain as the deviation from targeted water balance increases due to an excessive groundwater recharge (Figure 3-11a, compare also Figure 3-7). Emphasizing the demand for land, E_{LID} decreases also for the other LID strategies (infiltration swale, infiltration trench, bio-retention cell) because the increasing demand for land exceeds the reduction of the deviation from targeted water balance (Figure 3-11b-d).

The results using different values for the weighting factors show that the non-dominated LID strategies vary due to these factors. Depending on the emphasis on the individual objectives, which is a stakeholders' decision due to several boundary conditions, different LID strategies can appear to be reasonable and "most effective".

5 Conclusions

This thesis presents a methodology for a model-based assessment and selection of LID strategies in order to control water balance. The method further considers life cycle costs and demand for land. It can be applied for the selection of a suitable LID strategy as well as for the design of a certain LID strategy.

LIDs aim to mitigate the adverse impacts of urbanization on the water balance. For this purpose, hydrologic simulation is a reasonable option to evaluate LID performance. Pursuing a holistic approach, the evaluation has to consider the complete water balance and not only a certain component, e.g. the runoff. In contrast to several planning guidelines and evaluation approaches, a monitored precipitation time series is used instead of design storm events. Consequently, the conducted long-term and continuous simulations account for the hydrologic conditions at the start of a storm event.

The conducted storm-event based global sensitivity analysis (Paper **II**) revealed this need for long-term simulations even if dealing with single storm event evaluations. The results indicate that the inter-event time cannot be neglected when planning and/or modeling LIDs. The GSA results for individual storm events are affected by storm event characteristics like precipitation depth and antecedent dry time. These characteristics have influence on the occurrence of surcharged conditions (runoff) and restoration of retention volume. For the storm event-based GSA, a method to separate storm events was developed (Paper **I**). The method identifies storm periods that exceed a defined threshold and separates these periods according to a defined time gap. It has little computational effort and can be applied to other studies selecting the method's parameters according to the respective objectives.

The long-term GSA (Paper **II**) revealed LID parameters that are non-influential and that are highly influential for a certain water balance component. LID parameters determining the LID's retention volume and the restoration rate/emptying time were identified as influential. The results are helpful in order to know which parameter should be measured first and with the highest effort to reduce the variance of simulation results most. Non-influential parameters are of lower priority as they can be fixed anywhere in their range without affecting the model output. The results are also valuable for a model-based planning process of LIDs as they indicate which parameter can be adjusted to alter water balance. However, as the GSA results are depending on the precipitation and temperature time series, further investigations are needed for an application to another case study.

The developed method for a model-based assessment and selection of LID strategies to control water balance (Paper **III**) is based on long-term simulations and considers the complete water balance as well. The assessment and selection process is based on three objectives: (i) the deviation from a targeted water balance, (ii) the life cycle costs, and (iii) the demand for land. The simulation results revealed how the application of different LID strategies decreases the runoff volume due to the provided retention volume, increases evapotranspiration and groundwater recharge. The effect on the water balance components differs between the individual LIDs. All LID strategies are capable to reduce the runoff volume. The evapotranspiration is increased by a green roof, bioretention cell, and infiltration swale. The underground blind drain does not affect the evapotranspiration but results in a substantial increase of groundwater recharge, as well as the infiltration trench does. The effect of applying LIDs differs between the investigated case studies. The potential is increasing with an increasing imperviousness as areas with only a small impervious portion already provide a small runoff volume and high evapotranspiration.

The conducted simulations revealed that there is not one specific optimal LID strategy when considering the mentioned three objectives (water balance, demand for land, costs), which are aimed to be minimized. This requirement was used in order to identify non-dominated (pareto-optimal) LID strategies. The simulations revealed non-dominated options for different LID strategies. The results are a fair basis for stakeholders to make their decision. For this purpose, the efficiency of LID strategies (E_{LID}) was further introduced as a measure to evaluate the investigated LID strategies and the respective effect of invested money. The calculation of E_{LID} also provides the possibility to emphasize the individual objectives. Depending on the chosen weighting factors, different LID strategies can be appear to be non-dominated. The blind drain, e.g., is especially valuable when land is rare and/or expensive and a high weighting factor for the demand for land is chosen consequently. The simulation results for the application of a LID treatment train, where LIDs are coupled in series, also indicate a high potential. It is particularly suitable when combining a cost-saving LID that accounts for evapotranspiration (e.g. infiltration swale) and a downstream LID that accounts for infiltration without causing further demand for land (e.g. blind drain).

The method's results provide a well-founded and holistic basis for the selection of suitable LID strategies. Stakeholders can use the results for their stormwater management project considering the particular boundary conditions. They can investigate the effects of applying different LID strategies on the water balance and the respective life cycle costs and demand for land. Finally, they can emphasize a certain objective and choose from several non-dominated results.

The obtained quantitative results are restricted to different boundary conditions used: case studies and hydrologic conditions, precipitation and temperature time series, cost assumptions, etc.. Nevertheless, the method is feasibly applicable to areas with other boundary conditions. Furthermore, it can be used for investigations on the robustness of LID strategies to changing future conditions, e.g. climate change.

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I

PAPER I

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PAPER II

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II

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Sensitivity of Model-Based Water Balance to Low Impact Development Parameters

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Abstract: Low impact development (LID) strategies aim to mitigate the adverse impacts of urbanization, like the increase of runoff and the decrease of evapotranspiration. Hydrological simulation is a reasonable option to evaluate the LID performance with respect to the complete water balance. The sensitivity of water balance components to LID parameters is important for the modeling and planning process of LIDs. This contribution presents the results of a global sensitivity analysis of model-based water balance components (runoff volume, evapotranspiration, groundwater recharge/storage change) using the US Environmental Protection Agency Storm Water Management Model to the parameters (e.g., soil thickness, porosity) of a green roof, an infiltration trench, and a bio-retention cell. All results are based on long-term simulations. The water balance and sensitivity analyses are evaluated for the long-term as well as single storm events. The identification of non-influential and most influential LID parameters for the water balance components is the main outcome of this work. Additionally, the influence of the storm event characteristics precipitation depth and antecedent dry period on the sensitivity of water balance components to LID parameters is shown.

Keywords: global sensitivity analysis; low impact development; stormwater management

1. Introduction

Urbanization implies an increasing imperviousness of surfaces. This process considerably affects the water balance [1]. Runoff increases, whereas evapotranspiration and infiltration/groundwater recharge decrease, resulting in several negative impacts like larger runoff volumes and higher runoff peak rates, increase of flooding event frequency, urban heat islands (UHI), etc. [2–4].

Low impact development (LID) is a widely discussed and implemented concept in stormwater management, with the aim to mitigate the adverse impacts of urbanization. The main goal of LID strategies is to maintain or restore the pre-development hydrologic regime [5,6]. LID tools such as green roofs, bio-retention cells or infiltration trenches use hydrological functions similar to processes that can be observed in natural catchments, e.g., infiltration, evapotranspiration, storage, and attenuation [5,7].

Hydrological simulation is a reasonable and accepted option to evaluate the LID performance with respect to the water balance. Therefore, the pre- and post-development hydrological conditions of a catchment are analyzed. Usually, evaluation approaches (e.g., by Coffman [8]), planning guidelines (e.g., [9,10]) as well as previous studies dealing with LID performance (compare review papers by Ahiablame et al. [7] and Eckart et al. [6]) focus on the runoff component of the water balance. Alterations in evapotranspiration and groundwater recharge/infiltration are neglected, although they play an important role regarding the heat island effect or increased groundwater levels due to artificial groundwater recharge [4,11]. However, holistic approaches (e.g., Henrichs et al. [12], Eger et al. [13], Feng et al. [14]) considering all components of the water balance should be preferred in order to provide a reasonable basis for planning purposes.

Several modeling tools provide the possibility to simulate the hydrological processes of LIDs in order to evaluate their performance (for an overview compare reference by authors Jayasooriya and Ng [15]). The US Environmental Protection Agency Storm Water Management Model (SWMM) [16] used in this study is currently one of the most sophisticated tools in modeling LID performance [15]. The application requires the definition of a varying number of LID parameters (e.g., soil layer thickness, porosity, hydraulic conductivity, etc.) depending on the LID to be simulated, e.g., green roof or bio-retention cell.

The water balance estimation has to be based on continuous simulations to consider the inter-event time resulting in different boundary conditions, e.g., soil moisture, at the start of a storm event. The water balance components can be calculated for the entire simulation period (long-term) as well as for individual storm events.

Recent studies dealing with sensitivity analyses regarding LIDs focused on the green roof performance with respect to effective UHI mitigation [17], the sensitivity of the runoff volume and runoff peak to green roof parameters for calibration purposes [18], the sensitivity of the runoff volume to rain garden parameters to support the decision for future measurement installation sites and smart water control [19], or use a one-at-time (OAT) sensitivity analysis approach [20].

In contrast, this paper presents a global sensitivity analysis (GSA) of the complete water balance to the LID parameters, thus, following a holistic approach considering runoff volume as well as evapotranspiration and groundwater recharge/storage change. GSA focuses on the variance of model output and how it can be apportioned to the different model parameters. Compared to local sensitivity analysis, which investigates sensitivities at one point in the parameter space, global methods aim to assess the model response over the whole parameter space defined by given parameter ranges. Consequently, GSA methods also account for the influence of parameter interactions on the model output. The application of OAT sensitivity analysis to environmental models was demonstrated to be inadequate [21].

The main goal is the identification of non-influential parameters (parameter fixing) and parameters that affect a particular water balance component (parameter prioritization). This is valuable for the planning as well as for the modeling process of LIDs using SWMM. In addition to the long-term GSA, a storm event-based sensitivity analysis complements the investigations and widens the scope of the influence of LID parameters on the water balance. The application of LIDs for stormwater management affects the hydrograph, especially the timing and magnitude of the runoff peak, and is capable of pollutants removal. However, the focus of this paper is on the water balance.

2. Materials and Methods

The following LIDs, which are among the most implemented in stormwater management projects, are investigated: Green roof, bio-retention cell, and infiltration trench.

Bio-retention cells are depressions with an engineered and (partially) vegetated soil mixture placed above a gravel storage bed. Green roofs are a variation of a bio-retention cell with a (partially) vegetated soil layer above a drainage mat that conveys excess water off the roof. Infiltration trenches are ditches filled with gravel providing storage volume for captured runoff to infiltrate into the native soil below [22]. The SWMM setup only consisted of the single LID (green roof) or the LID and the contributing impervious area (bio-retention cell and infiltration trench). The contributing subcatchment to the bio-retention cell and the infiltration is modeled as totally impervious without depression storages.

SWMM simulates LIDs with a soil moisture model consisting of different layers and the corresponding parameters (see layer concept in Figure 1). The surface layer accounts for the runoff generation, the infiltration into the soil or storage layer, and optionally provides a surface storage. Storage volume for stormwater retention is provided by the soil and storage layer. The drainage mat layer of a green roof conveys percolated stormwater from the roof. An overview of the layers and parameters and their ranges used for the sensitivity analysis for the mentioned LIDs can be found in Table 1. For further information about the parameters refer to Rossman and Huber [22]. Please note that the hydrological computations are only affected by the difference between the soil properties and not by their absolute values. In order to reduce the number of parameters, we assumed the *wilting point* to be zero while adapting the other two soil properties accordingly. The *vegetation volume* for the infiltration trench was assumed to be zero, according to Rossman and Huber [22]. The optional underdrain for the infiltration trench and bio-retention cell was not considered, as the focus was on LIDs applicable for the restoration of the natural water balance without the projected runoff. Clogging was not considered either, assuming a pretreatment, and as it only affects the already investigated hydraulic conductivity of the soil underneath a gravel storage layer [22].

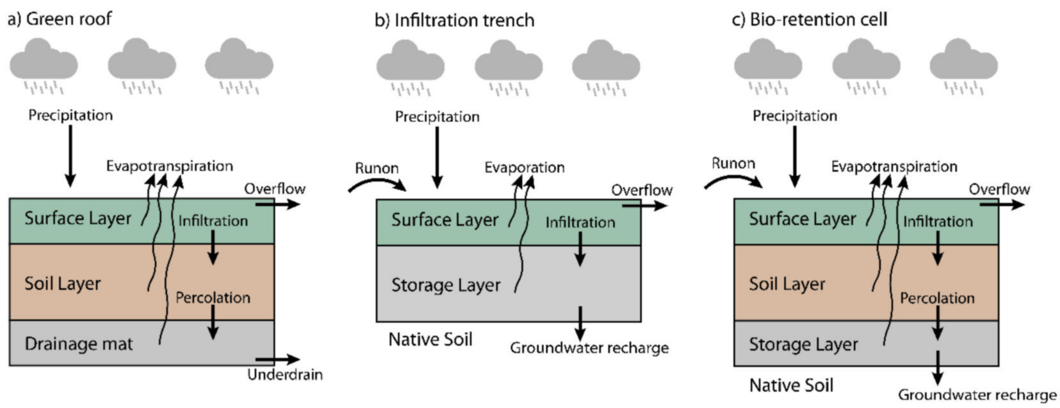

Figure 1. Layer concept and simulated processes in Storm Water Management Model (SWMM) for (**a**) green roof, (**b**) infiltration trench, and (**c**) bio-retention cell.

SWMM considers the processes of runoff, infiltration, and evapotranspiration (for details see Figure 1). Consequently, the water balance can be calculated:

$$\Delta S + GR = P - ET - R \tag{1}$$

where P is the precipitation, R is the runoff volume (overflow + underdrain), ET is the evapotranspiration, GR is the groundwater recharge and ΔS is the change in system storage. Runoff and evapotranspiration are key processes regarding the urban surface hydrology and are investigated individually. The remaining components, groundwater recharge and change in system storage, are investigated jointly.

The maximal number of parameters for the GSA is 13 (green roof) and the computation time per run is short (ca. 1–2 min.). These boundary conditions affect the selection of a reasonable GSA method (for the variety of GSA methods compare Saltelli et al. [23]). According to Saltelli et al. [24], the variance-based method of Sobol [25], which can be applied even if the model is non-linear or non-monotonic, is used to calculate the first-order sensitivity index S_i as well as the total effect sensitivity index ST_i.

$$S_i = \frac{V_{X_i}(E_{X\sim i}(Y|X_i))}{V(Y)} \tag{2}$$

$$ST_i = \frac{E(V(Y|X_{\sim i}))}{V(Y)} \tag{3}$$

where S_i is the first-order index, ST_i is the total effect index, Y is the variable (model output), X is the parameter, V is the variance, $X_{\sim i}$ are all parameters but X_i, and E denotes the average. $V_{X_i}(E_{X\sim i}(Y|X_i))$ is called the first-order effect of X_i on Y and is the variation of the average Y when fixing X_i at different values while varying the other parameters. $E(V(Y|X_{\sim i}))$ is called the total effect of X_i on Y and is the average variation of Y when varying X_i while fixing the other parameters at different values. Equation 4 shows the algebraic rule of how the variation of Y can be expressed:

$$E_{X_i}(V_{X\sim i}(Y|X_i)) + V_{X_i}(E_{X\sim i}(Y|X_i)) \ = \ V(Y) \tag{4}$$

The first-order index S_i represents the main effect contribution of each parameter X_i to the variance of the output. It indicates by how much the output variance could be reduced on average if X_i could be fixed. S_i can be used for the "parameter prioritization" setting finding the most influential parameter that one should measure first in order to reduce the variance. The total effect index ST_i accounts for the total contribution to the output variation due to factor X_i, thus, it summarizes its first-order effect plus all higher-order effects due to interactions. A total effect index ST_i of zero implies that X_i is non-influential and can be fixed anywhere in its distribution without affecting the variance of the output. Consequently, ST_i can be used for the "parameter fixing" setting. For further information about the GSA method used refer to Sobol [25], and Saltelli et al. [23].

In addition to these numerical results, input/output scatterplots (e.g., water balance component versus LID parameter values) are a very simple and informative way to evaluate the results of a sensitivity analysis. Identifying a pattern for such a scatter-plot indicates that this water balance component is sensitive to the LID parameter. The clearer the shape or pattern in the plot, the higher might be the sensitivity. Note that the minimum or maximum of a water balance component does not necessarily appear with the minimum or maximum of the investigated LID parameter as the simulation results are based on parameter samples where interactions between the parameters can occur. However, identifying a mainstream trend (shape or pattern) in the scatterplot indicates that this water balance component is sensitive to the LID parameter.

The sensitivity analysis was implemented using the open-source Python library for Sensitivity Analysis SALib [26]. It uses the sampling scheme proposed by Saltelli [27], which extends the Sobol sequence of quasi-random numbers [28]. Quasi-random sequences are designed to generate a sample that is uniformly distributed over the unit hypercube (considering the min–max range of the parameters). The total cost of the used method is a number of $N(k + 2)$ simulations, where N is the base sample and k is the number of inputs. With a chosen N of 1000 (in accordance to Saltelli et al. [24]), the total cost is 15,000 simulations for the green roof and bio-retention cell and 8000 simulations for the infiltration trench.

The precipitation time series used for the simulations has a length of 10 years (1996–2006, Figure 2) and is provided by the Austrian Water and Waste Management Association (OEWAV) [29]. It was measured at Graz/Austria and has an average annual precipitation depth of 783 mm. The evaporation rates are computed from daily max–min temperatures provided by the Central Institute for Meteorology and Geodynamics (ZAMG) [30]. SWMM offers this option using the Hargreaves method [31]. The temperature series shows a daily minimum of −21.2 °C, a mean of 10.6 °C, and a maximum of 37.2 °C.

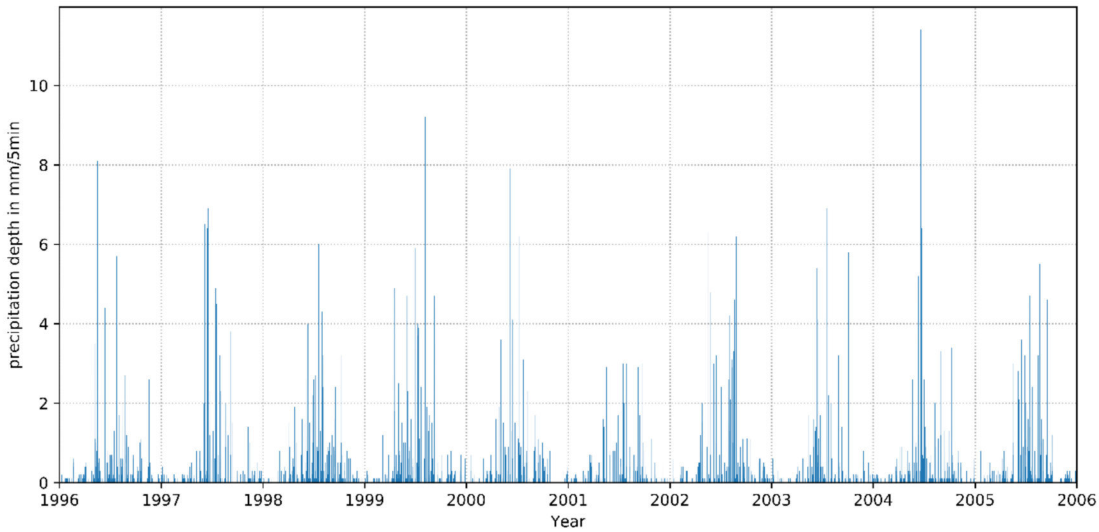

Figure 2. Precipitation time series used for the simulations; measured at Graz/Austria from 1996–2006.

The water balance and the appropriate sensitivities of the components to LID parameters were calculated with long-term simulations as well as for individual storm events within the long-term simulations. The storm events were detected using an event gap (minimum inter-event time) of 4 h and applying a threshold of 1 mm precipitation depth in 1 h to be considered as an individual storm event (for details see Leimgruber et al. [32]). The assessment period for the storm event-based water balance covers the time from the start of a storm event to the start of the next storm event, hence, it includes the storm event and the subsequent inter-event time. Subsequently, the term "water balance period" is used for this assessment period. The precipitation depth and the antecedent dry period were calculated for every storm event in order to investigate the effects of these storm event characteristics on the sensitivity of water balance components to the LID parameters.

Table 1. Low impact development (LID) parameter ranges for the sensitivity analysis.

Green Roof					
Layer	Parameter	min	max	Unit	Reference
Surface	*Berm height*	0	80	mm	[22]
	Vegetation volume	0	0.2	%	[22]
	Surface roughness	0.04	0.35	$s/m^{1/3}$	[33]
	Surface slope	2	100	%	
Soil	*Soil thickness (for extensive green roof)*	40	200	mm	[22]
	Porosity	0.36	0.65	-	[22,34], adapted
	Field capacity	0.1	0.35	-	[22,34], adapted
	Wilting point	0		-	
	Conductivity	18	100	mm/h	[34], adapted
	Conductivity slope	30	55	-	[22]
	Suction head	50	100	mm	[22]
Drainage mat	*Drainage mat thickness*	13	50	mm	[22]
	Drainage mat void fraction	0.2	0.4	-	[22]
	Drainage mat roughness	0.01	0.03	$s/m^{1/3}$	[22]

Table 1. *Cont.*

Layer	Parameter	min	max	Unit	Reference
Infiltration Trench					
Surface	*Berm height*	0	300	mm	[22]
	Vegetation volume	0			
	Surface roughness	0.012	0.03	$s/m^{1/3}$	[22]
	Surface slope	0	10	%	
Storage	*Storage thickness*	900	3650	mm	[22]
	Storage void ratio	0.2	0.4	-	[22]
	Storage seepage rate	7.2	72	mm/h	[35]
Bio-Retention Cell					
Layer	Parameter	min	max	Unit	Reference
Surface	*Berm height*	150	300	mm	[22]
	Vegetation volume	0	0.2	fraction	[22]
	Surface roughness	0.04	0.35	$s/m^{1/3}$	[33]
	Surface slope	0	10	%	
Soil	*Soil thickness*	300	2000	mm	[33]
	Porosity	0.3	0.55	-	[33]
	Field capacity	0.01	0.2	-	[33]
	Wilting point	0		-	
	Conductivity	50	140	mm/h	[33]
	Conductivity slope	30	55	-	[33]
	Suction head	50	100	mm	[33]
Storage	*Storage thickness*	150	1500	mm	[33]
	Storage void fraction	0.2	0.4	-	[33]
	Storage seepage rate	7.2	72	mm/h	[35]

3. Results and Discussion

3.1. Long-Term Results

3.1.1. Green Roof

The simulated long-term runoff volume for the green roof ranges between 10.2–54.3% of total precipitation (Equation (1)) and the evapotranspiration between 45.8–89.3% (Figure 3). As the change in system storage of the green roof water balance is approximately zero and, thus, negligibly small compared to the other components for the long-term observation, no further results are presented for this component.

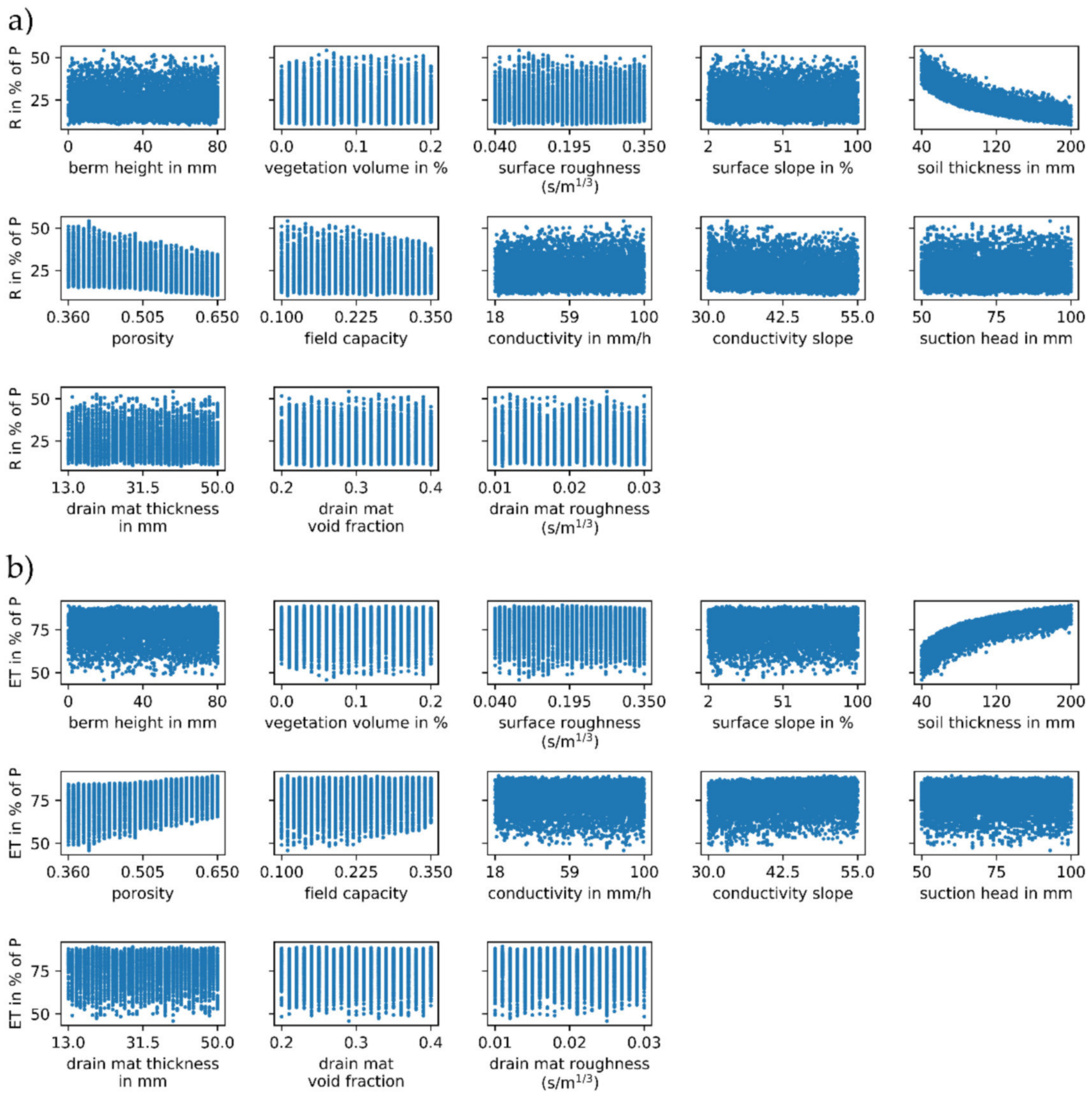

Figure 3. Results of the long-term simulations for the green roof depending on the value of the 13 green roof parameters. Each dot illustrates the result of a parameter sample. (**a**) Runoff volume (R); (**b**) evapotranspiration (ET).

The most distinct pattern in the scatter-plots for the green roof runoff volume can be observed for the *soil thickness* (Figure 3a) indicating that the runoff volume is affected by the *soil thickness*. A larger *soil thickness* results in smaller runoff volumes as more stormwater is retained in the green roof. A similar behavior, to a much smaller extent, can be seen for the parameters *porosity* and *field capacity*.

The visually derived results are confirmed by the obtained sensitivity indices (Table 2). Considering the values of the first-order index S_i, the most influential parameter for the green roof runoff volume is the *soil thickness*, followed by the *porosity*. These observations confirm results presented by Krebs et al. [16] who identified the *porosity* as one of the most influential parameters for green roof runoff without investigating the *soil thickness*. The influence of the *conductivity slope* and the *field capacity* is rather low. All other parameters show a total effect index ST_i of zero (*berm height*, *vegetation volume*, *surface roughness*, *surface slope*, *suction head*, *drainage mat thickness*, *drainage mat void fraction*, *drainage mat roughness*) or close to zero (*conductivity*) (Table 2). That implies that these parameters are non-influential.

Table 2. Result of the long-term sensitivity analysis for the green roof; blue-shaded: Non-influential parameters (ST_i < 0.01), green-shaded: Most influential parameters (highest S_i).

	Runoff Volume		Evapotranspiration	
Parameter	S_i	ST_i	S_i	ST_i
Berm height	0.000	0.000	0.000	0.000
Vegetation volume	0.000	0.000	0.000	0.000
Surface roughness	0.000	0.000	0.000	0.000
Surface slope	0.000	0.000	0.000	0.000
Soil thickness	0.795	0.804	0.798	0.807
Porosity	0.168	0.188	0.166	0.186
Field capacity	0.003	0.030	0.003	0.030
Conductivity	0.001	0.004	0.001	0.004
Conductivity slope	0.022	0.024	0.021	0.023
Suction head	0.000	0.000	0.000	0.000
Drainage mat thickness	0.000	0.000	0.000	0.000
Drainage mat void fraction	0.000	0.000	0.000	0.000
Drainage mat roughness	0.000	0.000	0.000	0.000

Basically, the findings described for the runoff volume are also valid for the evapotranspiration (see Figure 3b and Table 2). In contrast to the runoff volume, larger values of the *soil thickness*, *porosity*, *conductivity slope*, and *field capacity* result, on average, in an increase of the evapotranspiration. The values for the sensitivity indices are similar, thus, the results for the parameter prioritization as well as for the parameter fixing are identical. This is not surprising for green roofs as the runoff volume and the evapotranspiration are both related to the retention volume: The more stormwater that is retained in the green roof the less runoff can occur and the more water is available for evapotranspiration. Therefore, if the runoff volume is sensitive to a parameter, the evapotranspiration should also be sensitive to it and vice versa.

3.1.2. Infiltration Trench

The long-term runoff volume, evaporation, and groundwater recharge for the infiltration trench ranges between 0.0–6.7%, 8.3–9.3%, and 84.2–91.7%, respectively (Figure 4). The long-term change in system storage is negligibly small compared to the other components.

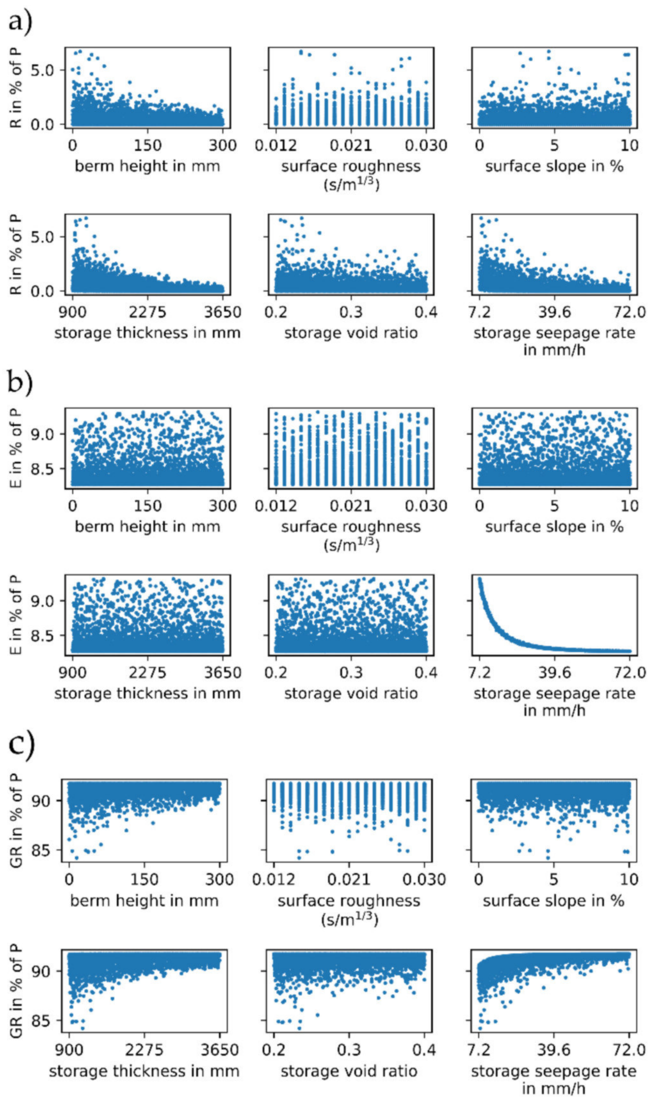

Figure 4. Results of the long-term simulations for the infiltration trench depending on the value of the six infiltration trench parameters. Each dot illustrates the result of a parameter sample. (**a**) Runoff volume (R); (**b**) evaporation (E); (**c**) groundwater recharge (GR).

The scatter-plots for the infiltration trench runoff volume (Figure 4a) and groundwater recharge (Figure 4c) show a rather clear pattern for the *berm height*, *storage thickness*, *storage void ratio*, and *storage seepage rate*. The larger the mentioned parameters are, the smaller the runoff volume is, whereas the groundwater recharge is larger as more stormwater can be retained (*berm height*, *storage thickness*, *storage void ratio*) or as stormwater infiltrates faster (*storage seepage rate*), resulting in fewer surcharged conditions and overflow events. The *surface roughness* as well as the *surface slope* does not show a pattern.

Regarding the evaporation of the infiltration trench, a distinct pattern can only be found for the *storage seepage rate* (Figure 4b). All other parameters do not show a pattern. A smaller seepage rate results in higher values for the evaporation as stormwater is retained for a longer period and, hence, is available for evaporation. However, the results show a very small range (only 1.0% between maximum and minimum), which can be explained with the relatively small evaporation rates of a maximum of 6.4 mm/day in summer compared to the minimal seepage rate of 7.2 mm/h (up to a maximum of 72 mm/h). Thus, infiltration is dominant for an infiltration trench and the investigated parameter ranges. Therefore, there is little variation for the time period in which water is available for evaporation. Additionally, SWMM ignores the response of evapotranspiration to the soil moisture variation [36]. This can also be a reason for little variations obtained for the evapotranspiration values.

The visual observations for the infiltration trench are confirmed by the obtained sensitivity indices (Table 3). The total effect index ST_i is zero for the *surface roughness* and *surface slope* for all three water balance components. Consequently, these two parameters are non-influential for the complete water balance. Regarding the evaporation, only the *storage seepage rate* appears to be sensitive, but as already mentioned, this result should be handled with care, considering the narrow range of the evaporation values. The *storage seepage rate* and the *storage thickness* are the most influential parameters for the runoff volume as well as for the groundwater recharge. Both parameters are affecting the occurrence of surcharged conditions resulting in overflow (runoff) and, thus, less groundwater recharge. The large differences between ST_i and S_i imply that there are strong interactions between the parameters.

Table 3. Results of the long-term sensitivity analysis for the infiltration trench; blue-shaded: Non-influential parameters (ST_i < 0.01), green-shaded: Most influential parameters (highest S_i).

	Runoff Volume		Evaporation		Groundwater Recharge	
Parameter	S_i	ST_i	S_i	ST_i	S_i	ST_i
Berm height	0.039	0.248	0.001	0.000	0.015	0.161
Surface roughness	0.000	0.000	0.000	0.000	0.000	0.000
Surface slope	0.000	0.000	0.000	0.000	0.000	0.000
Storage thickness	0.216	0.552	0.001	0.000	0.137	0.369
Storage void ratio	0.022	0.094	0.000	0.000	0.013	0.063
Storage seepage rate	0.285	0.465	0.999	1.000	0.533	0.642

The study of Song et al. [20] also revealed the *storage thickness*, *storage void ratio*, and *storage seepage rate* as influential parameters for the infiltration (groundwater recharge) but not the *berm height*. The difference in results to Song et al. [20] might be caused by their different approaches: Different range for *berm height* values, one-at-a-time sensitivity analysis instead of a GSA, and only a small storm event instead of the precipitation continuum used for the sensitivity analysis. The precipitation data used in the study [20] is also the reason why the runoff volume appeared to be insensitive to all infiltration trench parameters.

3.1.3. Bio-Retention Cell

The long-term runoff volume, evapotranspiration, and groundwater recharge for the bio-retention cell ranges between 0.0–5.7%, 17.3–17.7%, and 76.6–82.4%, respectively (Figure 5). The long-term change in system change is negligibly small compared to the other components.

The results for the runoff volume and groundwater recharge of the bio-retention cell are correlated. The *surface roughness*, *surface slope*, *porosity*, *field capacity*, *suction head*, and *storage void ratio* do not show a pattern in the scatter-plots for the runoff volume (Figure 5a) as well as for the groundwater recharge (Figure 5c) and have a ST_i of zero or close to zero (compare values in Table 4). Consequently, the mentioned parameters are non-influential for both water balance components. The most influential parameter for the runoff volume and the groundwater recharge is the *storage seepage rate*, followed by the *berm height*, the *conductivity*, and the *soil thickness*. These parameters affect the emptying time (*storage seepage rate*, *conductivity*) and retention capacity (*berm height*, *soil thickness*) of the bio-retention cell.

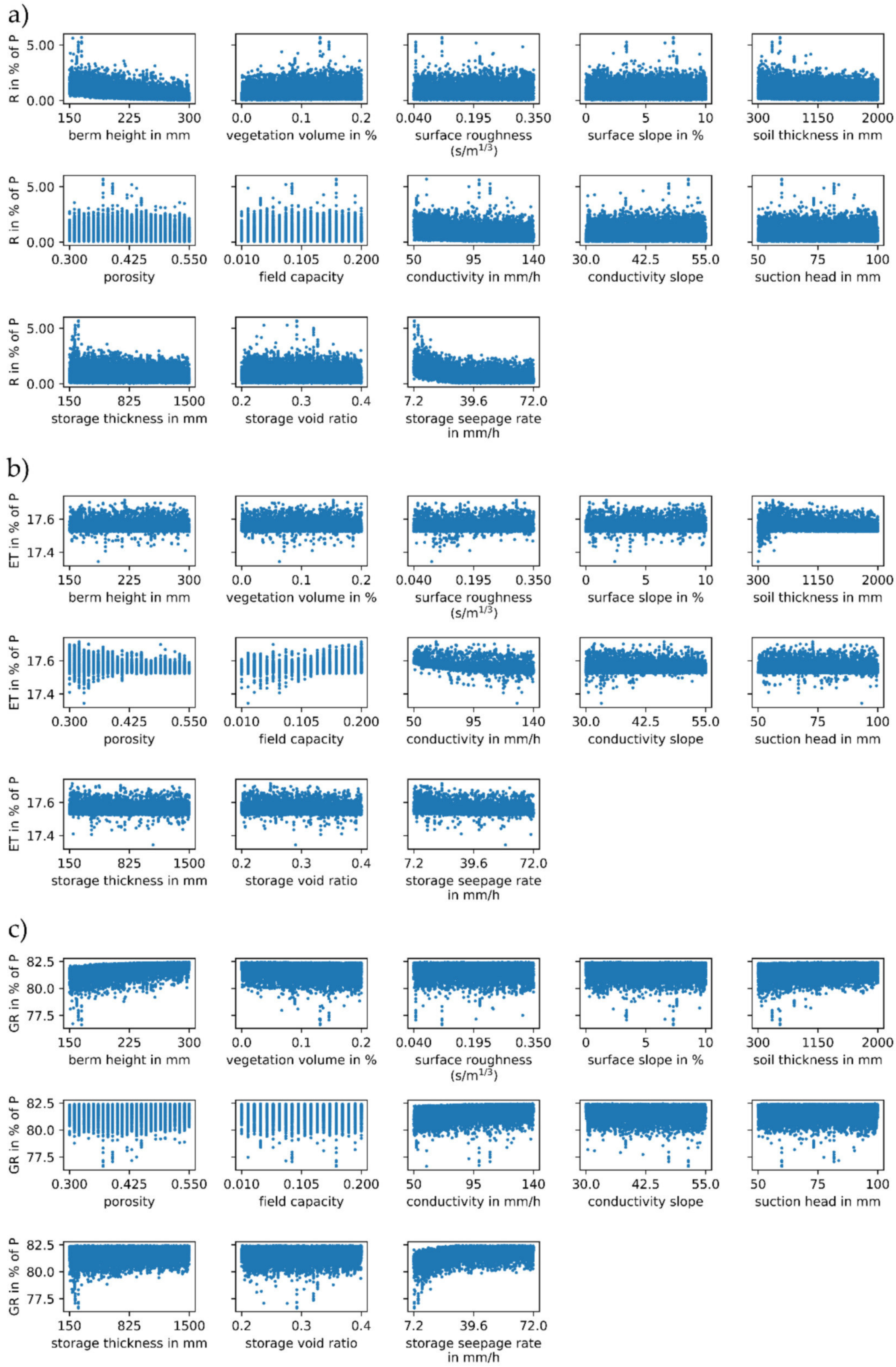

Figure 5. Results of the long-term simulations for the bio-retention cell depending on the value of the 13 bio-retention cell parameters. Each dot illustrates the result of a parameter sample. (**a**) Runoff volume (R); (**b**) evapotranspiration (ET); (**c**) groundwater recharge (GR).

In descending order, the evapotranspiration is most sensitive to the *conductivity*, *field capacity*, *porosity*, and *storage seepage rate* (compare S_i in Table 4), as they affect the volume of stormwater or the time that stormwater is available for evapotranspiration. However, the range of the evapotranspiration values is very small (only 0.4% between maximum and minimum) and the conclusions of the sensitivity analysis have to be regarded with suspicion, therefore. The reason for this small range is the same as for the infiltration trench: Because of the small evapotranspiration rates of a maximum of 6.4 mm/day in summer compared to the minimal seepage rate of 7.2 mm/h (up to a maximum of 72 mm/h), infiltration is dominant for a bio-retention cell and the investigated parameter ranges. Again, as SWMM ignores the response of evapotranspiration to the soil moisture variation, this can be a reason for little variations obtained for the evapotranspiration values as well.

Table 4. Result of the long-term sensitivity analysis for the bio-retention cell; blue-shaded: Non-influential parameters (*STi* < 0.01), green-shaded: Most influential parameters (highest *Si*).

	Runoff Volume		Evapo-Transpiration		Groundwater Recharge	
Parameter	S_i	ST_i	S_i	ST_i	S_i	ST_i
Berm height	0.296	0.336	0.000	0.000	0.282	0.319
Vegetation volume	0.026	0.032	0.000	0.000	0.025	0.030
Surface roughness	0.000	0.000	0.000	0.000	0.000	0.000
Surface slope	0.000	0.000	0.000	0.000	0.000	0.000
Soil thickness	0.052	0.081	0.009	0.134	0.051	0.083
Porosity	0.005	0.006	0.079	0.334	0.005	0.008
Field capacity	0.000	0.000	0.090	0.312	0.002	0.001
Conductivity	0.128	0.160	0.356	0.378	0.141	0.173
Conductivity slope	0.003	0.008	0.016	0.096	0.003	0.008
Suction head	0.002	0.001	0.005	0.004	0.003	0.001
Storage thickness	0.024	0.084	0.026	0.072	0.026	0.087
Storage void ratio	0.000	0.006	0.004	0.004	0.001	0.006
Storage seepage rate	0.348	0.420	0.055	0.111	0.345	0.419

3.2. Storm Event-Based Results

The storm event separation revealed 775 storm events. The event precipitation depth ranges between 1.1–124.0 mm with a mean of 8.7 mm. The duration of the storm events ranges between 10 min and 25 h with a mean of 3.6 h. The maximum storm event intensity (averaged over the duration) is 74.7 mm/h, the minimum 0.61 mm/h and the mean 3.8 mm/h, whereas the maximum storm peak is 11.4 mm/5 min. The maximal return periods are 19 years, 25 years, and 20 years for a duration of 15 min, 60 min, and 720 min, respectively. The water balance was evaluated based on these storm events in order to investigate the effects of storm event characteristics on the sensitivity of LID parameters to water balance components. The investigated LID parameters were those with the highest first-order indices S_i for the respective water balance component. Investigations of other influential parameters have been conducted as well but did not reveal new findings.

In difference to the long-term investigations the change in system storage may not be zero or negligibly small. It is investigated in combination with the groundwater recharge. The storm event characteristics considered for the investigations regarding the runoff volume and storage change/groundwater recharge are the precipitation depth and the antecedent dry period. For the evapotranspiration, the length of the water balance period and the precipitation depth per water balance period were used.

3.2.1. Green Roof

The parameters *soil thickness* (Figure 6a—Runoff volume, Figure 6c—Evapotranspiration) and *porosity* (Figure 6b—Runoff volume, Figure 6d—Evapotranspiration) were used for a storm event-based sensitivity analysis for the green roof.

The storm event characteristics precipitation depth and antecedent dry period show a clear effect on the sensitivity of the runoff volume to the green roof parameter *soil thickness*. The sensitivity tends to increase with an increasing precipitation depth, while it tends to decrease with an increasing antecedent dry period (Figure 6a). Storm events with a very small precipitation depth may not result in a runoff as the complete stormwater is retained in the green roof. Thus, the sensitivity is zero or at least small. The antecedent dry period affects the starting conditions, e.g., soil moisture, for the subsequent storm event. The longer the antecedent dry period, the larger is the green roof retention capacity restoration due to evapotranspiration. A long antecedent dry period results in small sensitivities as the green roof may have its full retention capacity at the start of the storm event. Thus, evapotranspiration is a key process controlling the green roof retention (according to Palla et al., Kasmin et al., Stovin et al. [37–39]). Especially the combination of a large precipitation depth, and a small antecedent dry period results in a high sensitivity of the runoff volume to the *soil thickness*, whereas the opposite combination of a small precipitation depth and a long antecedent dry period results in a very small sensitivity (Figure 6a).

The storm event-based sensitivity of the runoff volume to the green roof parameter *porosity* also shows a relation to the precipitation depth (Figure 6b) and antecedent dry period (Figure 6b), but it is less distinct than to the *soil thickness*. A longer antecedent dry period results in smaller sensitivity indices. A certain trend to higher sensitivity indices can be found for an increasing precipitation depth, but there are also some storm events with a small precipitation depth that result in high sensitivity indices.

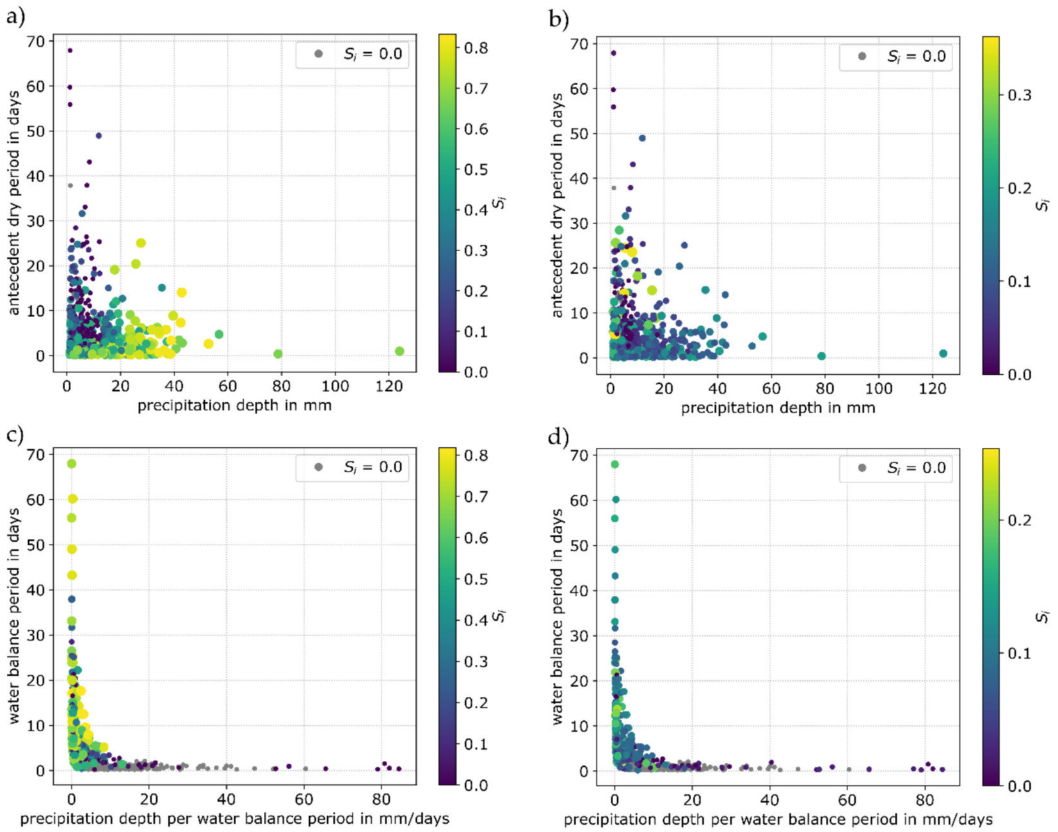

Figure 6. Results of the storm event-based sensitivity analysis for the green roof. *Si* depending on storm event characteristics (**a** + **b**: Precipitation depth—antecedent dry period, **c** + **d**: Water balance period—precipitation depth per water balance period) and green roof parameters. (**a**) *Si* for runoff volume and *soil thickness*; (**b**) *Si* for runoff volume and *porosity*; (**c**) *Si* for evapotranspiration and *soil thickness*; (**d**) *Si* for evapotranspiration and *porosity*. Water balance period: Period from start of a storm event to the start of the subsequent storm event.

SWMM ignores the response of evapotranspiration to the soil moisture variation [36]. Therefore, the availability of water is the most important boundary condition regarding the evapotranspiration. Only if there is water available, evapotranspiration can occur. With respect to the green roof, the availability of water is dependent on the precipitation depth of a storm event and the time to the next storm event (inter-event time) as the soil may become dry. The sensitivity indices tend to increase with an increasing water balance period, as the possibility that the soil falls dry increases (Figure 6c). A high precipitation depth per water balance period results in very small sensitivity indices as the likelihood that the soil falls dry is small (Figure 6c). The mentioned effects of the water balance period length and the precipitation depth per water balance period are also valid for the storm event-based sensitivity of the evapotranspiration to the green roof parameter *porosity* (see Figure 6d).

3.2.2. Infiltration Trench

The investigated parameters for the infiltration trench are the *storage thickness* (Figure 7a—Runoff volume, Figure 7c—Storage change/Groundwater recharge) and the *storage seepage rate* (Figure 7b—Runoff volume, Figure 7d—Storage change/Groundwater recharge). The range for the evapotranspiration values is very small (1.0%) for the long-term results and the storm event-based sensitivity analysis does not show any particularity. Therefore, no results are shown for this water balance component.

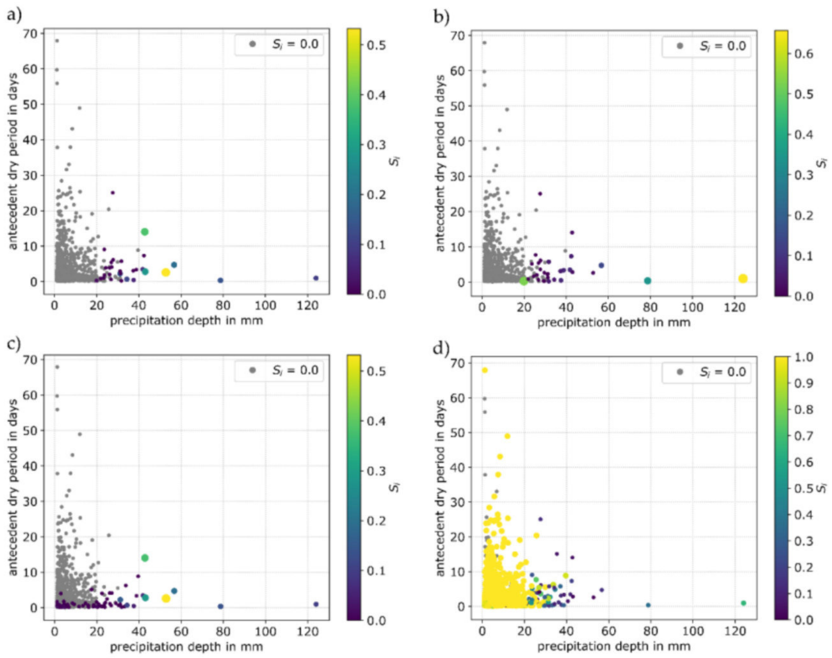

Figure 7. Results of storm event-based sensitivity analysis for the infiltration trench. *Si* depending on storm event characteristics (precipitation depth, antecedent dry period) and infiltration trench parameters: (**a**) *Si* for runoff volume and *storage thickness;* (**b**) *Si* for runoff volume and *storage seepage rate;* (**c**) *Si* for storage change/groundwater recharge and *storage thickness;* (**d**) *Si* for storage change/groundwater recharge and *storage seepage rate.*

According to planning guidelines, the infiltration trench should not show a runoff or at least only with a certain recurrence time. Therefore, the runoff should only be sensitive to an infiltration trench parameter for storm events resulting in surcharged conditions with runoff. Besides a high precipitation depth, a short antecedent dry period potentially causes overflow events as the infiltration trench may not have its full storage capacity at the start of the storm event. The obtained results confirm the mentioned assumptions: The runoff volume is only sensitive to the storage thickness (Figure 7a) as well as to the storage seepage rate (Figure 7b) for storm events with a high precipitation depth and/or a short antecedent dry period.

The storage change/groundwater recharge is highly sensitive ($S1 \approx 1.0$) to the *storage seepage rate* for the predominant part of the storm events (Figure 7d) as this parameter affects the emptying time of the infiltration trench having a big influence on the storage change/groundwater recharge especially for the short-term investigation. Only storm events with high precipitation depths and small antecedent dry periods tend to show smaller sensitivity indices. Such storm events potentially result in runoff, affecting also the storage change/groundwater recharge as overflowing water is not available for infiltration anymore. On the contrary, a sensitivity of the storage change/groundwater recharge to the *storage thickness* appears only for a small number of storm events with high precipitation depth and/or small antecedent dry period (Figure 7c). This result is correlated to the result for the runoff volume (Figure 7a) as the *storage thickness* influences the appearance of surcharged conditions resulting in a runoff and affecting the storage change/groundwater recharge.

3.2.3. Bio-Retention Cell

The investigated parameters for the bio-retention cell are the *storage seepage rate* (Figure 8a—Runoff volume, Figure 8c—Storage change/Groundwater recharge) and the *berm height* (Figure 8b—Runoff volume, Figure 8d—Storage Change/Groundwater recharge). Similar to the infiltration trench results, the range for evapotranspiration values is very small (0.4%) for the long-term results and the storm event-based sensitivity analysis does not show any particularity. Therefore, no results are shown for this water balance component.

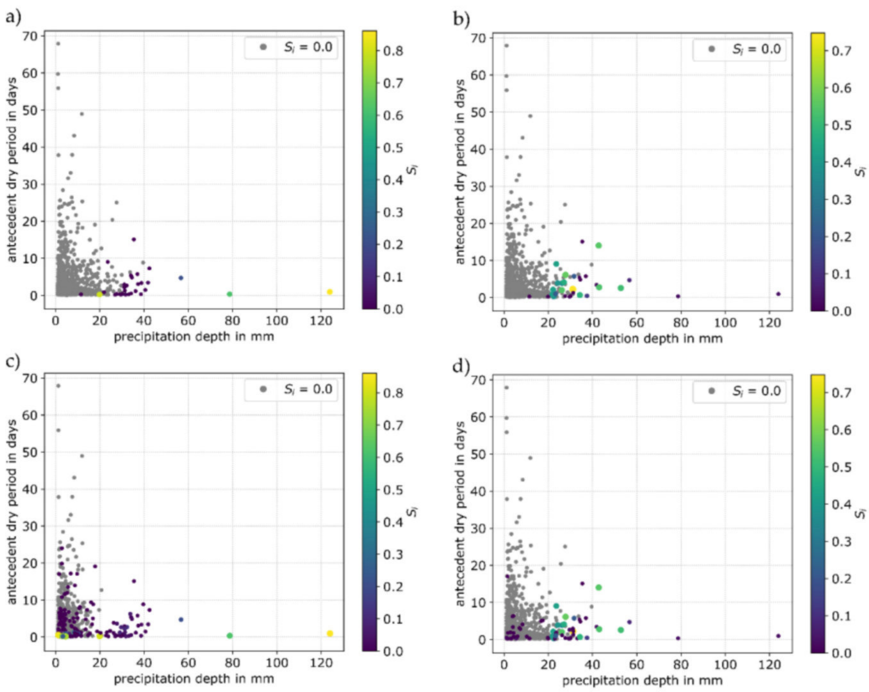

Figure 8. Results of storm event-based sensitivity analysis for the bio-retention cell. *Si* depending on storm event characteristics (precipitation depth, antecedent dry period) and bio-retention cell parameters: (**a**) *Si* for runoff volume and *storage seepage rate;* (**b**) *Si* for runoff volume and *berm height*; (**c**) *Si* for storage change/groundwater recharge and *storage seepage rate*; (**d**) *Si* for storage change/groundwater recharge and *berm height.*

The results for the sensitivities of the runoff volume to the bio-retention cell parameters *storage seepage rate* (Figure 8a) and *berm height* (Figure 8b) are in accordance with the appropriate results for the infiltration trench (Figure 7a,b): Sensitivities can only be found for storm events with a high precipitation depth and/or a short antecedent dry period that may cause surcharged conditions and runoff.

The storage change/groundwater recharge is sensitive to the bio-retention cell parameters *storage seepage rate* (Figure 8c) and *berm height* (Figure 8d) only for a few storm events. Regarding the *berm height*, the results are correlated to the results for the runoff volume (see Figure 8a). The *berm height* influences the occurrence of surcharged conditions resulting in runoff and affecting the storage change/groundwater recharge. Such surcharged conditions appear in conjunction with storm events that show a high precipitation depth and/or a small antecedent dry period. Regarding the *storage seepage rate*, the storage change/groundwater recharge is sensitive to it also for some storm events with smaller precipitation depths but again only for storm events with a short antecedent dry period.

3.3. General Discussion

The long-term GSA revealed non-influential and influential parameters for the water balance of the three investigated LIDs. These results are valuable when using SWMM for planning/modeling LIDs regarding the water balance.

The stormwater retention capacity (affected by the green roof *soil thickness* and *porosity*, the infiltration trench *storage thickness*, and the bio-retention cell *berm height*) and the emptying time (affected by the *storage seepage* rate of the infiltration trench and bio-retention cell) are important characteristics affecting the water balance. The simulated evapotranspiration shows a very small range as infiltration is the dominating process and as SMMM ignores the response of evapotranspiration to the soil moisture variation. The results are mostly in agreement with other studies. Krebs et al. [18] also identified the *porosity* as an important parameter for green roof runoff. The study of Song et al. [20] also revealed the *storage thickness*, *storage void ratio*, and *storage seepage rate* as influential parameters for the infiltration (groundwater recharge). Differences in results to this study are caused by different boundary conditions like the sensitivity analysis method used for the study, parameter ranges, or precipitation data.

The storm event-based GSA showed that the sensitivity of water balance components to LID parameters is influenced by storm event characteristics. The precipitation depth and antecedent dry period affect the occurrence of runoff or surcharged conditions by controlling the stormwater load and the restoration of available storage volume/retention capacity. The evapotranspiration and seepage are key processes controlling the LID retention capacity restoration, especially during the inter-event time. Palla et al., Kasmin et al., and Stovin et al. [37–39] identified the evapotranspiration as a key process controlling the green roof retention as well. The length of the water balance period, which depends on the inter-event time, is crucial for the evapotranspiration as it might limit the water availability. Consequently, long-term evaluations have to be used for a reasonable assessment of LID performance regarding the evapotranspiration.

The storm event-based GSA results indicate that the boundary conditions precipitation depth and antecedent dry period affecting the system state at the start of a storm event have to be considered using long-term simulations even if dealing with single storm event investigations.

The influence of storm event characteristics on the GSA results indicates that using another precipitation time series for the investigations could produce differing GSA results. E.g., a precipitation time series with less annual precipitation depth may not result in any runoff for the infiltration trench or bio-retention cell. Consequently, no sensitivities would be determined for the long-term nor for the storm-event based runoff. A similar impact is valid for the temperature that controls the evapotranspiration. Lower temperatures and consequently lower evapotranspiration rates affect the drying time, e.g., of the green roof soil. Hence, it can occur that the soil never falls dry, resulting in no sensitivities.

4. Conclusions

This study presents the results of a GSA of the simulated water balance to the parameters of a green roof, an infiltration trench, and a bio-retention cell. All evaluations are based on long-term simulations of 10 years using SWMM. The water balance and in succession the sensitivity indices were determined for the long-term and for storm event results. These evaluations account for an overall picture of the LID parameter influence on the water balance.

The long-term GSA revealed LID parameters that are non-influential for the complete water balance:

- There were nine parameters for the green roof (*berm height*, *vegetation volume*, *surface roughness*, *surface slope*, *conductivity*, *suction head*, *drainage mat thickness*, *drainage mat void fraction*, *drainage mat roughness*),
- There were two parameters for the infiltration trench (*surface roughness*, *surface slope*), and
- There were three parameters for the bio-retention cell (*surface roughness*, *surface slope*, *suction head*).

The most influential parameters were:

- *Soil thickness* for green roof volume and evapotranspiration,
- *Storage seepage rate* for the complete water balance of the infiltration trench as well as for the bio-retention cell runoff volume and groundwater recharge, and
- *Conductivity* for bio-retention cell evapotranspiration.

The identification of the most influential parameters is helpful for practitioners to know which parameter should be measured first and with the highest effort in order to reduce the variance of simulation results most. Consequently, non-influential parameters can be given a lower priority as they can be fixed anywhere in their range of variation without affecting the output of interest.

The storm event-based analysis showed that the influence of LID parameters on the water balance components varies. While several storm event results showed no sensitivity of water balance components to LID parameters, some other storm event results showed a very high influence of LID parameters on the water balance components. The storm event characteristics precipitation depth and antecedent dry period affect the runoff volume and storage change/groundwater recharge sensitivity, whereas the precipitation depth and length of water balance period affect the evapotranspiration sensitivity.

The storm event-based results indicate that the inter-event time cannot be neglected when planning and/or modeling LIDs. Thus, long-term simulations have to be used even if dealing with single storm event investigations.

The parameter fixing (identification of non-influential parameters) and parameter prioritization through the long-term sensitivity analysis is the main outcome of this study. The results should be considered when using SWMM for a holistic LID planning approach based on long-term simulations and considering the complete water balance.

This study focused on the water balance of LIDs. Potential areas for future research will be investigations on the sensitivity of the hydrograph (e.g., runoff peak and time to peak) and the pollutant removal efficiency to LID parameters. Furthermore, other types of LIDs could be investigated, and the GSA could be conducted using other precipitation and temperature time series.

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Conflicts of Interest: The authors declare no conflict of interest.

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PAPER III

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III

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Model-Based Selection of Cost-Effective Low Impact Development Strategies to Control Water Balance

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Abstract: Urbanization induces an increase of runoff volume and decrease of evapotranspiration and groundwater recharge. Low impact development (LID) strategies aim to mitigate these adverse impacts. Hydrologic simulation is a reasonable option to assess the LID performance with respect to the water balance and is applicable to planning purposes. Current LID design approaches are based on design storm events and focus on the runoff volume and peak, neglecting evapotranspiration and groundwater recharge. This contribution presents a model-based design approach for the selection of cost-effective LID strategies. The method is based on monitored precipitation time series and considers the complete water balance and life-cycle-costs, as well as the demand for land. The efficiency of LID strategies (E_{LID}) is introduced as an evaluation measure which also accounts for emphasizing different goals. The results show that there exist several pareto-optimal LID strategies providing a reasonable basis for decision-making. Additionally, the application of LID treatment trains emerges as an option of high potential.

Keywords: life cycle costs; stormwater management; storm water management model

1. Introduction

The increase of impervious land cover caused by urbanization considerably affects the water balance [1]. While the runoff increases, the evapotranspiration and groundwater recharge decreases. This results in several negative impacts, like higher runoff peak rates, larger runoff volumes, higher potential of flooding events, urban heat islands, etc. [2–4].

Low impact development (LID) strategies are a widely known and implemented concept in stormwater management. They aim to replicate hydrologic characteristics of natural catchments, thus mitigating the adverse impacts of urbanization [5,6]. LID strategies are applied to maintain or restore the pre-development hydrologic regime [5,7]. In order to evaluate the LID performance with respect to this purpose, the pre- and post-development hydrologic conditions of a catchment are analyzed. Hydrologic simulations are a reasonable and common option for such assessments. Several modeling tools allow for the simulation of hydrologic processes of LIDs (compare overview of Jayasooriya and Ng [8]). The US EPA Storm Water Management Model (SWMM) [9] was selected for this study as it is currently one of the most sophisticated tools for the hydrologic simulation of LIDs [8].

The design of LIDs (particularly infiltration systems), e.g., infiltration swales or infiltration trenches, implies the calculation of the required retention volume. Basically, it is the difference between the stormwater volume collected by the LID and the stormwater volume that infiltrates through the LID into the soil underneath. Planning guidelines or design manuals often propose to use design storm events of a certain duration and return period in order to determine the required LID retention volume (e.g., [10–12], for an overview of international approaches compare Ballard et al. [13]). Such approaches do not consider the actual storm characteristics, e.g., the time-variant intensity, affecting the performance of LIDs. In addition, conditions at the start of a storm event, e.g., soil moisture or storage capacity due to antecedent storm events and dry periods, are not taken into account. This can result in a divergent assessment of LID performance compared to monitoring in the field. Thus, long-term and continuous simulations have to be used, even if dealing with single storm event evaluations (compare [14]).

Planning guidelines (e.g., [10,11]), evaluation approaches (e.g., [15]), as well as previous studies dealing with LID performance (compare reviews by Ahiablame et al. [6] and Eckart et al. [7]) or LID effectiveness (e.g., [16]) focus on the runoff and neglect the groundwater recharge and evapotranspiration, although they control groundwater levels and the micro-climate by means of cooling and prevent urban heat island effects [4,17]. Therefore, in terms of an environmentally sustainable and reasonable application of LIDs, all components of the water balance have to be considered. Consequently, holistic approaches (e.g., [18,19]) are a suitable basis for planning purposes. Furthermore, the assessment of LID performance is conducted on site scale, as suggested by Burns et al. [20], in order to restore/protect natural hydrologic processes at small scales. That is reasonable considering micro-climate issues and the restoration of natural flow regimes at larger scales downstream.

Various LID design approaches aim to design a certain LID strategy but do not provide recommendations for the selection of the proper LID strategy. Furthermore, little attention is paid to the possibility of combining LIDs to LID treatment trains, which can be well-performing LID strategies as well (e.g., [21–24]). Of course, the selection of LID strategies is also influenced by the cost-effectiveness (e.g., [25–28]), considering the life cycle costs. Several cost-estimating tools for LIDs have been developed (e.g., [29,30]).

Although individual approaches considering the water balance, cost-effectiveness (life cycle costs), or LID treatment trains exist, recommendations for a combined and holistic assessment are not available. This paper presents an approach for selecting suitable LID strategies considering a combined evaluation of the complete water balance (runoff volume, evapotranspiration, groundwater recharge) and the cost-effectiveness for both stand-alone LIDs and treatment trains.

2. Materials and Methods

2.1. Case Studies and Data

The study was conducted using three case studies that represent characteristic urban areas: Two residential areas and one commercial area (Figure 2). The commercial area is 100% impervious and covers 16000 m^2, including a roofage of 6000 m^2. Both residential areas cover 1100 m^2 each. They differ in the degree of development (dod), which is the proportion between built-up area and building site area. The first residential area (low-developed) has a roofage of 200 m^2 (dod = 0.18) whereas the second residential area (high-developed) has a roofage of 600 m^2 (dod = 0.55). Both residential areas comprise a driveway of 40 m^2, while the remaining plot is covered by lawn. All roofs are tiled in the initial state.

The precipitation series used for the long-term simulations was obtained in Graz/Austria, has a length of 10 years (1996–2006), and an average annual precipitation depth of 783 mm. It was provided by the Austrian Water and Waste Management Association (OEWAV) [31]. Daily minimum–maximum temperatures for the computation of evaporation rates, using the Hargreaves method [32], were provided by the Central Institute for Meteorology and Geodynamics (ZAMG) [33].

2.2. Investigated LID strategies and Model Development

The US EPA Storm Water Management Model (SWMM) [9], which was used in this study, is a dynamic rainfall-runoff model. It can be used for a single event or a continuous long-term simulation and simulates hydrologic processes on the surface as well as routing of runoff in the sewer system. SWMM accounts for a variety of hydrologic processes, like time-varying precipitation, interception of depression storage, evaporation of surface water, evapotranspiration out of the soil and/or LIDs, infiltration of stormwater into the soil, and percolation of infiltrated water into groundwater.

The following LIDs, which are frequently implemented in stormwater management projects, were selected for this study: Green roof, infiltration trench, bio-retention cell, infiltration swale, and blind drain.

Green roofs consist of an engineered and (partially) vegetated soil mixture above a drainage mat that serves as stormwater conveying layer. Infiltration swales are depressions that retain and infiltrate stormwater, whereas infiltration trenches are ditches filled with gravel, providing retention volume for stormwater to infiltrate into the native soil below. Bio-retention cells are a combination of infiltration swale and infiltration trench. They provide retention volume through a surface depression as well as an engineered and (partially) vegetated soil mixture and an underlying gravel storage bed. Blind drains are underground infiltration bodies filled with gravel or other filling material.

The mentioned LIDs, except for the blind drain, were simulated with a soil moisture model comprising different layers, e.g., surface, soil, and storage, which is implemented in SWMM (see Figure 1a–d). The layers simulate the different hydrologic functions of the LID. The surface layer accounts for the runoff generation and allows for infiltration into the soil or storage layer. Optionally, a retention volume on the surface can be defined. The soil and storage layer provide retention volume as well and permit infiltration into the native soil. The drainage mat conveys percolated stormwater off the roof. The LID parameters were chosen in agreement with literature parameter ranges (e.g., [34–36]). In order to facilitate a comparison, all LIDs were similarly parameterized to provide comparable retention capacities and hydrologic behavior (Table 1). LIDs collect direct rainfall as well as runoff from other catchments. The runoff from LIDs was directed to the sewer system or to another LID catchment (LID treatment train). For additional information about the LID simulation in SWMM, the reader is referred to Rossman et al. [34]. The blind drain was simulated with a storage node that allows for infiltration to the native soil and prevents evapotranspiration while simulating the surface above the blind drain as well (Figure 1e). The blind drain storage depth was defined to 30cm.

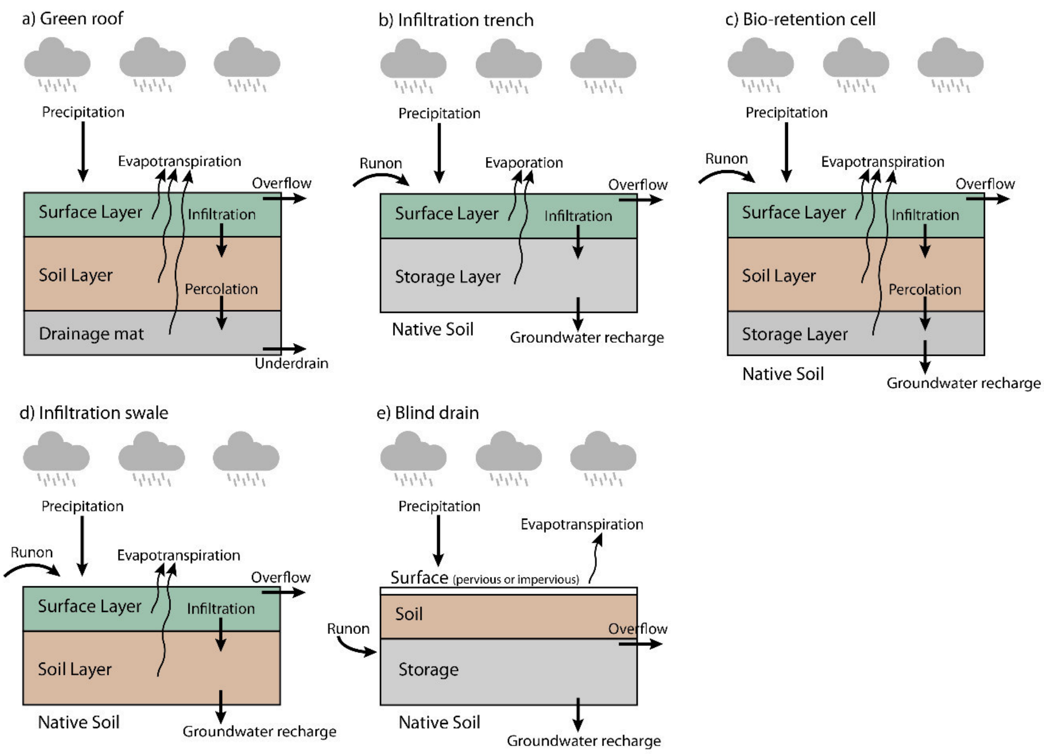

Figure 1. Scheme and simulated processes of the investigated low impact development (LID) strategies: (**a**) Green roof; (**b**) infiltration trench; (**c**) bio-retention cell; (**d**) infiltration swale; (**e**) blind drain.

Table 1. Parameters of investigated LIDs.

Green roof			**Infiltration trench**		
Parameter		Unit	Parameter		Unit
Berm height	10	mm	*Berm height*	300	mm
Vegetation volume	0.2	%	*Vegetation volume*	0.0	
Surface roughness	0.1	s/m$^{1/3}$	*Surface roughness*	0.02	s/m$^{1/3}$
Surface slope	1.0	%	*Surface slope*	1.0	%
Soil thickness	100	mm	*Storage thickness*	1000	mm
Porosity	0.55	-	*Storage void ratio*	0.3	-
Field capacity	0.4	-	*Storage seepage rate*	10	mm/h
Wilting point	0.1	-			
Conductivity	50	mm/h			
Conductivity slope	30	-			
Suction head	65	mm			
Drainage mat thickness	30	mm			
Drainage mat void fraction	0.4	-			
Drainage mat roughness	0.02	s/m$^{1/3}$			
Bio-retention cell			**Infiltration swale**		
Parameter		Unit	Parameter		Unit
Berm height	300	mm	*Berm height*	300	mm
Vegetation volume	0.1	fraction	*Vegetation volume*	0.1	fraction
Surface roughness	0.16	s/m$^{1/3}$	*Surface roughness*	0.16	s/m$^{1/3}$
Surface slope	1	%	*Surface slope*	1.0	%
Soil thickness	300	mm	*Soil thickness*	300	mm
Porosity	0.5	-	*Porosity*	0.5	-
Field capacity	0.2	-	*Field capacity*	0.2	-
Wilting point	0.1	-	*Wilting point*	0.1	
Conductivity	120	mm/h	*Conductivity*	120	mm/h
Conductivity slope	40	-	*Conductivity slope*	40	-
Suction head	50	mm	*Suction head*	50	mm
Storage thickness	100	mm			
Storage void fraction	0.3	-			
Storage seepage rate	10	mm/h			

A potential total LID area (A_{pot}) was assigned to the three areas according to the space available (Figure 2): 2500 m^2 for the commercial area, 60 m^2 for the low-developed residential area, and 120 m^2 for the high-developed residential area. The maximal extent of the underground blind drain was selected accordingly. Each A_{pot} was divided into 50 sections that consequently had a dimension of 50 m^2, 1.2 m^2, and 2.4 m^2 per section, respectively. Each section could be occupied by an LID type or left in the initial state. The sections were incrementally used for the application of a LID type (e.g., infiltration swale applied to 1, 2, 3 ... 50 sections) and a simulation was conducted for every state. In addition, two different LID types were applied to the sections, directing the runoff from the first LID to the second LID. Thus, different LID treatment trains were simulated (Figure 3). Again, the application of LIDs to the sections was executed incrementally.

$$\begin{gathered} A_{LID1} = \frac{A_{pot}}{50} \cdot n_{LID1} \\ A_{LID2} = \frac{A_{pot}}{50} \cdot n_{LID2} \\ \max(n_{LID1} + n_{LID2}) = 50 \\ \text{for single LID strategies}: \; n_{LID2} = 0, \end{gathered} \tag{1}$$

where A_{LID1} is the area of LID1 in m^2, A_{LID2} is the area of LID2 in m^2, A_{pot} is the potential LID area for the respective case study, n_{LID1} is the number of sections occupied by LID1, and n_{LID2} is the number of sections occupied by LID2.

With respect to the roof, the green roof system was not applied incrementally. Only the two options "tiled roof" and "green roof" covering the complete roofage were simulated (Figure 3).

The potential total LID area could theoretically be divided into an infinite number of sections in order to get continuous results, but this would result in high computational effort. Therefore, the discrete results for the water balance using the grid of 50 sections were used as supporting points for a linear interpolation.

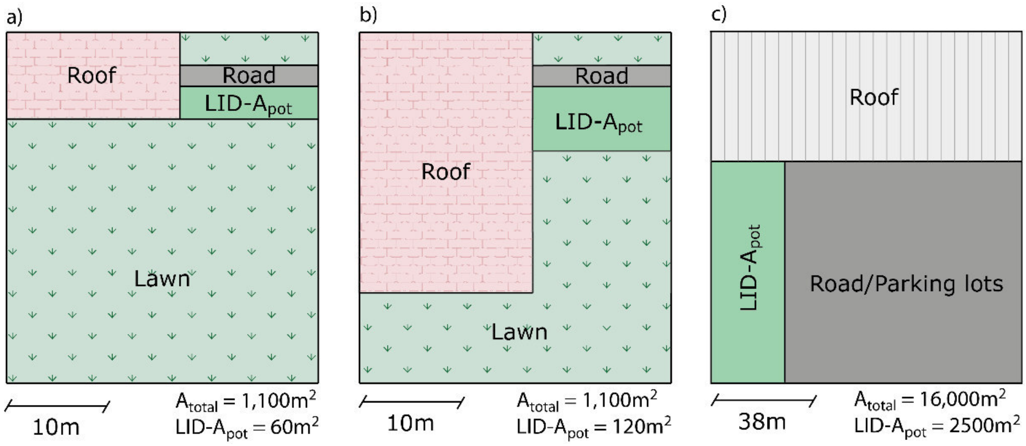

Figure 2. Schematic setting of the investigated case studies: (**a**) Low-developed residential area; (**b**) high-developed residential area; (**c**) commercial area. A_{total} is the total area of the case study and LID-A_{pot} is the total potential LID area.

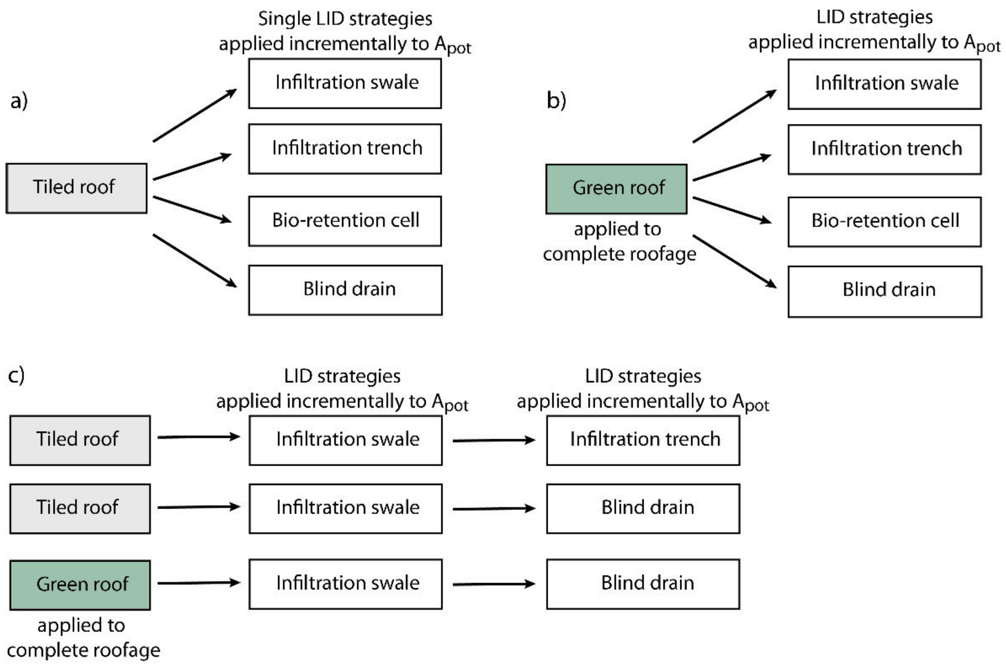

Figure 3. Investigated LID strategies. (**a**) Single LID strategies; (**b**) LID treatment trains with green roof; (**c**) two-part and three-part LID treatment trains.

2.3. Relations between Water Balance, Life Cycle Costs, and Demand for Land

All three areas (Figure 2) were simulated for the investigated LID strategies. Based on the SWMM simulation results, the water balance can be computed:

$$\Delta S = P - ET - R - GR, \quad (2)$$

where P is the precipitation (mm), R is the runoff volume (mm), ET is the evapotranspiration (mm), GR is the groundwater recharge (mm), and ΔS is the change in system storage (mm).

The water balance components can also be expressed as fraction of the precipitation:

$$1 = \frac{\Delta S + ET + R + GR}{P} \tag{3}$$

The life cycle costs, including construction and maintenance costs, were calculated for every LID strategy based on the size (number of sections) of each LID and following a dynamic cost comparison calculation [37]. The interest rate was assumed to be 3% and the intended life of LID practice based on routine maintenance was assumed to be 30 years [38]. According to the investigated references (see Table 2), 5% of the construction costs were used as annual maintenance costs. The reference date was defined at the start of the LID life span. The singular construction costs were distributed uniformly and added to the annual maintenance costs:

$$TC_a = C_o \cdot \frac{i \cdot (1+i)^n}{(1+i)^n - 1} + C_o \cdot \mathrm{p} \tag{4}$$

where TC_a is the total annual cost per unit (€/year), C_0 is the construction cost per unit (€), n is the life span (years), i is the interest rate (%) to discount future costs, and p is the proportion of maintenance to construction costs (%).

Table 2. Construction costs and maintenance costs for the investigated LIDs.

	Construction Costs (C_0)		**Maintenance Costs ($C_0 \cdot$ p)**		**Total Costs (TC_a)**		**Reference (Values Adapted)**
LID							
Green roof	35	€/m^2	1.75	€/(m^2·year)	3.54	€/(m^2·year)	[39–41]
Infiltration swale	30	€/m^2	1.5	€/(m^2·year)	3.03	€/(m^2·year)	[38–41]
Infiltration trench	105	€/m^3	5.25	€/(m^3·year)	10.61	€/(m^3·year)	[38–41]
Bio-retention cell	135	€/m^3	6.75	€/(m^3·year)	13.64	€/(m^3·year)	[38–41]
Blind drain	105	€/m^3	5.25	€/(m^3·year)	10.61	€/(m^3·year)	[38–41]

Besides the LID performance with respect to the water balance and the economic aspect regarding the construction and maintenance costs, the demand for land is an additional important factor that has to be evaluated. Especially in highly urbanized areas, available land is rare and/or expensive. Consequently, the demand for land ($\mathrm{d_{land}}$) is used as a further indicator of LID performance:

$$\begin{gathered}\text{Forbio-retentioncell, infiltrationswale, andinfiltrationtrench}:\\ d_{land} = A_{LID}\\ \text{For blind drain}:\\ d_{land} = 0\end{gathered} \tag{5}$$

where d_{land} is the demand for land and A_{LID} is the area of the LID (see also Equation (1)).

2.4. Assessment and Efficiency of LID Strategies

LID strategies can be used in order to achieve, or at least approximate, a certain targeted water balance with a limited budget regarding the costs and/or demand for land. The challenge is to identify an LID strategy that meets the desired water balance while resulting in minimum costs and demand for land. Usually, there is not one optimal solution that equally satisfies the mentioned requirements. Thus, the relation between the water balance, costs, and demand for land has to be identified in order to find a reasonable LID strategy as a kind of trade-off.

The obtained simulation results are used to calculate the deviation from a targeted water balance. This deviation is defined as the sum of the absolute deviations of the particular water components:

$$D_{WB} = \overline{R_{sim} - R_t} + \overline{ET_{sim} - ET_t} + \overline{GR_{sim} - GR_t}, \quad (6)$$

where D_{WB} is the deviation from a targeted water balance (in percentage points), R is the runoff volume (in % of precipitation depth), ET is the evapotranspiration (in % of precipitation depth), GR is the groundwater recharge (in % of precipitation depth), *sim* denotes the simulated value, and t denotes the value of target state.

The targeted water balance can be either defined by stakeholders based on case-specific boundary conditions like the capacity of the present sewer system or based on hydrologic simulations, aiming for natural conditions (e.g., [19]). For demonstration purposes, an arbitrary defined targeted water balance with a runoff volume of 5%, an evapotranspiration of 45%, and a groundwater recharge of 50% is used.

The deviation from the targeted water balance (Equation (6)), the costs (Equation (4)), and the demand for land (Equation (5)) have to be minimized. This requirement is used to identify all nondominated (pareto-optimal) results. The approach of gridding methods (e.g., compare [42]) was used for this purpose, as the mentioned objectives were evaluated for a defined number of points (grid of 50 sections).

The deviation from the targeted water balance and the demand for land are used to evaluate the effect of invested money. The efficiency of LID strategies, as a function of costs, is computed as the sum of the normalized deviation from the targeted water balance and the normalized demand for land. Additionally, weighting factors are introduced to emphasize a certain goal:

$$E_{LID}(C) = 1 - \left(w_{land} * \frac{d_{land}}{\max(d_{land})} + w_{WB} * \frac{D_{WB}}{\max(D_{WB})} \right) \quad (7)$$
$$\text{with}: \; w_{land} + w_{WB} = 1,$$

where E_{LID} is the efficiency of LID strategies, C is the cost, d_{land} is the demand for land, D_{WB} is the deviation from the targeted water balance, w_{land} is the weighting factor for the demand for land, and w_{WB} is the weighting factor for the deviation from targeted water balance.

3. Results and Discussion

The change in system storage is almost zero or at least negligibly small compared to the other water balance components for the long-term assessment. Consequently, it is not further taken into consideration. Concerning the investigated LID treatment trains, only results for selected strategies, that show high potential, are illustrated.

3.1. Relations between Water Balance, Life Cycle Costs, and Demand for Land

3.1.1. Single LID Strategies

The qualitative results regarding the runoff volume are the same for all three investigated areas while the absolute values reveal some differences. A decrease in runoff volume is identified with an increasing number of LID sections and an associated increase of costs (Figures 4a, 5a and 6a). The larger the LID area, the more stormwater can be retained, resulting in smaller runoff volumes. The decrease curves start steep and flatten, converging to a runoff volume of zero. Thus, the effect of invested money on the runoff volume decreases with an increasing LID area. The results for the infiltration swale show the steepest costs-runoff-curve due to the smallest costs per implemented section. However, regarding the demand for land, the bio-retention cell and infiltration trench show a better and similar performance (Figures 4d, 5d and 6d) because they provide a larger and similar retention volume per LID section. The infiltration trench has smaller costs per section compared to the bio-retention-cell and a larger retention volume due to the surface storage (berm height) compared to the blind drain. Consequently, the performance is better regarding the costs (Figures 4a, 5a and 6a). The underground blind drain does not require land and is a suitable option when land is rare and/or expensive (Figure 4d,e, Figure 5d,e and Figure 6d,e).

The evapotranspiration is expectedly constant for the underground blind drain for all three areas (Figure 4b,e, Figure 5b,e and Figure 6b,e). The value of this constant evapotranspiration depends on the investigated area, thus on the kind of surface above the blind drain (impervious road/parking lot for commercial area, pervious lawn for residential areas) and the ratio of impervious to pervious surface in the area (different dod for residential areas). The kind of surface of sections that are not used for applying LIDs is also the reason for different results between the residential and commercial area with respect to the infiltration trench and evapotranspiration (Figure 4b,e, Figure 5b,e and Figure 6b,e). Applying an infiltration trench to residential areas shows an almost constant evapotranspiration as the evapotranspiration performance of an infiltration trench is similar to those of the appropriate lawn area; stormwater infiltrates into the native soil and is not available for evapotranspiration for a longer period. In contrast, applying an infiltration trench to the commercial area results in an increasing evapotranspiration as the reference evaporation from the road/parking lot is very small. The infiltration swale and bio-retention cell show an equal increase of evapotranspiration with an increasing LID area for all investigated areas as stormwater is retained in the soil layer and available for evapotranspiration (Figure 4b,e, Figure 5b,e and Figure 6b,e). The increase is linear, as SWMM does not account for the response of evapotranspiration to the soil moisture variation [43].

The consequence of a constant evapotranspiration for the blind drain and infiltration trench applied to residential areas is that the groundwater recharge shows the complete opposite of the runoff volume (Figure 4c,f, Figure 5c,f and Figure 6c,f). An increasing LID size results in an increase of the groundwater recharge. The increase curve mirrors the runoff volume decrease curve. The result for the infiltration trench applied to the commercial area, the infiltration swale, and the bio-retention cell is similar, except a small decrease of groundwater recharge for larger LIDs (Figure 4c,f, Figure 5c,f and Figure 6c,f). This is caused by the increasing retention volume, resulting in a runoff volume that converges to zero and an evapotranspiration that increases linearly.

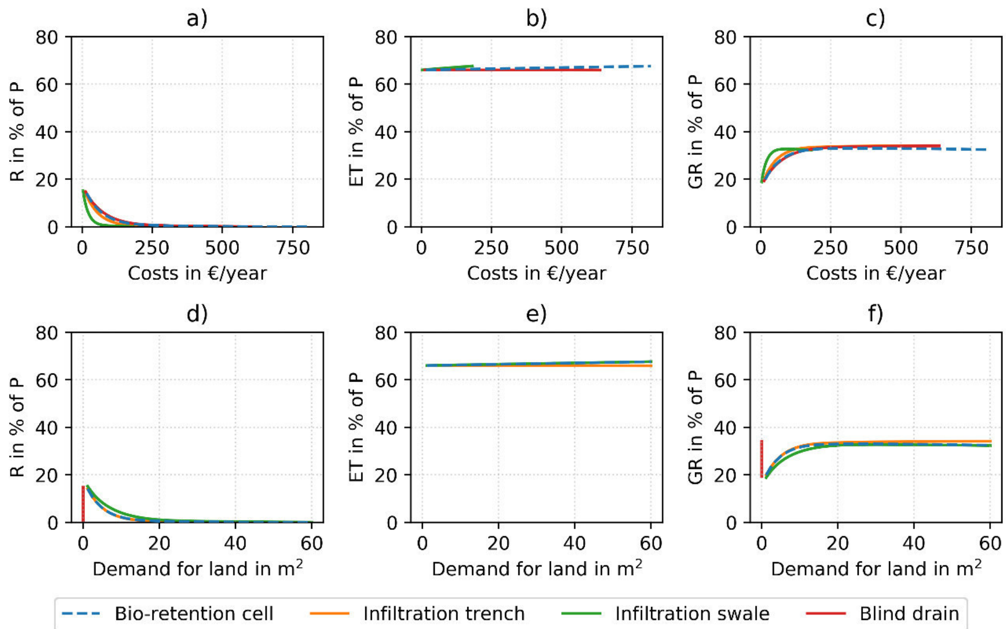

Figure 4. Simulated long-term water balance for the low-developed residential area applying single LID strategies of increasing size. Relation between costs and (**a**) runoff volume, (**b**) evapotranspiration, (**c**) groundwater recharge. Relation between demand for land and (**d**) runoff volume, (**e**) evapotranspiration, (**f**) groundwater recharge.

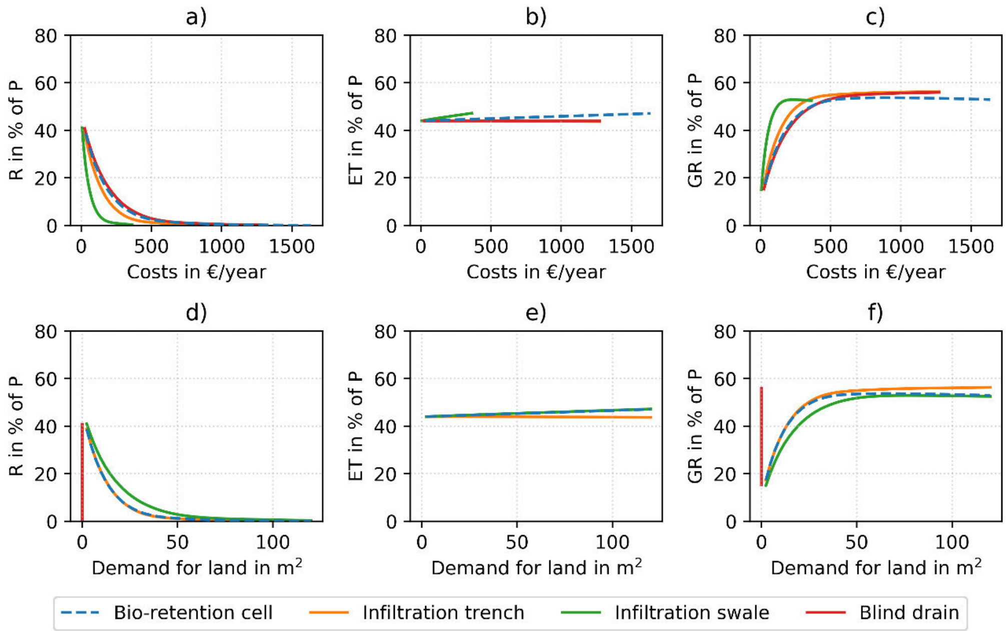

Figure 5. Simulated long-term water balance for the high-developed residential area applying single LID strategies of increasing size. Relation between costs and (**a**) runoff volume, (**b**) evapotranspiration, (**c**) groundwater recharge. Relation between demand for land and (**d**) runoff volume, (**e**) evapotranspiration, (**f**) groundwater recharge.

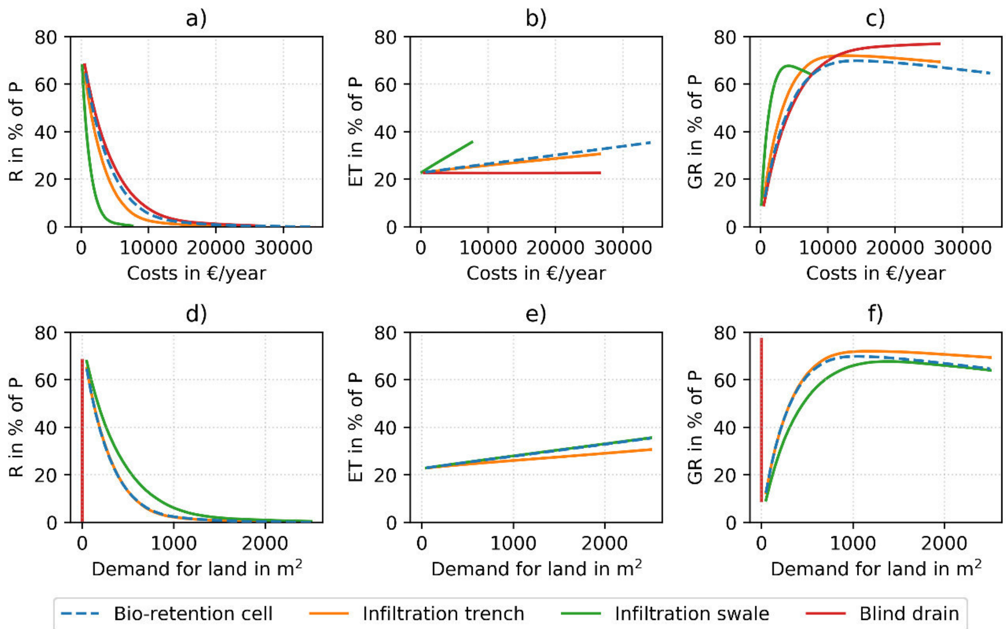

Figure 6. Simulated long-term water balance for the commercial area applying single LID strategies of increasing size. Relation between costs and (**a**) runoff volume, (**b**) evapotranspiration, (**c**) groundwater recharge. Relation between demand for land and (**d**) runoff volume, (**e**) evapotranspiration, (**f**) groundwater recharge.

It is obvious that the extent of the mentioned effects of applying single LIDs on the water balance differs between the investigated types of area. It increases with an increasing degree of imperviousness. The low-developed residential area already has a large lawn area resulting in a small runoff volume and high evapotranspiration in the initial state, whereas the commercial area shows the highest potential of applying LIDs.

3.1.2. Two-Part LID Treatment Train with Green Roof

The application of a green roof within the scope of a LID treatment train shows two general effects on the water balance. The first is related to the different hydrologic performance of the green roof itself compared to a tiled roof. The second is related to the consequently changed runoff volume to the downstream LID.

The green roof retains stormwater, which is consequently available for evapotranspiration. Thus, the runoff volume from the roof decreases, whereas evapotranspiration increases compared to the scenarios with a tiled roof (compare subplots a and b of Figures 4–6 with tiled roof and Figures 7–9 with green roof).

Consequently, the runoff to the downstream LID is reduced compared to scenarios with a tiled roof, resulting in an overall reduced runoff volume, whereas the groundwater recharge is decreased. The overall evapotranspiration increases due to the substantially increase of roof evapotranspiration. The effect of increasing the downstream LID area of infiltration swale, infiltration trench, bio-retention cell, and blind drain is basically the same as for the single LID investigations; the runoff volume decreases whereas the groundwater recharge increases. The evapotranspiration increases for the downstream bio-retention cell and infiltration swale and is constant for the blind drain. The application of the infiltration trench shows the already mentioned difference between residential and commercial areas, namely a constant evapotranspiration for the residential areas and an increasing evapotranspiration for the commercial area.

The magnitude of effects applying a green roof differs again between the investigated areas. The results for the low-developed residential area show that downstream LIDs have very little impact on the water balance (Figure 7). The green roof and lawn area generate small runoff volumes and a high evapotranspiration. Implementing an LID treatment train with green roof on a high-developed residential area shows larger but still small effects on the water balance (Figure 8). In contrast, as a large part of the commercial area consists of an impervious road/parking lot, the application of downstream LIDs shows the largest effect (Figure 9).

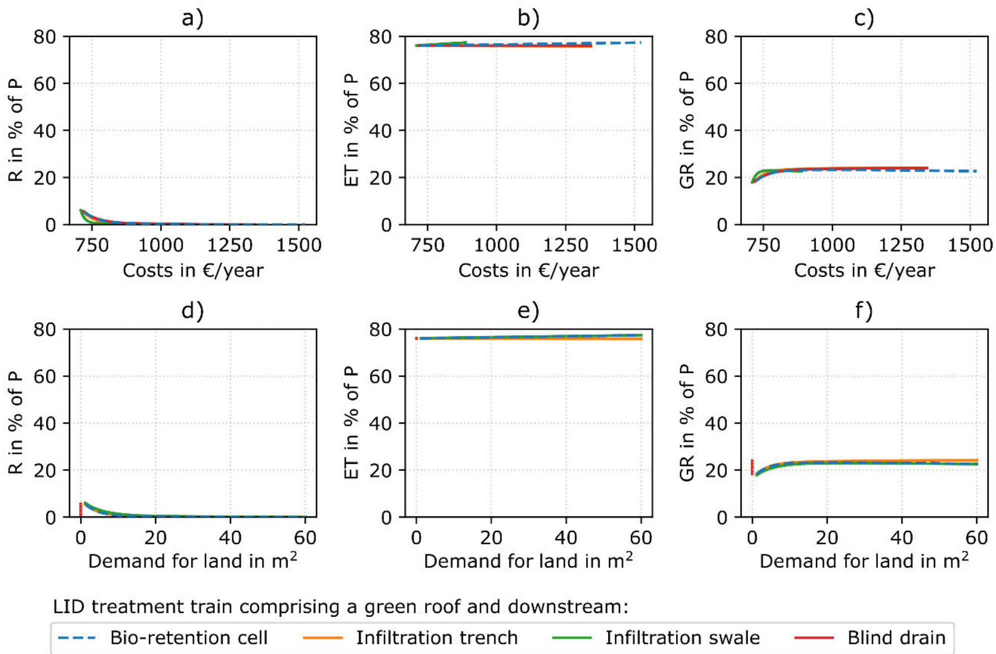

Figure 7. Simulated long-term water balance for the low-developed residential area applying a green roof and different downstream LIDs of increasing size (LID treatment train). Relation between costs and (**a**) runoff volume, (**b**) evapotranspiration, (**c**) groundwater recharge. Relation between demand for land and (**d**) runoff volume, (**e**) evapotranspiration, (**f**) groundwater recharge.

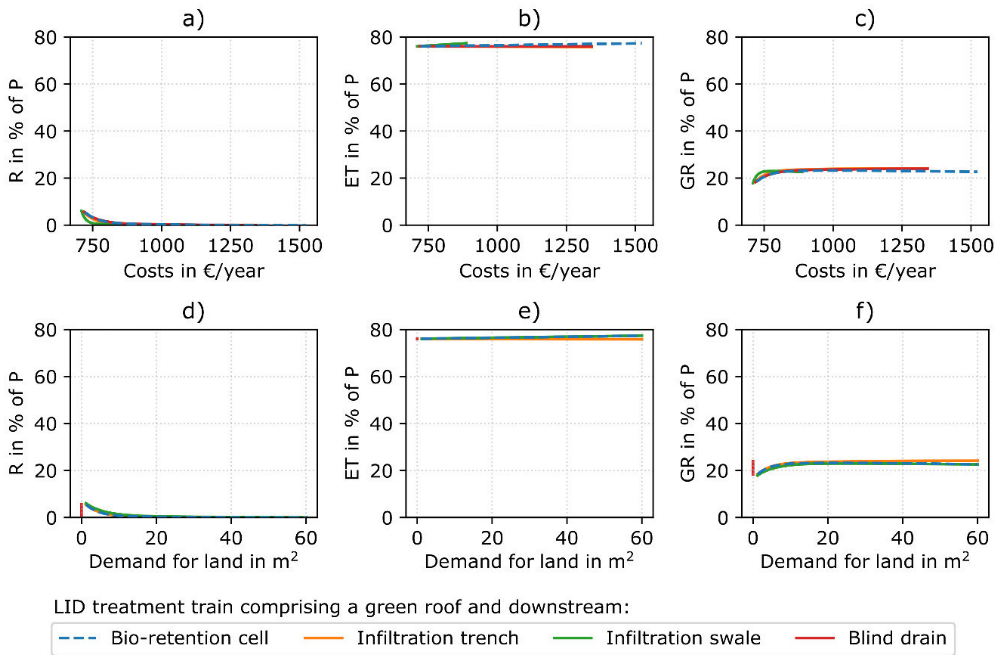

Figure 8. Simulated long-term water balance for the high-developed residential area applying a green roof and different downstream LIDs of increasing size (LID treatment train). Relation between costs and (**a**) runoff volume, (**b**) evapotranspiration, (**c**) groundwater recharge. Relation between demand for land and (**d**) runoff volume, (**e**) evapotranspiration, (**f**) groundwater recharge.

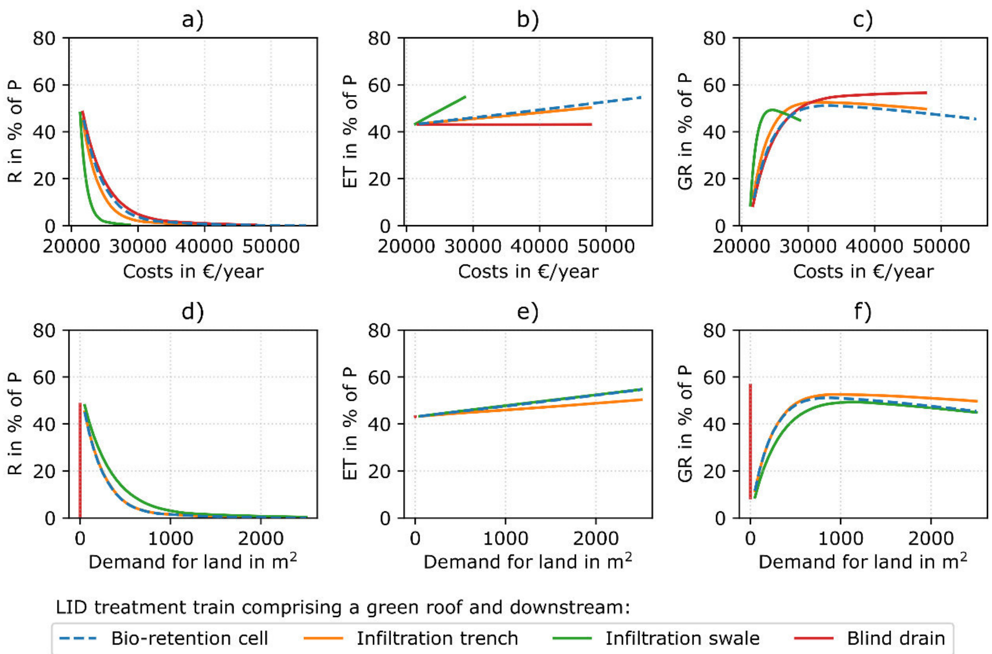

Figure 9. Simulated long-term water balance for the commercial area applying a green roof and different downstream LIDs of increasing size (LID treatment train). Relation between costs and (**a**) runoff volume, (**b**) evapotranspiration, (**c**) groundwater recharge. Relation between demand for land and (**d**) runoff volume, (**e**) evapotranspiration, (**f**) groundwater recharge.

3.1.3. Two-Part LID Treatment Train: Infiltration Swale—Infiltration Trench

The results for the single LID strategies and the two-part LID treatment trains with green roof showed that the largest effect on the water balance is obtained for the commercial area, whereas the impact is small for the residential areas, especially for the low-developed residential area.

As the qualitative performance is similar, the commercial area is used for illustrating effects of other LID strategies.

The investigations on applying single LIDs showed that the infiltration swale performs well regarding the costs, but has some shortcomings regarding the demand for land, e.g., compared to an infiltration trench. Consequently, an LID treatment train comprising an infiltration swale and a downstream infiltration trench is promising. This assumption is verified by the conducted simulations (Figure 10).

LID treatment trains provide the possibility of selecting LID strategies as a kind of trade-off between water balance, costs, and demand for land. An example illustrates this conclusion: Assuming a targeted runoff volume of 10%, applying only an infiltration swale results in costs of €2500 per year and a demand for land of 815 m^2, whereas applying an infiltration trench results in costs of €6100 per year and a demand of land of 573 m^2 (Figure 10). The mentioned strategies with a single LID would result in an evapotranspiration of 27% (infiltration swale) or 24.7% (infiltration trench). In contrast, an LID treatment train with a demand for land of 694 m^2 comprising equal fractions of infiltration swale and infiltration trench results in costs of €4733 per year. The mentioned LID treatment train results in the targeted 10% runoff volume and an evapotranspiration of 25.8%.

Selecting different proportions for the infiltration trench and infiltration swale on the total LID area moves the results in a certain direction. Assuming a certain limit for costs, increasing the proportion of the infiltration swale results in smaller runoff volumes and larger evapotranspiration, but is associated with a larger demand for land. On the other hand, assuming a certain limit for the demand of land, increasing the proportion of the infiltration swale results in larger runoff volumes and larger evapotranspiration, associated with lower costs. Thus, certain goals (e.g., desired runoff volume, evapotranspiration, groundwater recharge, maximal costs, or demand for land) can be achieved by selecting the proportion of the infiltration trench and infiltration swale within the scope of an LID treatment train.

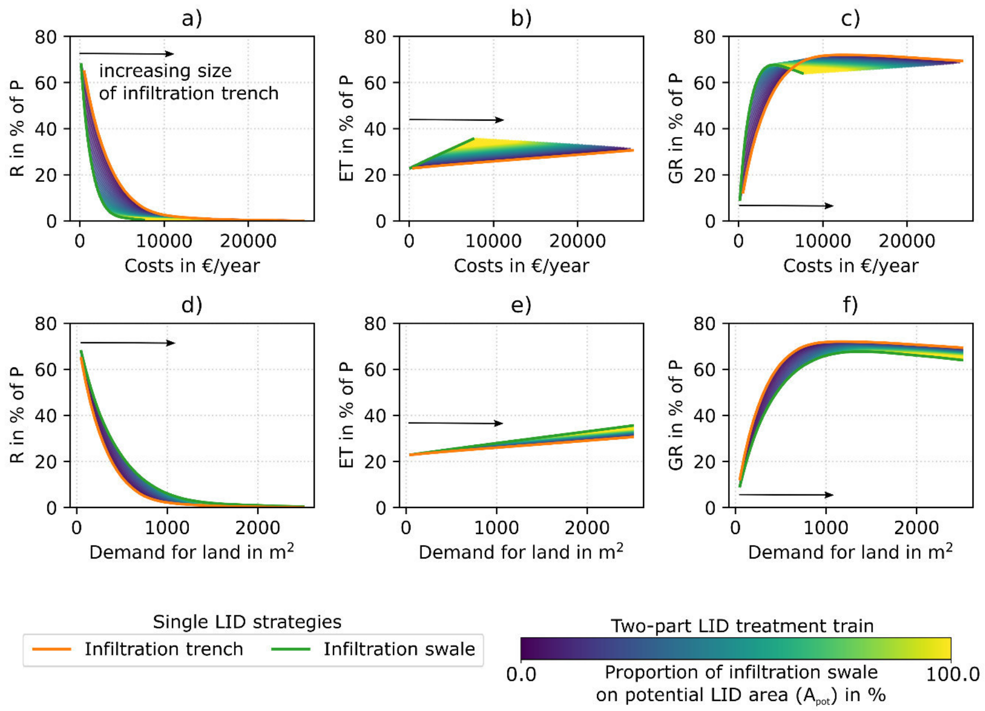

Figure 10. Simulated long-term water balance for the commercial area applying an LID treatment train comprising an altering proportion of infiltration swale on total LID area (A_{pot}) and a downstream infiltration trench of increasing size. Each colored line of the LID treatment train illustrates the simulation results for a constant proportion of infiltration swale on A_{pot} and an increasing size of the infiltration trench (indicated by the arrow). Relation between costs and (**a**) runoff volume, (**b**) evapotranspiration, (**c**) groundwater recharge. Relation between demand for land and (**d**) runoff volume, (**e**) evapotranspiration, (**f**) groundwater recharge.

3.1.4. Two-Part LID Treatment Train: Infiltration swale—Blind Drain

The investigations on single LIDs revealed a good performance in runoff volume reduction and an increase of groundwater recharge with an outstanding demand for land of zero for the application of a blind drain. However, the evapotranspiration performance is basically null. Combining the blind drain with an infiltration swale in an LID treatment train can mitigate this fundamental shortcoming (Figure 11).

The infiltration swale accounts for an increase of evapotranspiration (Figure 11b,e), while the downstream blind drain decreases the runoff volume and increases the groundwater recharge without causing an additional demand for land (Figure 11d,f). Thus, this LID treatment train is suitable to control/improve the complete water balance, especially when land is rare and/or expensive. The size of the infiltration swale can be chosen due to the maximal land available and/or due to economic aspects. The size of the blind drain is either limited by a defined limit of costs or can be determined to control the runoff volume of the LID treatment train.

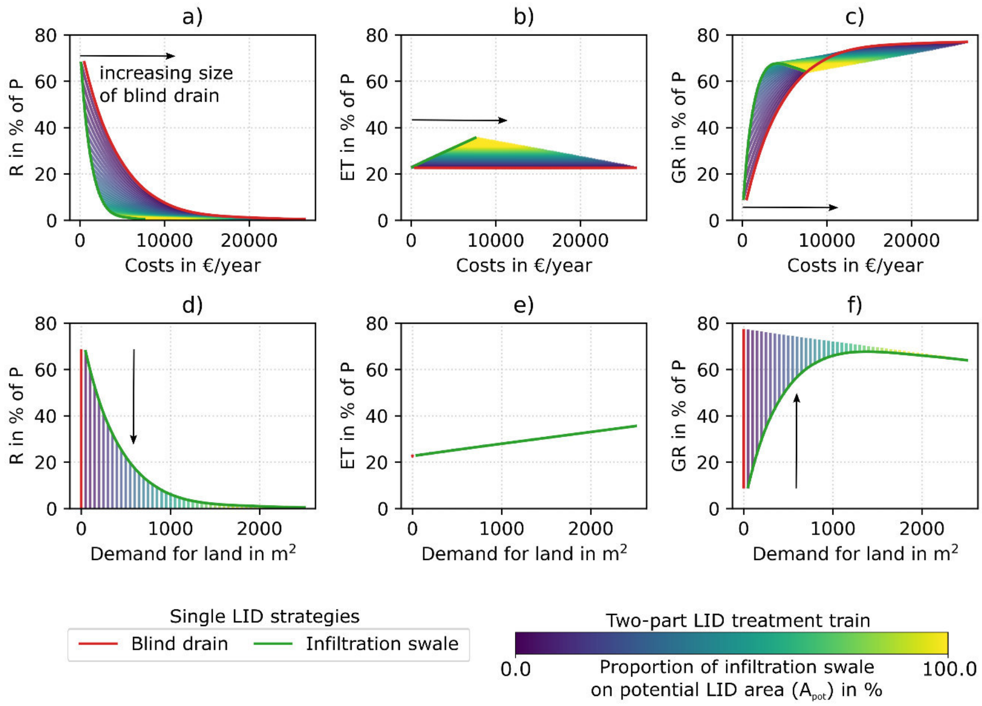

Figure 11. Simulated long-term water balance for the commercial area applying an LID treatment train comprising an infiltration swale with altering proportion on potential LID area (A_{pot}) and a downstream blind drain of increasing size. Each colored line of the LID treatment train illustrates the simulation results for a constant proportion of infiltration swale on A_{pot} and an increasing size of the blind drain (indicated by the arrow). Relation between costs and (**a**) runoff volume, (**b**) evapotranspiration, (**c**) groundwater recharge. Relation between demand for land and (**d**) runoff volume, (**e**) evapotranspiration, (**f**) groundwater recharge.

3.1.5. Three-Part LID Treatment Train: Green Roof—Infiltration Swale—Blind Drain

The application of a green roof within a three-part LID treatment train with a downstream infiltration swale and a blind drain shows the same effects as identified for the two-part LID treatment trains with a green roof (see Section 3.1.3): The overall runoff volume and groundwater recharge decrease, whereas the evapotranspiration increases (Figure 11a,b and Figure 12a,b) as stormwater is retained and evaporated on the green roof.

The green roof is especially valuable for the evapotranspiration (Figures 11b and 12b, increase of ca. 21 percentage points) while causing substantially higher costs (additional €21,240 per year).

The demand for land in order to achieve a certain runoff volume decreases when implementing an upstream green roof as the runoff to the infiltration swale is reduced.

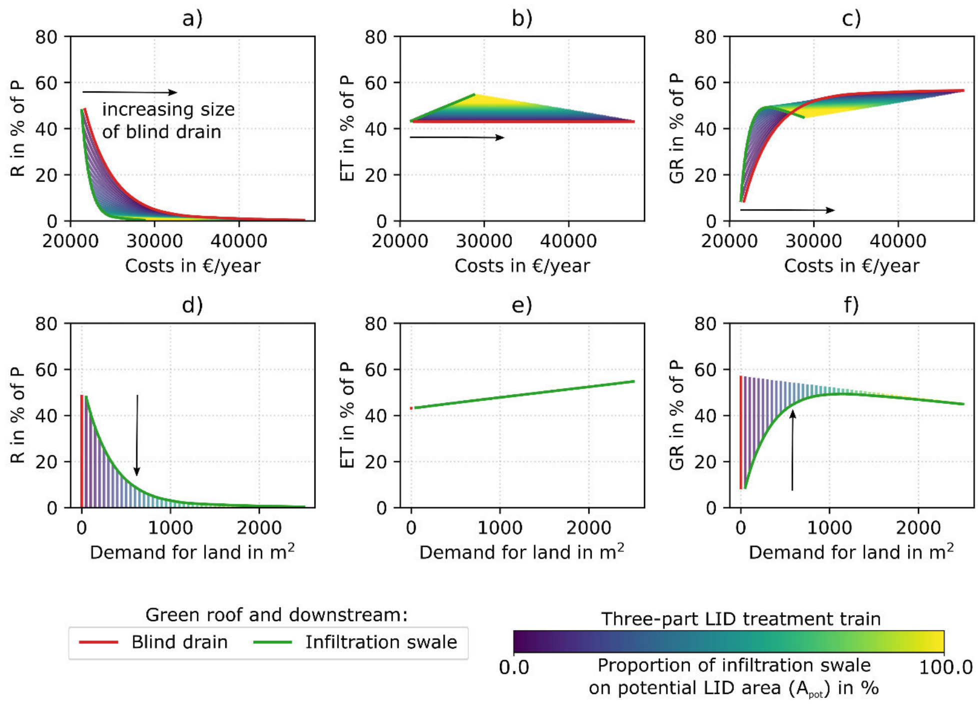

Figure 12. Simulated long-term water balance for the commercial area applying an LID treatment train comprising a green roof, an infiltration swale with altering proportion on total LID area (A_{pot}), and a downstream blind drain of increasing size. Each colored line of the LID treatment train illustrates the simulation results for a constant proportion of infiltration swale on A_{pot} and an increasing size of the blind drain (indicated by the arrow). Relation between costs and (**a**) runoff volume, (**b**) evapotranspiration, (**c**) groundwater recharge. Relation between demand for land and (**d**) runoff volume, (**e**) evapotranspiration, (**f**) groundwater recharge.

The effects of applying LIDs are in agreement with many field and laboratory studies, as well as evaluations based on hydrologic simulations (for an overview compare [6,7]). All LID strategies decrease the runoff volume due to the provided retention volume. The decrease curve starts steep and flattens, converging to zero. The green roof, bio-retention cell, and infiltration swale provide an increase of evapotranspiration. The increase is linear, as SWMM does not account for the response of evapotranspiration to the soil moisture variation [43]. In contrast, the infiltration trench applied to residential areas and the underground blind drain do not affect the evapotranspiration, but substantially increase the groundwater recharge.

The results indicate that the potential of applying LIDs is increasing, with an increasing imperviousness of the investigated area as slightly impervious areas already show a relatively small runoff volume and high evapotranspiration. Nevertheless, LIDs are applicable for both residential and commercial areas (in agreement with Dietz et al. [44]).

The green roof as part of an LID treatment train shifts the water balance components compared to the LID applications without a green roof (Figures 7–9 and 12) as stormwater is retained in the soil layer and available for evapotranspiration. This is in agreement with several field, laboratory, and modeling studies (for overview compare Ahiablame et al. [6] or Eckart et al. [7]). Consequently, the overall runoff volume and groundwater recharge are decreased.

3.2. Assessment and Efficiency of LID Strategies

The results for the commercial area (Figure 13) show a minimum deviation from the targeted water balance of 28 percentage points for the application of an infiltration swale, but at the same time result in a maximal demand for land. Assuming the same cost limit, the infiltration swale generally shows best results regarding the deviation from targeted water balance compared to other LID strategies. On the other hand, with respect to the demand for land, the blind drain shows expectable good results. However, at a certain point (ca. €4800 per year), the application of additional blind drain volume only results in higher costs without further reducing the deviation from targeted water balance.

It is obvious that strategies with a very small runoff volume going below the targeted runoff volume may increase the deviation from targeted water balance. The same can occur for strategies resulting in a groundwater recharge larger than the targeted one. However, following a holistic approach considering the complete water balance, the challenge is to find a solution that addresses the deviation from the complete targeted water balance and not a solution that only considers the deviation from target state of a particular water balance component. However, investigations on a larger scale can shift the point of view. LID strategies applied to a site, resulting in an exceedance of a certain component of the targeted water balance, can also be reasonable. They are applicable to counterbalance the respective component of the targeted water balance component of another site where it cannot be achieved or only associated with very high costs or demand for land. Nevertheless, the assessment on a site scale should be preferred, as suggested by Burns et al. [20].

All single LID strategies show a range of nondominated options. Thus, all single LID strategies provide pareto-optimal options. However, LID strategies resulting in small costs but a large deviation from targeted water balance will not be suitable in practice. Nevertheless, the results can be used to select a reasonable LID strategy. Stakeholders have the opportunity to emphasize a certain goal (deviation from targeted water balance, costs, demand for land) in the decision process.

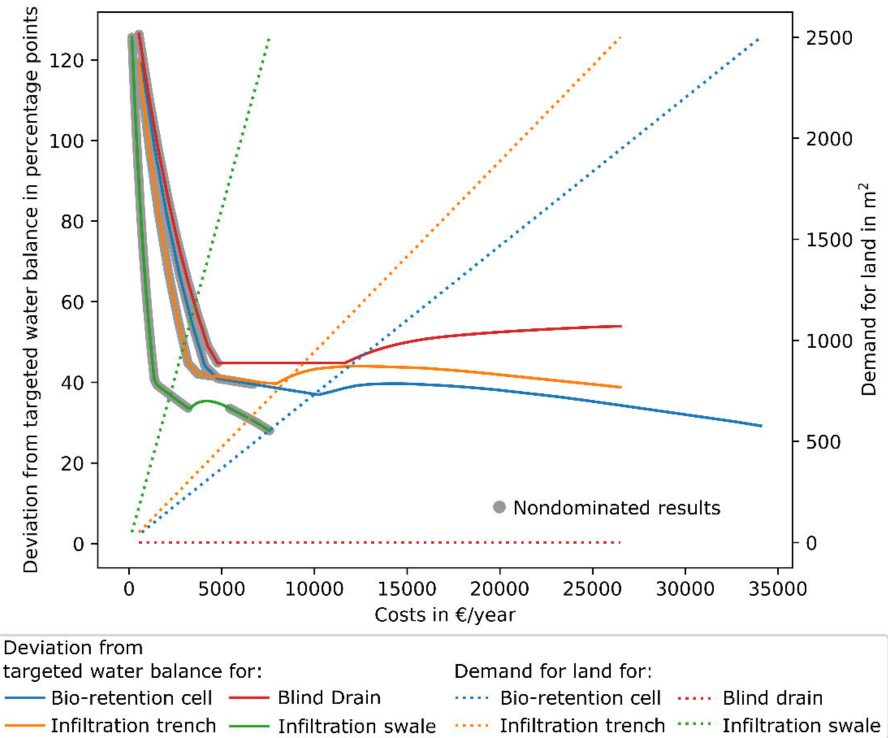

Figure 13. Assessment of applying single LID strategies to the commercial area with respect to a targeted water balance and demand for land. The nondominated results (grey-bold) are only illustrated for the relationship between costs and deviation from targeted water balance.

The trend in the results for the high-developed area is similar to those of the commercial area (Figure 14). In contrast to the commercial area, a deviation from targeted water balance of almost zero is achieved, applying an infiltration swale or a bio-retention cell. The costs to obtain this condition are higher for the bio-retention cell (€360 per year) than for the infiltration swale (€116 per year), but the demand for land is smaller for the bio-retention cell (26.4 m^2) than for the infiltration swale (38.4 m^2).

Once again, all single LID strategies show a range of nondominated options. As already mentioned, the decision process can be seen as a trade-off between the deviation from targeted water balance, costs, and demand for land.

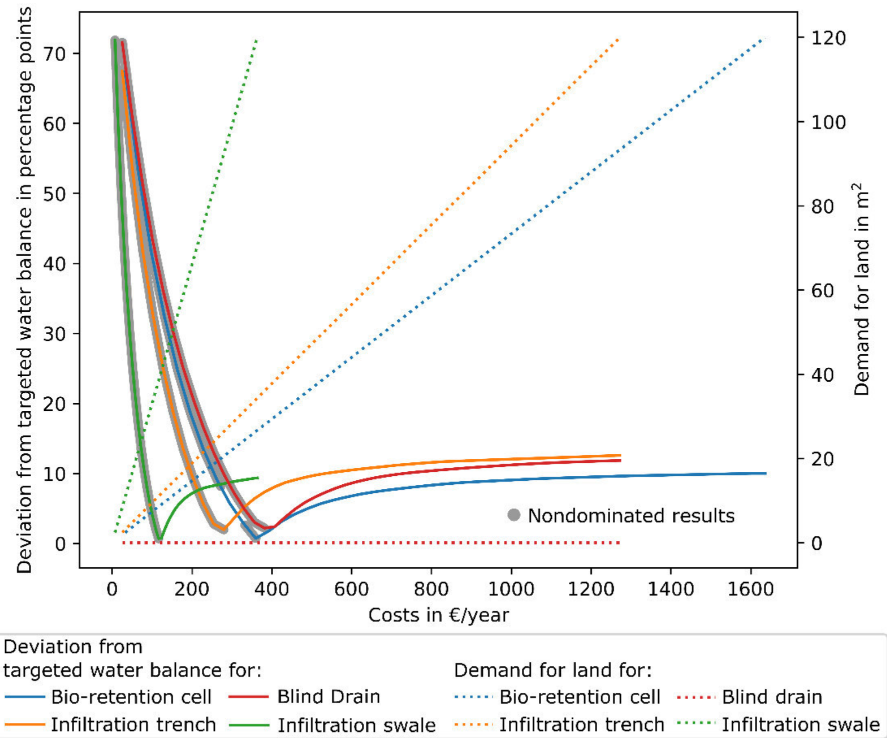

Figure 14. Assessment of applying single LID strategies to the high-developed residential area with respect to a targeted water balance and demand for land. The nondominated results (grey-bold) are only illustrated for the relationship between costs and deviation from targeted water balance.

The efficiency of LID strategies shows that the infiltration swale provides the best results when only the deviation from the targeted water balance is considered (w_{land} = 0.0, w_{WB} = 1.0, Figure 15a, compare also Figure 13). An increasing weighting factor for the demand for land results in an increasing E_{LID} for LID strategies comprising a blind drain (Figure 15). This is valid for a single blind drain as well as for an LID treatment train comprising an infiltration swale and a downstream blind drain, providing pareto-optimal results. Thus, when land is rare, the application of a blind drain can be a reasonable option. Implementing it as part of an LID treatment train with an infiltration swale is especially valuable. The infiltration swale is cost-saving and accounts for evapotranspiration, while the blind drain collects and infiltrates possibly occurring runoff from the infiltration swale while causing no further demand for land and.

If only the deviation from the targeted water balance is considered for E_{LID} (w_{land} = 0.0, w_{WB} = 1.0, Figure 15a), the improvement of E_{LID} is small at a certain point (ca. €4000 per year for the infiltration trench and the bio-retention cell) as the deviation from the targeted water balance can only be reduced slightly while the demand for land and costs increase. Concerning the blind drain, E_{LID} even decreases as the deviation from the targeted water balance increases, caused by an overly high groundwater recharge (compare also Figure 6). Emphasizing the demand for land, E_{LID} also decreases more and more for the other single LIDs (infiltration trench, bio-retention cell, infiltration swale) as the increase of demand for land exceeds the reduction of deviation from targeted water balance.

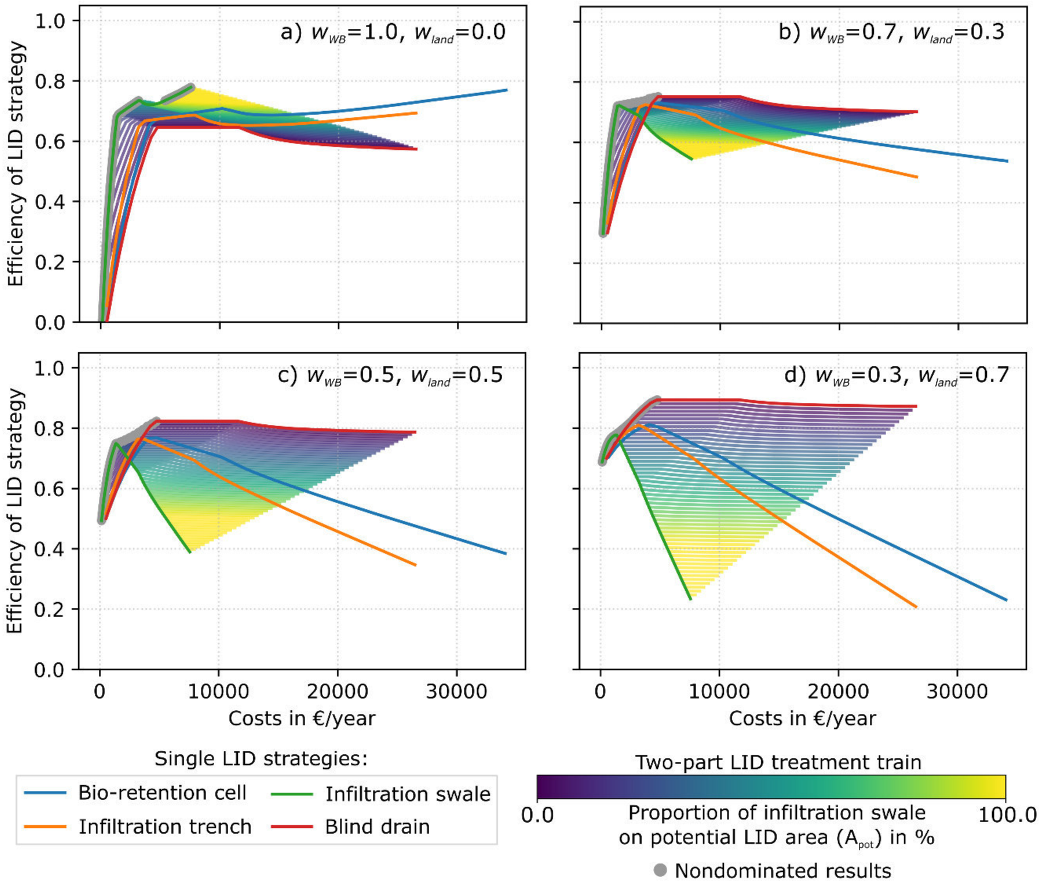

Figure 15. Assessment of applying different single LID strategies of increasing size and an LID treatment train consisting of an infiltration swale with altering proportion on total LID area (A_{pot}) and a downstream blind drain of increasing size to the commercial area. Calculation of LID efficiency (E_{LID}) with varying weights deviation from targeted water balance (w_{WB}) and demand for land (w_{land}). Each colored line of the LID treatment train illustrates E_{LID} for a constant proportion of infiltration swale on A_{pot} and an increasing size of the blind drain. The nondominated results are illustrated in grey-bold.

The assessment of LID strategies with respect to a targeted water balance shows that the decision is dependent on the main goal of the stormwater management project. Besides the deviation from the targeted water balance, the demand for land and costs have to be taken into consideration. Depending on the emphasis given on the individual goals, different LID strategies can appear to be "most effective".

4. Conclusions

This paper introduces a method for a model-based selection of cost-effective LID strategies to control water balance. The method is based on a holistic approach considering the complete water balance. The objectives within the design and selection process are the deviation from the targeted water balance, the demand for land and the costs. The efficiency of LID strategies (E_{LID}) is defined as a measure to evaluate the investigated LID strategies, providing also the possibility of weighting the individual objectives.

The conducted simulations illustrate how LID strategies affect the water balance depending on the applied size of LID: Reduction of runoff volume, increase of evapotranspiration, and groundwater recharge. The results are valuable for the planning process in order to estimate the respective effect on the water balance components of different LID strategies.

The investigations revealed that there is not one specific optimal LID strategy when the water balance, as well as costs and demand for land, are taken into consideration. Nevertheless, the method's results provide a well-founded and holistic basis for the selection of a reasonable LID strategy. Stakeholders can choose from several nondominated results, emphasizing a certain objective.

The application of an LID treatment train shows high potential. It is especially valuable combining a cost-saving LID that accounts for evapotranspiration (e.g., infiltration swale) and a downstream LID that accounts for infiltration and results in no further demand for land (e.g., blind drain).

The quantitative results are restricted to the investigated areas and their hydrologic boundary conditions, the precipitation time series, the assumed costs, and the LID strategies used. However, the developed method is applicable to other areas, other precipitation time series, and other LID strategies. Further research is related to this assumption, as well as using the method's findings on a larger scale.

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