Combining physically - based and block model approaches for urban stormwater management systems: implications of flow in variably saturated media for the design and planning process.

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Highlights

- Design of a large-scale trench system with a sand filled retention volume for drainage and storage function
- Coupling a block rainfall-runoff model (STORM®) and a 2D physically based unsaturated flow model approach (PCSiWaPro)
- Recommendations for substrate selection, structural design and construction to ensure the dual system functionality

Introduction

Due to increasing urbanization and climate change, cities are challenged with water management, e.g. for the irrigation of urban green spaces (Krebs, 2020). Innovative stormwater management systems (SWMS) aim to mitigate extreme events such as heavy rain and drought periods by providing infiltration and storage functionalities. There is a conflict of objectives here: dry periods require as much water storage as possible, whereas runoff retention benefits from empty storage conditions.

Conventionally, rainfall-runoff models (like STORM®) are used to plan and optimize SWMS systems. In contrast, 1D (Browne et al., 2008, Tu et al., 2020) and 2D (Gamache et al., 2015) subsurface flow models have primarily evaluated the unsaturated flow processes in research contexts. STORM® uses the Limit method and uses HORTON and PAULSEN approach for infiltration and PCSiWaPro (Gräber et al., 2020) models the flow in the variably saturated soil using the RICHARDS equation according to the approach of Šimůnek et al., (2008) and J. Šimůnek et al., (2012).

The Combination of the models facilitated to answer questions about the horizontal and vertical flow rates, considering the water withdrawal of the plant roots and from the water extraction points. In addition to that, the influence of variably saturated soil on transpiration rates was examined. Changes in the structural design and layout of the system as well as operational conditions were derived to increase the reliability of stormwater retention and irrigation water supply.

This contribution compares both model approaches and presents a workflow to combine the benefits of each model in an actual planning process. In order to provide greater planning certainty, overcome the limitations of each model approach the use and comparison of models is useful. Consideration of alternative models can help to increase system understanding, systematically investigate issues, and provide more decision support (Enemark et al., 2019). In addition to that, constructive recommendations can be developed from the modelling findings in the decisive early planning phases to ensure the functionality of the drainage and irrigation system.

Methodology

Study area and system concept

A SWMS is implemented in the urban development project in Hamburg "Grasbrook". An extensive system of tree trenches will be constructed in combination with a large - scale sand filled retention volume as a water reservoir. The surface runoff water from all impervious areas is routed to infiltration swales, filtered by the top layer of the soil, and then percolates through the underlying tree trench substrate. Water that is not directly absorbed by the trees accumulates in the storage area below the tree pits and is retained there. The storage reservoir consists of a 40 cm layer of sand on top of an impervious geomembrane in which water flows horizontally to the extraction points of a drainage system and can be used for irrigation of the trees in the urban district. In addition, as a new measure, trees are planted directly in the trench layer to supply themselves with the water in the reservoir through capillary rise. The conceptual design of the system is shown in the following Figure 1.

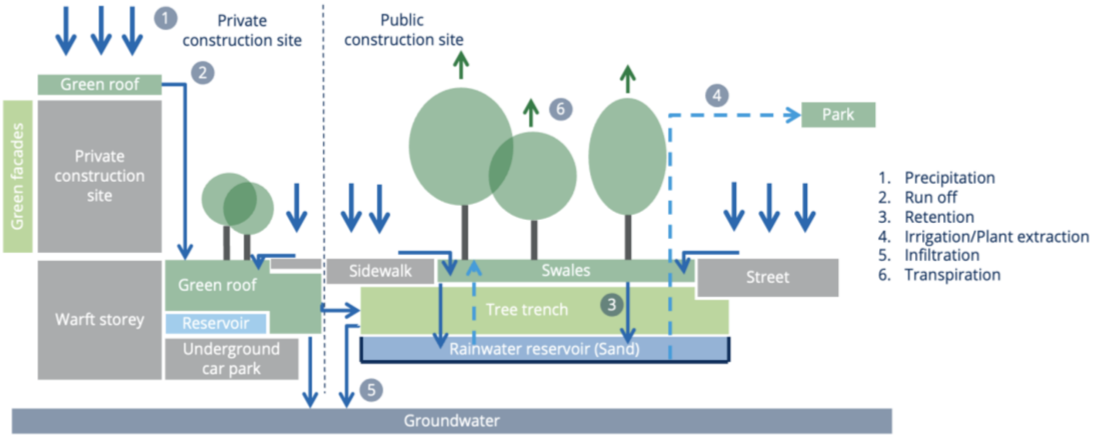

Figure 1. Schematic of the system structure planned and designed by Ingenieurgesellschaft Prof. Dr. Sieker mbH

Data collection

Input data, including precipitation data, transpiration data, evaporation data, spatial data and soil and material properties were required as input data for both model approaches. Precipitation and evapotranspiration data were taken from the open-source database “Climate Data Center” (CDC) of the meteorological station Hamburg "Fuhlsbüttel". Transpiration rates of individual trees were taken and compared from literature values including Wessolek and Kluge,(2021) and Thom et al., (2020). The spatial data was provided by the landscape architects. The pervious area that relates to the SWMS is about 80.000 m² and the potential green spaces that functioning as swales is about 15.500 m². This area was abstracted, defined, and transferred to a conceptual and numerical model for each model approach.

In STORM® the study area was divided and collected in homogeneous pervious and impervious areas. Each fraction contains input parameters like rain gage, total area, Manning's roughness for both pervious and impervious areas and depression storage.

PCSiWaPro works with the finite element method. A mesh was created using “Gmsh” (Geuzaine and Remacle, 2009) and first (groundwater level) and second (infiltration rates, transpiration, evaporation, extraction rates, no Flow conditions) boundary conditions were defined for the unsaturated flow model. After the model run, the parameters (Van Genuchten parameter, plant root extraction coefficients, initial pressure head), model run parameters (termination criteria, increment of iterations), the time and space discretization and the mesh structure of PCSiWaPro were calibrated and adjusted. Then the results were validated by a loss criteria for water balance and an error analysis was made (König and Weiss, 2009).

Workflow of linking the models

STORM® maps the model area as a horizontal plane (the x - and y - dimension), PCSiWaPro maps the model area as a vertical plane (x- and z- dimension). The first model interface was a STORM® model run. The resulting runoff from the connected impervious areas served as inflow boundary condition for the infiltration swale in PCSiWaPro. Subsequently, model run in variants of the unsaturated flow model PCSiWaPro was performed. The results of PCSiWaPro served as a reference for the simulation of infiltration and storage processes in the STORM® model. The processes and parameters in the block model were modified to reproduce the results of the physically - based model. Hence, long-term simulations were performed with the faster block model.

Case study

The selection of simulation time periods and specific rainfall events for the comparison of the models was carried out conceptually. The behavior of the system in PCSiWaPro was examined under different initial conditions "dry", "medium moist" and "wet". Conceptually, Two representative rain events were selected from each of the years 2017 (wet year), 2018 (dry year) and 2019 (medium-wet year). Of these, one rain event each is comparable with a return period of 0.2 a and a duration of approx. 300 min and three rain events examine the cases of medium heavy rain (T3, D160), drought conditions (T0.02, D40) and medium rain (T2, D300) that occurred in the respective years. A dry period of 7 days was implemented before and after the rain event.

Results and discussion

Under natural conditions, 51.8% of the annual rainfall in the undeveloped area will be evapotranspiration 47.3% will percolate and 0.9% will be subsurface runoff (Max Schmit, 2022). The development of the area will result in the paving of approx. 134,500 m². Of this, 80,000 m² will drain into the extensive system of tree trenches in combination with a large sand filled retention volume and 20,000 m² will be treated by other SWMS. Which sums up to 74% of the pervious area is treated by SWMS. By using the system and combining it as a tree site and using it as an irrigation system the urban water balance approaches the natural balance. It is estimated that in 60 years 45.6% of annual rainfall evaporates, 44.5% percolates 9.9% will be subsurface run off. To ensure this development, the security of irrigation supply must be provided.

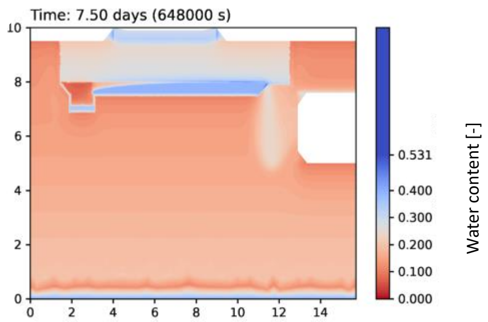

Figure 2: Example of the distribution of the water content in the substrates modelled with PCSiWaPro

By changing the conceptual model in STORM, the results of PCSiWaPro could be implemented and the inertia of the system could be depicted better. This approach was used to investigate the occurrence and impact of dry periods in a long-term simulation. It has been found that dry periods increase for medium and wet years to 74% and 76%. During drought periods the storage capacity is not sufficient to ensure additional irrigation of the trees outside the system. The planned system is functional; however, the security of irrigation supply is exaggerated compared to the results of the uncombined model run with STORM®.

The result of this work provides the basis for further planning and the development of an irrigation strategy. Constructive proposals were made like the implementation and dimensioning of a retention and drainage system under consideration of the variable horizontal flow rate. Therefore, the SWMS can be divided into an “active” (drainage system) and a “passive” (sand reservoir) storage part. The active volume is the easy access retention and is available for external irrigation which is 250 m³ of the 6.270 m³ potential volume of the whole system. The water rate that flows horizontally into the drainage system depends on the water content. Under average initial conditions, the drainage system can theoretically be filled once a day. Based on this and with a safety margin of 0.5, a daily potential irrigation capacity was calculated (cf. Table 1) from which a suitable irrigation strategy can be developed.

Table 1. Irrigation volume in L/d per tree for the supply cases Trees outside the storage system are irrigated and the total number of trees must be irrigated

Tree age	Active irrigation volume for trees outside the storage system l/d/tree	Active irrigation volume Total number of trees in l/d/tree
10 a	48.4	25.6
30 a	60.6	28.3
60 a	69.2	32.0

It is found that physically-based model approach can significantly increase the understanding of the system and provide a good extension for the planning process. The PCSiWaPro model depicts the flow processes better and more completely than the STORM model. It is important to note that the system works best when the water is circulated, and the substrate is prevented from drying out.

Tree trench Substrate properties

An appropriate substrate for the infiltration trench was proposed that enables the duality of drainage function and water provision to trees. No more than 15% of clay and silt particles are recommended in the substrate. A high organic content leads to a high-water storage capacity in the substrate, which has a positive effect on the water storage capacity, but reduces the vertical flow into the reservoir, so that the security of supply is reduced. An organic content of 2 - 4 % is recommended (Sandoval et al., 2017).

Conclusions and future work

Coupling hydrodynamic and physically based modelling approaches allows to improve representation of infiltration SWMS in simulation of urban environments. With the help of modelling, reliable evaluation criteria for the design, dimensioning and applicability of planned systems can be provided. Physically based modelling can reduce conceptual and parameter uncertainties in the design process for new SWMS. Specific improvements in structural design, layout and operation conditions were derived for the investigated large scale trench system. Long term simulations supported the applicability as a combined stormwater retention and irrigation supply system.

A suitable irrigation strategy and easy access retention volume need to be further developed to ensure supply security. For future work a long-term simulation with PCSiWaPro is planned and the integration of RICHARDS equation and the plant root extraction approach in STORM® can be developed further (Šimůnek et al., 1998). The implemented flow model approach of OSTROWKSI in STORM® will be tested and compared. The realization of a test field in the construction project to carry out further on – site measurements is planned.

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