

Modelling the Flood Attenuation of combined SUDS in Urban Areas

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ABSTRACT

The assessment of the effectiveness of Flood Probability Reduction Measures such as Sustainable Drainage Systems (SUDS) is not systematically verified and their practice is not well established yet. The objective of this paper is to quantify and model the hydrologic effects of combined SUDS elements on the catchment level of urban areas at extreme storm events with a new integrative method. The theoretical concept aims at high level of physical soundness and level of detail, but spatial aggregation and data processing in the model are necessary to enhance the flexibility for spatial planning tasks for studying different scenarios of urban developments. The concept has been implemented in a semi-distributed rainfall runoff model and the application is demonstrated with scenario studies.

INTRODUCTION

While future oriented and sustainable approaches for flood risk management along rivers and large streams have been developed, efficient strategies for pluvial flooding have become recently a major issue of research (El Kadi et al, 2007). Traditional structural measures of flood risk management (e.g. raising the flow capacity of storm water pipes) are not appropriate to cope with the emerging flood risk in urban areas as shown by Pasche et al, 2008. Uncertainties due to the impact of future urban developments and climate change call for a risk based approach (Ashley et al, 2007). Therefore a focus has to be set on adaptive responses. In this concept Sustainable Drainage Systems (SUDS) are regarded as an appropriate set of measures to manage pluvial flood risk (Kellagher et al, 2005). They include source control measures (e.g. green roofs), detention structures (e.g. ponds, swales) and infiltration techniques (e.g. filter drains, soakaways) (Tourbier et al, 2007). They can be combined in many ways like green roofs draining into swales with filter drains placed underneath.

Uncertainty exists about the hydrological effectiveness of SUDS to control especially extreme floods in urban catchments. The flood attenuation performance of SUDS for single allotments can be determined by hydraulic calculations, but the assessment of their flood mitigation on the catchment level is complex and requires mathematical models. They should be easy to handle in order to support engineers, spatial planners, landscape architects and decision makers in their task to accomplish an integrative water-sensitive urban design. In this paper the application of a new theoretical approach for modelling the hydrological effectiveness of combined SUDS to attenuate the flood volume will be discussed in scenario studies with green roofs combined with swale filter drains.

THEORETICAL APPROACH

SUDS like green roofs and swales can be regarded as little reservoirs where storage effects (retention) dominate over water movement (translation). Thus hydrological models which are based on the linear reservoir theory and the lumped model approach are considered as appropriate to model the hydrological impact of SUDS on a catchment level.

The theoretical approach for modelling green roofs is based on the subdivision of the SUDS element into three layers: the storage layer, the substrate layer and the filter layer (Fig. 1). The storage layer is an open layer to enhance the retention capacity of the green roof. In the substrate layer vegetation is planted according an extensive or intensive green roof definition. On the plane roof a filter layer is provided above a root protection and insulating layer to drain the water to the rain water downpipe. At each layer the hydrological processes are balanced on the basis of the following continuity equation:

$$\frac{dsw(t)}{dt} = inf(t) - perk(t) - ET_a(t) - \frac{Q_{Drain}(t)}{A_{swale}} \quad (1)$$

The soil water content [sw] within the layers of the SUDS element changes according to the infiltration rate [inf], the percolation rate [perk] into the layer below, the evapotranspiration rate [ET_a] and the drainage through the downpipe [Q_{Drain}]. In the first layer the inflow inf(1) of the green roof is the effective precipitation [P_{inflow}] which includes loss through interception by the vegetation of the roof. The evaporation in the storage layer is equivalent to potential evapotranspiration [ET_p(1)]. Instead of the drainage in the downpipe the water balance is effected by an overflow [Q_{overflow}] when the water level reaches the height of the emergency spill [h_{ex}]. It prevents the overloading of the green roof. The effective flow through the overflow pipe is the minimal discharge calculated with the Poleni formula (with the water level [h_{ov}], the diameter of the overflow pipe [d_{pipe}] and the overflow coefficient [μ]) and the maximal capacity of the pipe with the flow resistance [λ]):

$$Q_{overflow}(t) = \text{MIN} \begin{cases} \frac{2}{3} * \pi * d_{pipe} * \mu * \sqrt{2 * g * (h_{ov})^3} & \text{(Poleni Approach)} \\ \frac{\pi * (d_{pipe})^2}{4} \sqrt{\frac{2 * g * d_{pipe}}{\lambda}} & \text{(Max. pipe capacity)} \end{cases} \quad (2)$$

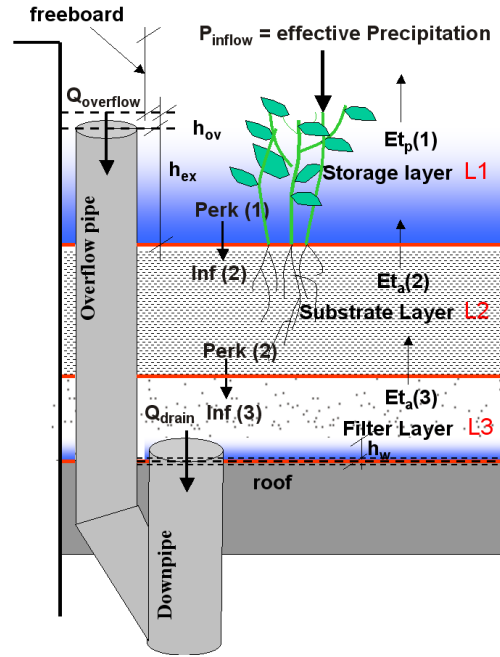


Fig. 1: Theoretical approach of a green roof unit

In the last layer, the filter layer, the percolation [Perk(t)] is set to 0. The drainage through the downpipe begins when the water content in the filter layer is above field capacity. Due to backwater effects at the downpipe the free water will store in the filter layer to the water height h_w . The effective flow through the downpipe is the minimal discharge calculated according to the Poleni approach (eq. 2 by taking into account the porosity in the filter layer) and the maximum capacity of the pipe.

For the combined swale-filter drain systems, Pasche et al (2007 and 2009) developed a theoretical concept. It divides the SUDS-system into four layers with an open swale layer, a colmation layer, a filter layer and a base layer. The water level in the swale changes in dependence of the inflow and outflow components illustrated in Fig. 2. The soil water content [sw] in the layers is calculated respectively as in the theoretical approach of the green roof (eq. 1). The percolation rate and therewith the water uptake capacity of the substratum is defined by a maximal percolation rate. If the percolation rate into the substratum [Perk (4)] exceeds the infiltration capacity of the substratum [inf_{GW}], the saturation of the base layer (L4) starts. The drainage through the drain pipe begins when the base layer is saturated and when water is accumulated in the filter layer above the field capacity.

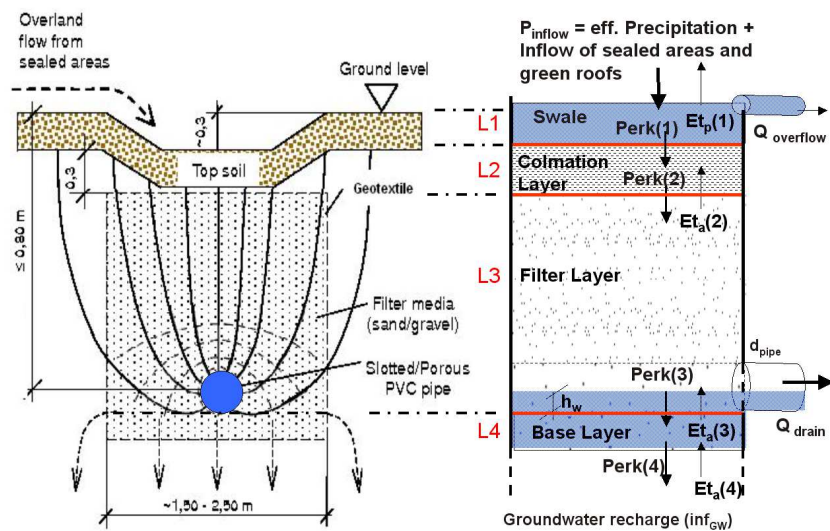


Fig. 2: Theoretical approach of a swale combined with filter drain (according to Pasche et al 2009)

The flow into the perforated drain pipe in the filter layer is calculated according to the Poleni approach with the water level in the filter layer [h_w], the diameter of the drainage pipe [d_{pipe}], the coefficient of the inflow into the drainage pipe [μ] and the porosity [e]:

$$Q_{drain}(t) = \frac{2}{3} * \pi * d_{pipe} * \mu * \sqrt{2 * g * (h_w)^3} * e \quad (3)$$

IMPLEMENTATION

The new methods to simulate the hydrological processes in green roofs and combined swale-filter drains have been implemented into the Open Source software application KALYPSO-Hydrology of the modelling platform KalypsoEnterprise (<http://kalypso.wb.tu-harburg.de>). Kalypso Hydrology is a conceptual deterministic and

nonlinear semi-distributed rainfall runoff model, which divides the catchments into smaller units, the sub-catchments and links them according to the lumped model approach to a chain of reservoirs.

Special focus was given to simplify the definition and parameterization of SUDS components that spatial planners and decision can use this modelling tool. The user input is restricted to geometrical parameters, which can be easily determined.

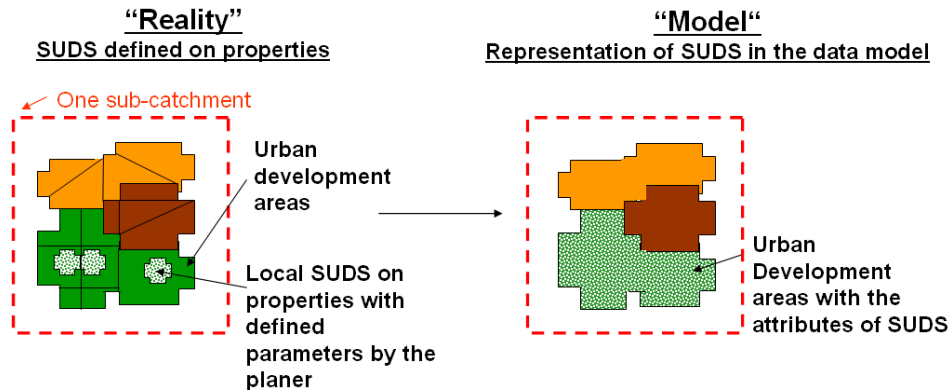


Fig. 3 Integrative approach to model SUDS on the catchment level

All other parameters like soil permeability, field capacity of each layer in the filter drain are predefined and set as standard values. The SUDS on each property (reality of fig. 3) are aggregated and assigned to the land use areas (Fig. 3 “Model”).

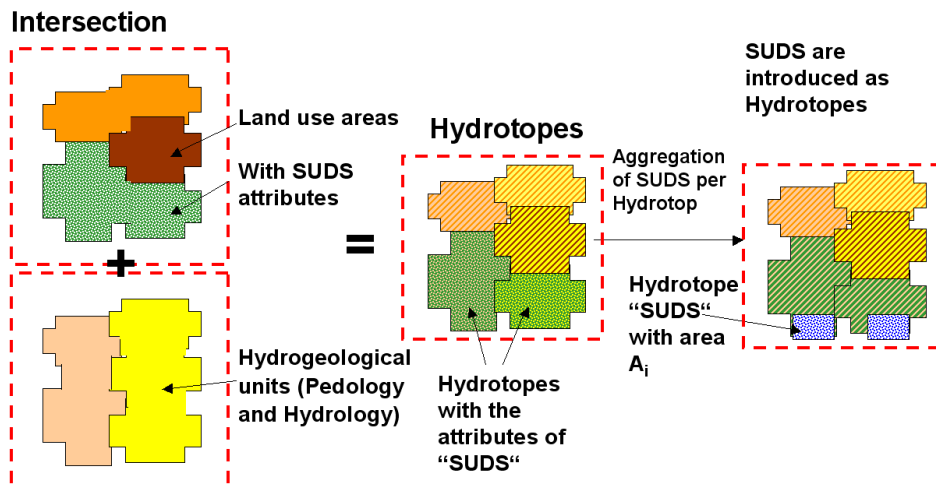


Fig. 4 Data Processing in a semi-distributed Rainfall Runoff Model

The model data is further processed by intersecting land use areas with hydrogeological units (Fig. 4). In this way hydrotopes are created which are hydrogeological similar response units with uniform pedology, hydrology and runoff characteristics. For example, in the scheme of Fig. 4 the land use area with the attributes of SUDS is intersected with two hydrogeological units. After the intersection two hydrotop areas with the attributes of SUDS are created, whereby the area A_i of the

SUDS hydrotop i is resulting from total area of the SUDS [$A_{\text{SUDS,total}}$] multiplying with the ratio of the hydrotope area [$A_{\text{hydrotope}}$] to the land use area [$A_{\text{land use area}}$]

$$A_i = A_{\text{SUDS,total}} * \frac{A_{\text{hydrotope}}}{A_{\text{land use unit}}} \quad \text{eq. 4}$$

APPLICATION AND DISCUSSION

This new approach to model SUDS has been tested at a small urban catchment of the city of Hamburg. In different scenarios the hydrological impact of various combinations of SUDS and climate conditions has been analysed. The catchment has a total area of 3.6 km² and consists of mainly low-density urban developments with dominating private detached housing, commercial facilities and open spaces. The substratum consists of loamy layers with a maximal percolation rate of 10⁻⁸ m/s, which means that hardly any water will percolate into the groundwater aquifer. The scenarios cover the present state (Scenario 0), the natural state with 70% meadows and 30% forest (scenario 1) and two different scenarios of flood mitigation through SUDS: Swale-filter-drains as standalone (scenario 2) and combined with green roofs (Scenario 3). In this scenario 10% of the area, draining into the swale are prior drained by green roofs. The performance of SUDS to compensate the climate change effects has been considered in the scenarios 0,1,2, and 3 by increasing the precipitation with 10%, leading to the climate change scenarios of 0A,1A,2A and 3A.

Tab. 1: Geometrical design parameters of SUDS simulated in scenario 1, 1A, 2 and 2A

Scenario	Description parameter	[km ²]	[%] of Catchment area
Present state	Unsealed area	3,15	85,82
Scenario (0,0A)	Sealed area connected to storm water pipe	0,52	14,18
Combined SUDS Scenario (3,3A)	unsealed area	3,13	85,29
	Area covered by swales	0,02	0,52
	Sealed area connected to storm water pipe	0,252	6,87
	Sealed area connected to swales	0,24	6,58
	Green roof area connected to swales	0,03	0,73

The design parameters of the SUDS units have been defined according to the present practice. The swale filter drain has been designed with a swale depth of 0.4m, a colmation layer of 0.3m, a filter layer with 0.7m and a base layer of 0.1m depth. The infiltration capacity of the colmation layer is $k_f=10^{-5}$ m/s and the one of the filter layer is $k_f=4 \times 10^{-5}$ m/s. As the infiltration rate of the colmation layer is lower than the one of the filter layer the colmation layer controls the infiltration rate into the filter drain. This design principle of the two layers is due to the function of colmation layer to retain particles and pollutants. The green roof has been designed with a maximal storage height of 0.2m on top of the green roof and a freeboard of 0.1m before the crest of the overflow pipe is reached. The substrate layer has a height of 0.2m and the filter layer of 0.1m. In

general in Germany SUDS are designed for a 5 year storm event. They should reduce the stormwater flow to a runoff which approximates the one of a non-sealed surface. By iteration it was found in scenario 2 that for the 5 year storm event 45,8% of the sealed

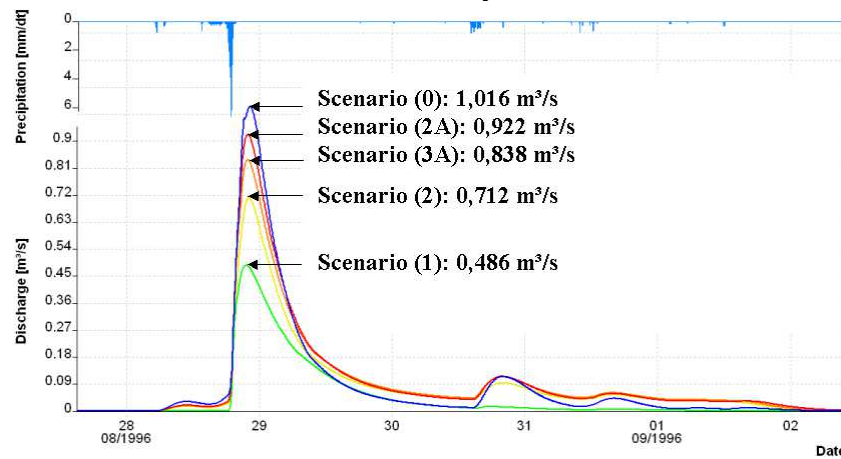


Fig. 5: Hydrographs of different scenarios for a 5 year flood at the end of the catchment

areas has to drain into swale-filter-drains and the swales must cover 0.52 % of the total catchment area to avoid overflow of the swale. In this situation the total runoff of the catchment is considerably reduced compared to the present state (fig. 5) and approximates the one of the natural state (scenario 1). In case of climate change (scenario 2A) the retention effect of the swale-filter-drains is less as the swales produce

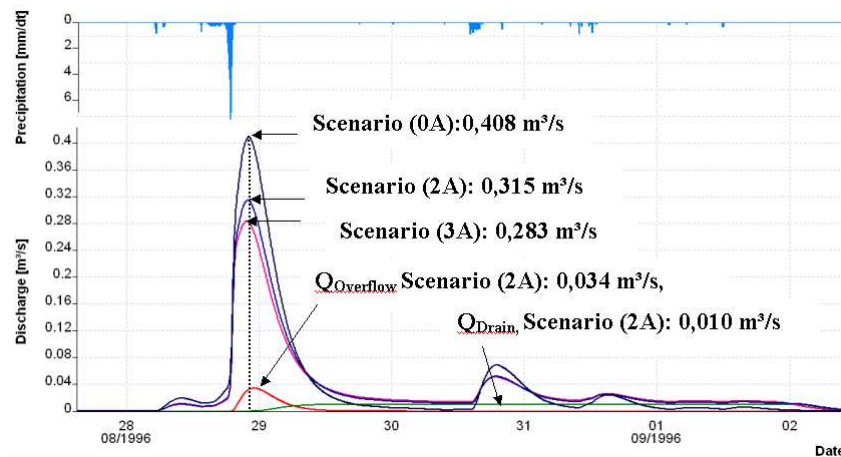


Fig. 6: Effects of SUDS at a 10-year flood with climate change (Scenarios 0A, 2A and 3A)

an overflow. But still the total runoff is less compared to the present state (scenario 0). This is due to the fact that during the whole flooding of the swale the stored water infiltrates with a rate of 0,200 m³/s into the filter layer. Even for the more extreme storm event (10 year flood of climate change condition) in fig. 6 the swale-filter-drains designed for a 5 year flood show a hydrological effect. The peak of the total runoff from a subcatchment is less than 20 % without swales (scenario 0A compared with scenario 2A). This effect is caused by the fact, that the conductivity of the colmation layer is

lower than the one of the filter drains. By reducing the inflow into the filter drain the filter drain is never totally saturated during the whole flood event.

If the green roofs are added according to Tab. 1 the attenuation of the flood peak is considerable. The whole rain falling on the green roof can be stored without storage overload. Only runoff from the drainage pipe occurs. This detention of the storm water on the roof has the effect that no longer overflow in the swales occurs. So the overflow hydrograph from the swales in scenario 2A will no longer occur in scenario 3A (fig. 6).

The results presented in fig. 5 and 6 proof that swale-filter-drains still have a positive impact on the flood hydrograph even though the storage in the swales is overloaded. Additionally combination of different SUDS components will increase the overall retention capacity in the urban catchment. This implies the assumption that SUDS are effective even for extreme stormwater flow conditions and that they are able to compensate the impact of climate change on urban stormwater through successive adaption of the SUDS by adding more SUDS components and draining more sealed area via SUDS. In order to proof this assumption all scenarios have been analysed systematically for storm events of different precipitation intensities. The result is given in fig. 7. It shows the peak discharge of storm events with different flood probabilities ranging from a 1-year flood to a 200-year flood.

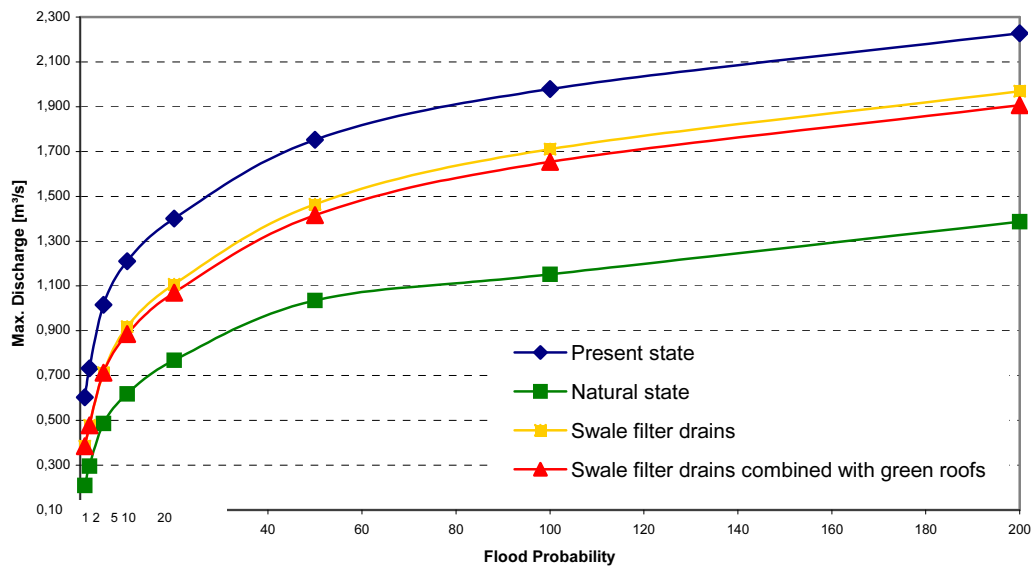


Fig. 7: Hydrological Effectiveness of combined SUDS for floods with different probabilities

The diagram shows a hydrological effectiveness of the SUDS for all flood events. Of course at a 1-year and 5-year flood the effect is maximum approximating the potential natural state best. But for extreme floods with exceedence flow the effect is significant. Also the cumulative retention effect of combined SUDS can be at the extreme flood events. For small floods (below a 5 year flood) no effect is given which is obvious as already the swale-filter-drains detain the whole runoff.

CONCLUSIONS AND OUTLOOK

The refined modelling approach of SUDS have shown a strong attenuation effect of SUDS on urban floods. This is in contradiction to what has been observed in previous work (Pasche et al, 2004) where the numerical studies did not show hardly an effect of swale-filter-drains for extreme flood events. This can be explained by the improved modelling of the physical processes. As Pasche et al, 2004 did not simulate the infiltration into the filter drains they could not show the attenuating effect of this process on the flood hydrograph. The model also shows that by combining different SUDS component the urban areas can be adapted to the increasing flood probability due to climate change giving communities the flexibility to gradually adapt to the changing climate condition. Further case studies with different climate and urban drainage conditions in order are needed to assure the most relevant findings of this study.

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