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Mapping of Multiple Linked Green Infrastructure Systems in Rainfall-Runoff Models

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ABSTRACT

In this paper, the development of a theoretical approach to integrate green infrastructures in catchment based model discretisation as well as its implementation in a conceptual semi-distributed rainfall-runoff model (RRM) is presented. This model type has been distinguished as most promising related to model application in practice. The approach integrates the differentiated description of sustainable urban drainage systems (SUDS) as polygon geometries overlaying the basic data of a catchment. These overlays are defined with an additional functionality to receive and redistribute water within the model net. The user interface (UI) of the model provides a work flow allowing the user to build up and maintain models containing various types of SUDS. The model has been applied to assess the efficiency of SUDS and retention spaces to mitigate the flood peak discharge in several case study areas summarised in this paper. The results demonstrate the potential of green infrastructures (e.g. SUDS) and multipurpose retention spaces for flood peak mitigation.

KEY WORDS: Sustainable urban drainage systems (SUDS), conceptual semi-distributed rainfall-runoff model, efficient and pragmatic user interface, model application in practice.

INTRODUCTION

At present, a rethinking in urban drainage management is going on especially in areas that have a high population density. Advanced management approaches use more decentralised drainage systems and green infrastructure instead of centralized systems (Hoang, Fenner 2015). Hence, green infrastructure incorporating sustainable drainage systems (SUDS) gain a growing importance in urban water management in the recent years, mainly due to their positive effects on water quality and quantity distribution over time as well as their adaptive or multifunctional nature. These approaches accentuate the implementation of a combination of 'natural' systems with 'engineered' systems to collect, drain, treat, attenuate and reduce stormwater runoff (Zhou 2014; Butler, Davies 2011).

Although the awareness and knowledge of these measures is enlarged recently, there is still a dearth of numerical tools that can be applied properly in practice. It has been stated that the availability of effective SUDS modelling tools may motivate and encourage the implementation of SUDS in urban areas (Elliott and Trowsdale 2007). The tools can be used to design these measures and demonstrate the outcomes that can be used for the decision-making process in polity and for education (Elliott and Trowsdale 2007).

This paper presents a review of the state of the art in model development and the implementation of a theoretical approach to represent SUDS in a semi-distributed rainfall-runoff model (RRM).

REVIEW OF RAINFALL-RUNOFF MODELS

Models are playing an increasing role in urban water management to study the often highly complex systems in urban and rural areas. The main development of so called rainfall-runoff models and water-balance models was in the period from 1950 to 1970 (Liebscher, Mendel 2010). The continuous enhancement of these models goes along with the fast development of computer technology. State of the art rainfall-runoff models may be classified according to their complexity (Vaze et al. 2011; Burton, Pitt 2002) ranging from simple empirical methods (e.g. curve number) to conceptual semi-distributed model approaches and fully-distributed physical based hydrological models. Despite of the complexity, all of these models conceptualize the "real" processes using some sets of mathematical equations and are distinguished with strength and weaknesses. Selecting the right model depends on understanding the objectives and the system being modelled (Vaze et al. 2011; Urbonas 2007).

Although there is a tendency to use more and more physical based approaches, the more simple conceptual (semi-distributed) models don't loose there importance in practical application. A high complexity of the hydrological catchment, missing data and errors on data sources, which are higher than the uncertainty in the applied model type, are some reasons why the more "simple" models are still more likely to be applied (Messal, 2000). The level of expertise with the conceptual type of RRM within water industry and the likelihood that previously calibrated models are available for catchments may be further criteria (Vaze et al. 2011).

Progress is made in incorporating attributes to model SUDS with different types of rainfall-runoff models, but there are still areas for further development, including the representation of small-scale hydrological elements (like SUDS) on a catchment scale (Elliott and Trowsdale 2007) and the correlation of measures within the overall catchment system. Integrating such large numbers of spatially distributed heterogeneous measures and linking them into existing model nets is a tedious, time consuming and error prone work. Hence, an optimised approach to integrate such data into existing RRM is required.

THEORETICAL APPROACH

The design and implementation of SUDS and multipurpose spaces in urban areas depend on local features of the land use and soil type. For example, the distribution of green roofs depends on the availability of corresponding building types, whereas the distribution of retention spaces and infiltration measures depends on the availability of free spaces. Sufficiently detailed GIS-based land-use maps matching this spatial detail are mainly already available by municipalities for land-use planning and have to be integrated in the modelling approach.

SUDS such as green roofs and swales can be regarded as small-scale reservoirs where storage effects (retention) dominate over water movement (translation). Thus, hydrological models which are based on the linear reservoir theory are considered as appropriate to model the hydrological impact of SUDS.

Semi-distributed conceptual models allow the simulation of the entire land-based part of the water balance on the basis of given precipitation time series. The catchment is divided into smaller hydrological systems: in the first order: sub-catchments and in the second order: hydrotopes (a.k.a. hydrologic response units), that is, units with distinguished land use, drainage and soil characteristics, for which the water balance is computed. Depending on the level of details, the defined land-use units are composed of heterogeneous elements. For example, the land-use class ‘detached buildings’ contains both, a building and a green space. In the case that several SUDS elements are to be applied, this differentiation has to be made as green roofs and swales can be applied only on buildings or green spaces, respectively (Hellmers et al. 2016).

METHDODOLOGY

In order to take into account the effects of SUDS, the existing data model concept of hydrotopes has to be redefined by integrating a differentiated description of the SUDS elements. Firstly, those SUDS elements should be spatially distributed to be in accordance with the given land-use data, as shown in Figure 1. The green roofs are, for instance, allocated on the existing or planned buildings, whereby the distribution of retention spaces is dependent on the availability of free space. The additional information of SUDS and retention areas is represented in the form of ‘overlays’. The final hydrotopes are created by geometrically intersecting the land use, soil type, watershed and overlay polygons. The main parameters and the data mapping processes are outlined in Figure 1. Secondly, for modelling the physical processes in the individual SUDS elements, they are subdivided into a sequence of vertical layers which are defined based on their characteristics and functionality as shown in Figure 2. For example, green roofs are subdivided into three layers: the upper layer with vegetation, the substrate layer and the drainage layer. In the substrate layer, vegetation is planted according to 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.

The parameters of the vertical layers of different SUDS are assigned to the corresponding units (i.e. green roofs, swales or cisterns) in the redefined hydrotopes and input into the model. Further information about the parameters is given in Hellmers et al. 2016.

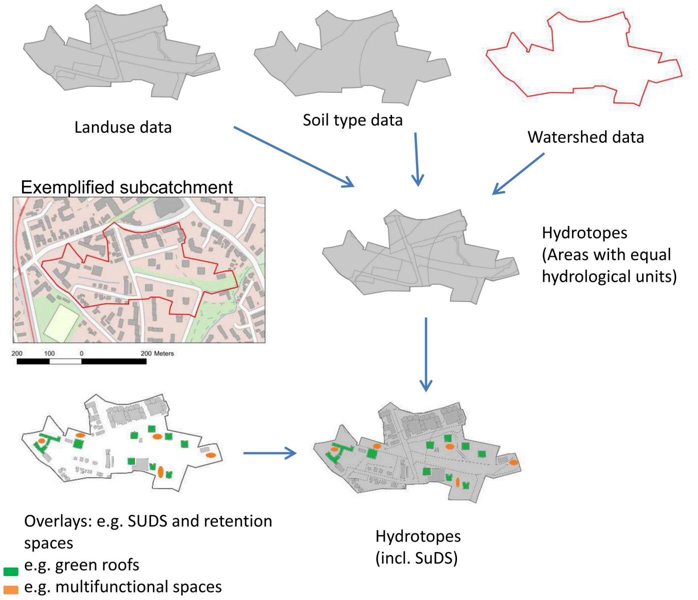

Fig. 1 Spatial mapping (intersection and aggregation) to define equal hydrological response units containing the SUDS information as additional attributes (adopted from (Hellmers et al. 2016)).

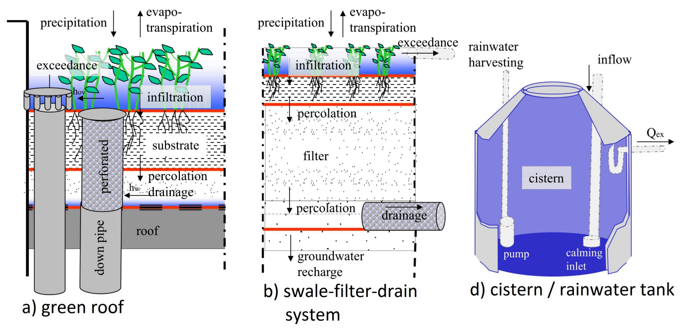

Fig. 2 Schematic design of SUDS (from left to right): green roof, swale-filter-drain system, cistern (adopted from (Hellmers et al. 2016)).

IMPLEMENTATION

The implementation of the theoretical approach has been done in the semi-distributed rainfall-runoff model KalypsoHydrology[1]. It is an open-source semi-distributed RRM for the simulation of the land-based water balances in river catchments (TUHH 2013) and has been enhanced to include the differentiated description of SUDS and retention areas in the form of overlays. The hydrological model supports the simulation of snow, evapotranspiration, evaporation from water surfaces in retention ponds, soil moisture, interflow, baseflow and groundwater flow processes.

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[1] Link: www.sourceforge.net/projects/kalypso/

The calculation core written in FORTRAN has been reworked to support the new functionalities. The network in the hydrologic model used to describe the runoff concentration from upstream to downstream sections in a river system consists of sub-catchments, drainage strands and drainage nodes (cp. Fig. 3).

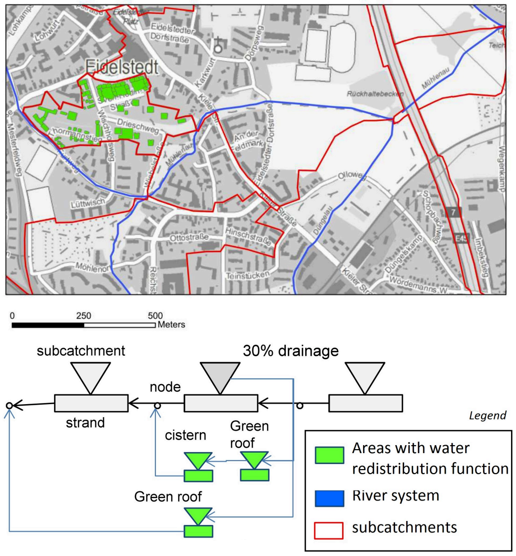


Fig. 3 Implementation of overlays (here: green roofs and cisterns) in the system plan of a semi-distributed RRM (adopted from (Hellmers et al. 2016))

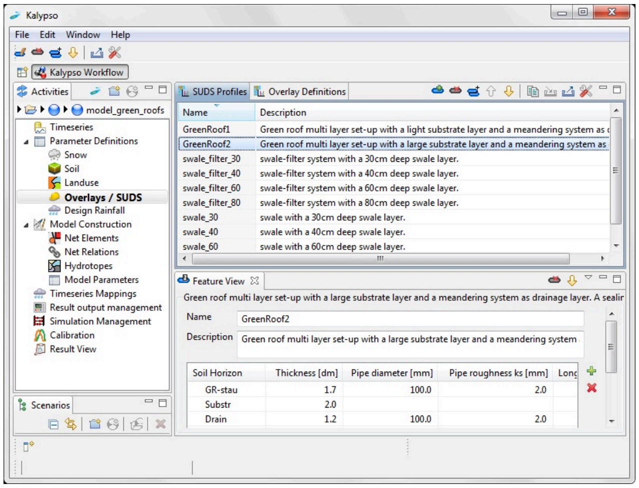
The enhanced methodology allows the conveyance of exceedance flow in a chain of small-scale SUDS measures and larger-scale retention spaces. For this purpose, the new model accounts for the possibility that a single SUDS measure or designated area may both receive and distribute water. For that purpose, the model network has been enhanced with additional linkages to redistribute water from drainage nodes to areas. The areas with the functionality to drain and receive water are defined in the model as overlays (see Figure 3 'system plan with overlays'). This functionality is defined here as "mapping" the information of small-scale units in a meso-scale system, e.g. the sub-catchment. During the computation, these areas are transformed into additional hydrological systems, and an algorithm has been implemented in the model KalypsoHydrology to cross link these hydrological systems in the overall drainage net with drainage strands and drainage nodes. The partial or entire distribution of the water in the model network plan is attributed to drainage nodes. The exceedance flow is distributed to retention areas in the larger system (e.g. multipurpose spaces, such as a sports field) or to the drainage network, when the design capacity of the elements on properties (e.g. green roofs, swales) is reached by a storm event.

MODELL APPLICATION KALYPSOHYDROLOGY

A major issue for the model application in practice is an efficient user interface (UI) supporting the data management and the import of spatial data. The presented RRM in this paper is part of the open-source project Kalypso which comprises a set of applications and client specific developments based on Java technology. It is based on the Java version 8 and Eclipse 4.5. It is developed according to modern information and communication technologies (ICT) viewpoints (BCE 2016).

The Kalypso applications include modeling systems in the areas of flood forecasting, rainfall-runoff modeling (KalypsoHydrology), hydraulic modelling (Kalypso1D/2D), assessing of eco-morphological conditions, flood inundation (KalypsoFlood), flood risk assessment (KalypsoRisk) and the evacuation of flooded areas (KalypsoEvacuation). The modules are provided with a strong functionality on spatial GIS analysis, temporal time series management and data processing features. These are main functionalities in nowadays data management practice and software application.

Furthermore Kalypso has been developed with a strong focus on early feedback to invalid user input or data which makes it especially efficient in regard to models linking hundreds of SUDS into an existing model network. Since KalypsoHydrology Version 13 the user is supported to build up a model by a workflow based interface (see Fig. 4).



Name	Description
GreenRoof1	Green roof multi layer set-up with a light substrate layer and a meandering system as
GreenRoof2	Green roof multi layer set-up with a large substrate layer and a meandering system as
swale_filter_30	swale-filter system with a 30cm deep swale layer.
swale_filter_40	swale-filter system with a 40cm deep swale layer.
swale_filter_60	swale-filter system with a 60cm deep swale layer.
swale_filter_80	swale-filter system with a 80cm deep swale layer.
swale_30	swale with a 30cm deep swale layer.
swale_40	swale with a 40cm deep swale layer.
swale_60	swale with a 60cm deep swale layer.

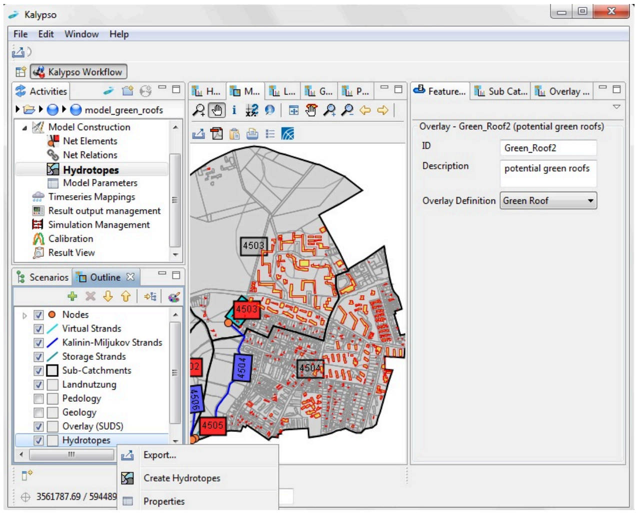
Green roof multi layer set-up with a large substrate layer and a meandering system as drainage layer. A sealir

Name: GreenRoof2
Description: Green roof multi layer set-up with a large substrate layer and a meandering system

Soil Horizon	Thickness [dm]	Pipe diameter [mm]	Pipe roughness ks [mm]	Long
GR-stau	1.7	100.0	2.0	
Substr	2.0			
Drain	1.2	100.0	2.0	

Fig. 4 Workflow of KalypsoHydrology and parameter set-up for multiple layer elements (e.g. SUDS)

Multiple layer elements like SUDS are defined in profile tables and multiple layer definitions. A more detailed description of the input parameters is given in (Hellmers et al. 2016). The UI supports a GIS based data management and basic GIS based functions (e.g. intersection of shape files). An example is illustrated in Fig. 5.



Overlay - Green_Roof2 (potential green roofs)

ID: Green_Roof2

Description: potential green roofs

Overlay Definition: Green Roof

Fig. 5 GIS based data management and processing functions (e.g. creation of hydrotopes)

CASE STUDYS

The novel functionality to model SUDS with the presented RRM KalypsoHydrology has been applied for the following case studies and has been continuously optimised during the specific application cases. The first application case study was done for the small urban catchment Garforth, West Yorkshire in England (Pasche E. et al. 2009; Hellmers 2008) and a first verification of the theoretical approach has been presented. The implementation has been enhanced in the second case study of the Krückau catchment area (274km²) in North Germany to analyse the effectiveness of green roofs, swales and swale-filter-drain systems (Hellmers 2010; Hellmers, Pasche 2011). The results illustrated promising results to mitigate the effects of climate change impacts on flood peak discharge. The third case study focused on the urban Wandse catchment (88km²). This case study was analysed in detail within the German Research Project KLIMZUG-Nord. Here, the module was enhanced with the functionality of multiple linked measures. The module was applied within the overall Kalypso set-up for flood risk management: KalypsoHydrology, KalypsoWSPM, KalypsoFlood and KalypsoRisk. The results demonstrate the potential to mitigate the flood risk and related damage costs [in €/a] of specific flood events (Hellmers et al. 2015).

CONCLUSIONS

A semi-distributed conceptual RRM (namely KalypsoHydrology) has been enhanced with the attributes of mapping of multiple linked green infrastructure systems. This model type is distinguished to be the most promising type to be applied in practice for decision making processes in politics and for enlarging the knowledge in research. The strong features of a GIS based data management tool and the importance of a user friendly interface are presented within the Kalypso tool in this paper. The numerical model has been applied for different case studies in recent years, demonstrating the potential of green infrastructures (e.g. SUDS) and multipurpose retention spaces for flood peak mitigation.

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