Modelling sustainable drainage and decentralised flood mitigation techniques

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ABSTRACT

Assessing the performance of decentralised flood mitigation practices requires novel hydrological modelling approaches that can handle a large number of spatially distributed measures and enables a water redistribution functionality to simulate exceedance flow control. This becomes one of the key tasks of the stormwater management in urban areas considering the present and future conditions mainly driven by climate change and urban growth. A combination of local drainage systems and water retention in public spaces may provide an appropriate strategy to cope with these effects. This paper presents the implementation of a SUDS modelling approach in a semi-distributed hydrological model that enables the simulation of flow among multiple linked SUDS and retention spaces. The objectives of the implemented model are the representation of SUDS as model elements with water redistribution functionality as well as its possible integration into a flood risk management tool. The application of this model is presented for two case studies in Germany. The results show a high potential for SUDS and multipurpose spaces in flood mitigation management.

KEYWORDS

Adaptation, SUDS, hydrologic modelling, flood modelling

INTRODUCTION

Adaptive strategies are needed to manage the uncertainties of the future development mainly shaped by climate change (IPCC, 2012) or rapid urbanisation (UN, 2011). In that sense, decentralised strategies (here referred to as SUDS), which drain the water in a natural way using infiltration, retention and storage devices in urban areas (Butler & Davies, 2011) are increasingly being considered as the appropriate strategy to manage stormwater in cities due to their adaptive or multifunctional nature (e.g. Wong et al., 2013). These measures are (mostly vegetated) source-control structures such as swales or green roofs, with a limited capacity and a specific design threshold. By combining those individual measures into cascades, an adaptable system can be created. If the design value of an element (e.g. green roof) is exceeded, the exceeding flow can be conveyed by roads or streets to a multipurpose area (e.g. a park or open green space). Measures such as flood abatement systems can be used to divert the flow or to protect the adjacent properties if required.

There is a significant body of literature analysing and acknowledging the multiple benefits of those systems (e.g. Wong et al., 2013; Butler & Davies, 2011). However, a research need is seen in quantifying the hydrologic performance of those cascades of individual SUDS measures and their performance on site scale as well as on catchment scale (Stovin et. al., 2013). A range of available modelling tools allow the simulation of SUDS (e.g. InfoWorks ICM and CS, MUSIC, WINDES) for different purposes and applications. The selection of the most suitable model is mainly driven by the purpose (planning or design), the spatial scale of the modelling analysis (site scale or catchment scale) or by the type of SUDS elements to be modelled (Velasco et al., 2013).

This paper will introduce a new approach for a detailed modelling of SUDS for the planning purpose on both spatial scales and its implementation into the semi-distributed hydrologic model KalypsoHydrology. To test its applicability the tool has been applied at two selected study areas in northern Germany. In case 1 for different socio economic scenarios which include SUDS (the Wandse area, Hamburg- catchment scale) and in case 2 for a cascade system on a site scale in the city of Elmshorn. The results will be presented and the conclusions drawn on its applicability for planning process in urban flood risk management.

METHODOLOGY

The approach for modelling of SUDS

Semi distributed hydrologic models (SDHM) 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 hydrotops (a.k.a. hydrologic response units), i.e. units with the same land use, drainage and soil characteristics, for which the water balance is performed. However, in the defined hydrotops, the landuse units are composed of heterogeneous elements. For example the landuse class “detached buildings” contains both, a building and a green space. In the case that different 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 resp.

Therefore, in order to take into account the effects of SUDS, the existing network of hydrotops in a SDHM should 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 landuse data as shown in Fig. 1. The green roofs are for instance allocated on the existing or planned buildings, whereby the distribution of retention spaces and infiltration measures is bound to the available free space. Secondly, in order to simulate the physical processes in the individual SUDS elements, for the modelling purposes they are subdivided into a sequence of vertical layers which are defined based on their characteristics and functionality as shown in Fig. 2. The parameters of the vertical layers of different SUDS are assigned to the corresponding units (i.e. green roofs, swales or swale-filter-drain-system) in the redefined hydrotops and input into the model. A detailed description of the modelling procedure and parameters of the individual measures is given in the previous work of the author (Hellmers, 2010). The main parameters are outlined in Fig. 1.

Implementation- the method of overlays

KalypsoHydrology, a semi-distributed hydrological model for the simulation of the land-based water balances in river catchments (Pasche, 2003), has been enhanced to include the differentiated description of SUDS and retention areas in the form of “overlays”. The new, redefined, hydrotops are finally created by geometrically intersecting the land use, soil type, watershed and overlays (see Fig. 1). The model network in the hydrologic model used to describe the runoff concentration from upstream to downstream sections in a river system consisting of sub-catchments, drainage strands and drainage nodes. By including the “overflow” parameters into the description of SUDS and consequently of the hydrotops, it has been made possible to consider the exceedance flow. 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.

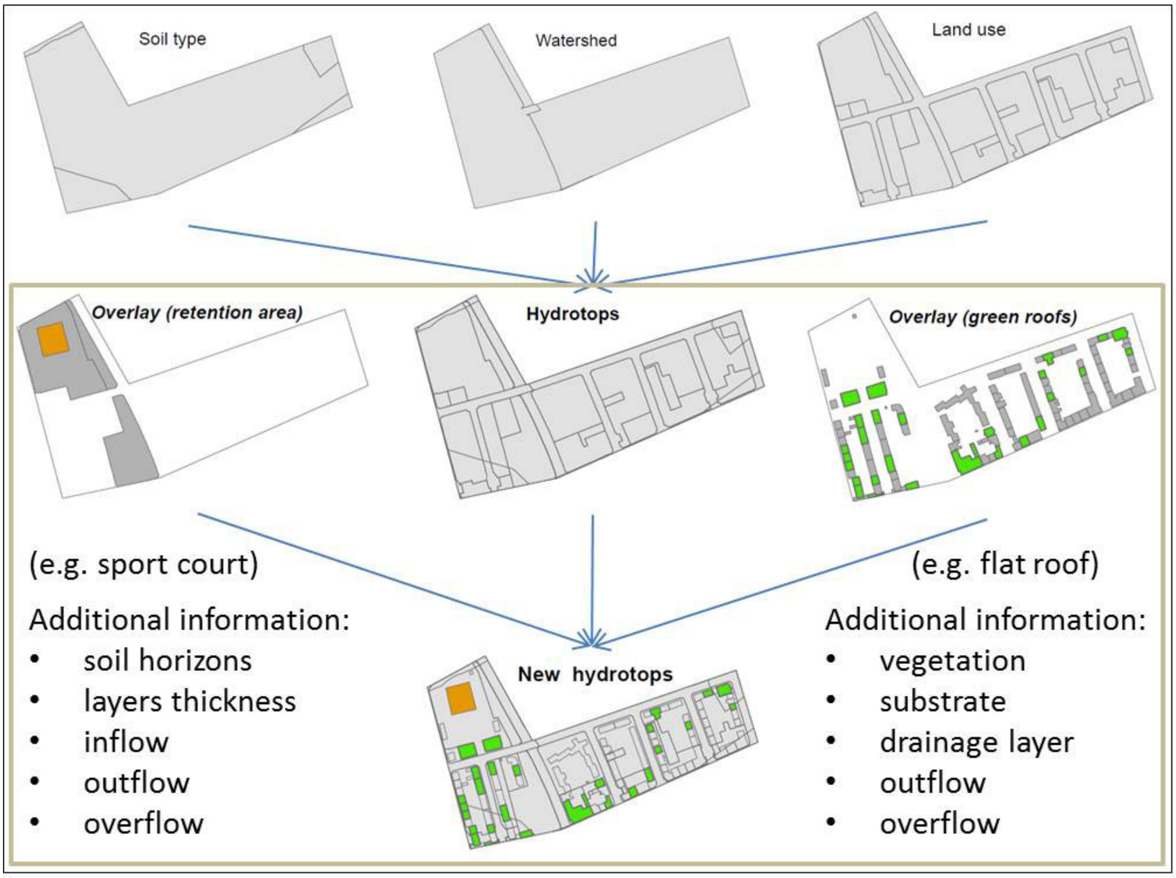

Fig. 1 Spatial intersection and aggregation define equal hydrological response units (hydrotops). The new hydrotops contain the SUDS information in the overlay layer

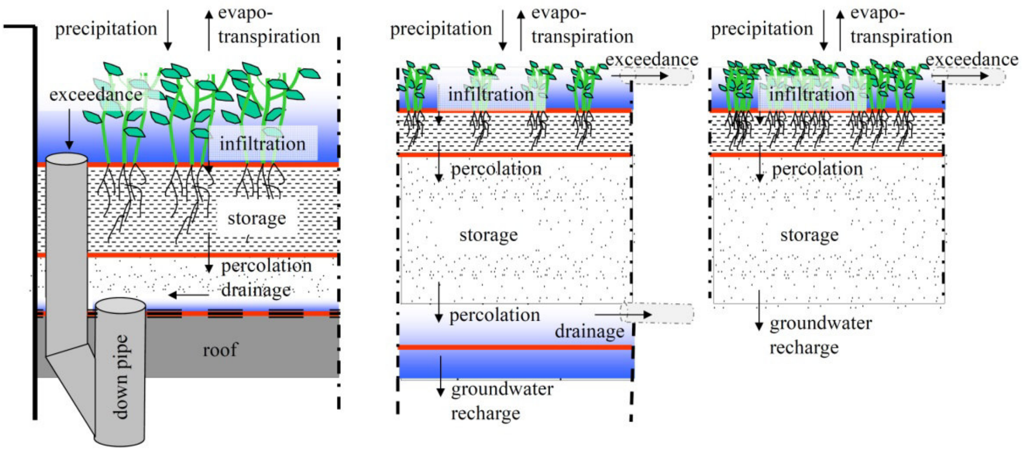

Fig. 2 Schematic design of SUDS: green roof (left), swale-filter-drain-system (middle), swale (right) (adopted from Hellmers, 2010)

During the computation, these areas are transformed into additional drainage subcatchments and an algorithm has been implemented in the model KalypsoHydrology to cross link these subcatchments 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 enhanced methodology allows designated areas to receive and distribute water, so that a conveyance of the exceedance flow in a chain of small-scale SUDS measures and large-scale multipurpose retention spaces is enabled (see Fig. 3). When the design capacity of the elements on properties (e.g. green roofs, swales) is reached 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 system. The numerical core of the hydrological model within KalypsoHydrology has been refined to enable the detailed simulation of the water balances in SUDS elements as defined in Fig 3 (Hellmers, 2010).

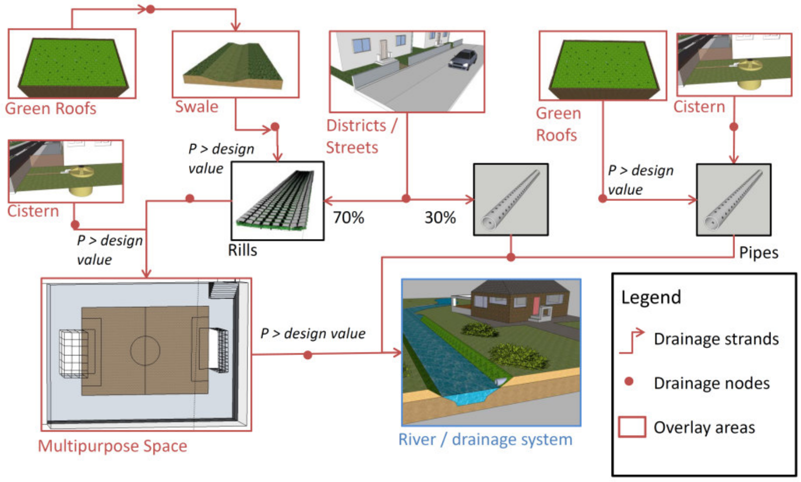

Fig. 3 Overlay areas linked with drainage strands and drainage nodes in a model net

Integration in urban drainage and flood risk management

The enhanced hydrological model, KalypsoHydrology, is part of the open source modelling platform Kalypso (http://kalypso.bjoernsen.de). The core part of Kalypso comprises hydrologic and hydrodynamic simulation models. Derived from the calibrated basic model, scenario simulations can be created in the software tool with GIS data of future urban development projections and areas of overlays with the attributes of adaptation strategies like SUDS or larger retention areas. In the process chain of Kalypso steady-state non-uniform rivers hydraulics are computed with a one-dimensional water surface profile model (KalypsoWSPM). Additionally, an unsteady and 1D-2D coupled surface flow can be calculated with the module Kalypso1D2D. In the post-processing the inundated areas and flow depth can be computed on the basis of digital terrain data with the module KalypsoFlood (Fig. 4).

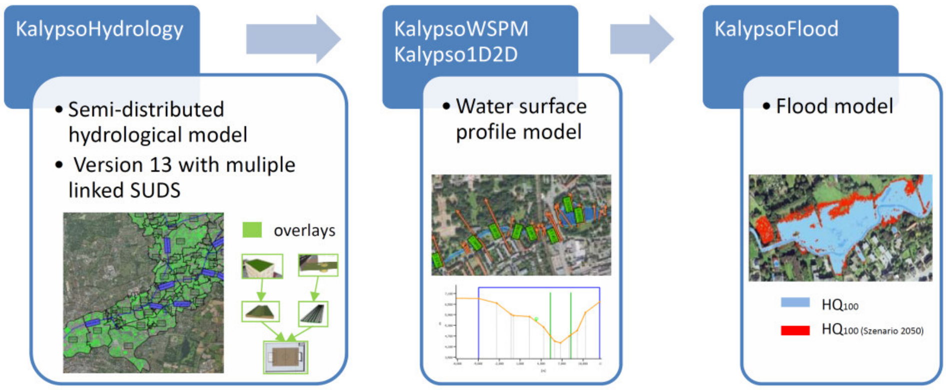

Fig. 4 Kalypso modules for the process of flood risk management planning. The procedure can be performed for the present state and different future scenarios

APPLICATION

The SUDS model has been applied to quantify the impacts of urban growth projections for 2050 in the Wandse catchment in Hamburg assuming adaptation strategies with local SUDS measures and larger-scale retention areas. Another application study focused on a cascading system of multipurpose spaces. This study has been performed within the catchment of the river Krückau in Elmshorn.

1. Application study: Wandse, Hamburg

The river Wandse stretches over 21 km and drains an area of 88 km². The area upstream is mainly vegetated whereas downstream regions are more urbanised and have a higher fraction of impervious areas. In the KLIMZUG-Nord project (www.klimzug-nord.de), socio-economic scenarios for 2050 have been defined (Rottgardt et. al., 2014). The first scenario (S1) assumes a decrease in population in the inner city, which means people moving into the suburbs. Because of less financial support, the structure of the inner city remains more or less the same in terms of further developments. In this scenario, no adaptation strategy is applied. The second scenario (S2) assumes an increase of the population in the city of Hamburg. New buildings are constructed and the infrastructure is enlarged. In this scenario, the impervious areas in the city increase, which raises the need for alternative urban drainage systems. In this scenario, a moderate implementation of SUDS measures is assumed to be financially supported. In the third scenario (S3), an increase of inhabitants is assumed, too. But here the demand for new living space is assumed to be met by increasing the height of buildings. Impervious areas increase to a lesser extent than in the second scenario. In this scenario, the government strongly subsidises the implementation of adaptation strategies like SUDS and larger water retention facilities in the city. Small-scale SUDS and larger-scale retention areas have been defined in the model as overlay areas. The detailed spatial distribution of these areas is illustrated for the socio-economic scenarios in Fig. 5.

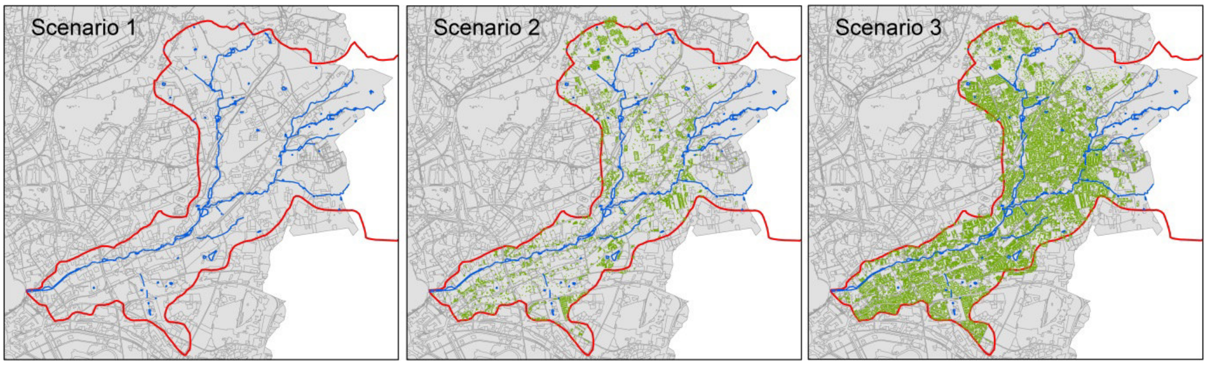

Fig. 5 Spatial distribution of decentralized drainage measures in the Wandse catchment for the urban growth scenario S1 (left: no measures), scenario S2 (middle) and S3 (right)

These measures increase the potential evapotranspiration and infiltration of water in urban areas. By way of illustration the results of evapotranspiration, base flow and river discharge according to scenarios S1 (no measures) and S3 (including measures) for a subcatchment over a yearly period are shown in Fig. 6.

Based on peak discharges resulting from with KalypsoHydrology, the river hydraulics were computed with the one-dimensional water surface profile model KalypsoWSPM. The inundated areas and flow depth were calculated on the basis of digital terrain data with the module KalypsoFlood. The computed inundated areas and water flow depths are illustrated in Fig. 7 for an urban area, an urban-suburban area and a suburban area.

For this catchment, a maximum increase of 20% in flood peak discharge due to climate change is projected for 2050 (Hellmers & Hüffmeyer, 2014).

For the selected urban and urban-suburban areas, minor impacts on the inundated areas of a 100 year flood were calculated for the climate change and urban growth scenarios. This can be explained by the high river banks which prevent flooding of adjacent properties. On the contrary, in the upstream river section, i.e. the suburban area, the river topography is shallow. Here, the increased peak discharges due to climate change and urban growth enlarges the inundated areas. In particular, the northern side of the river is affected. The implementation of adaptation strategies in scenario S3 mitigates these impacts. The results show a positive mitigating performance efficiency that can be reached using SUDS and exceeding flow control in urban areas.

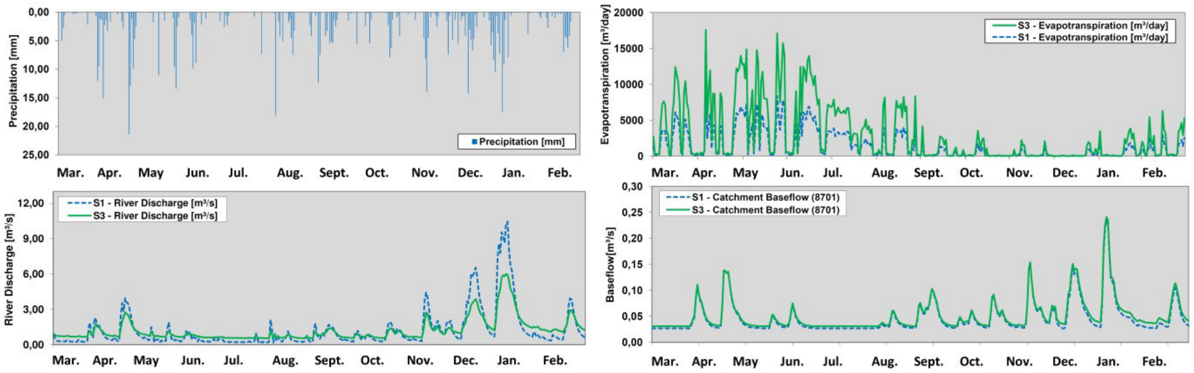

Fig. 6 Longterm water balance simulations for a subcatchment S1 (no measures) and S3 (including measures)

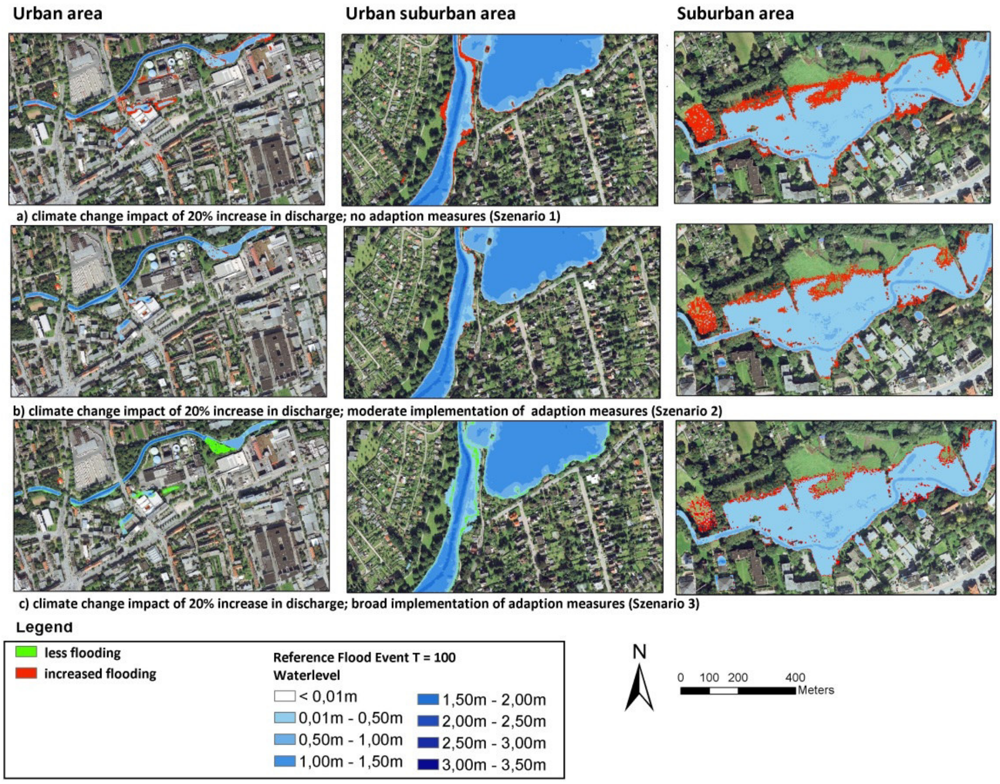

Fig. 7 Change in flow depth and inundated areas of a 100 year flood event on the basis of the three land use scenarios S1 (top), S2 (middle) and S3 (bottom) and a climate change impact of 20% increase in flood peak discharge. The results are illustrated for a highly urbanised (left), an urban-suburban (middle) and a suburban area (right)

2. Application study: Urban district in Elmshorn

The river Krückau is located in the region of Schleswig-Holstein and drains an area of around 275 Km². It rises in the North West of Hamburg and flows south for 37 Km before merging into the river Elbe. The city Elmshorn is located at the downstream section of the river, which is influenced by the tide. The river plays a crucial role on the drainage management of the city of Elmshorn, since approximately 95% of the precipitation which is neither infiltrated nor retained locally is discharged into it. During heavy rainfall events, high rainwater discharges might lead to high water levels in the river, especially at high tides. Within the framework of the KLIMZUG-Nord project, adaptation strategies to handle this problem were developed. The investigation embraced accordingly new approaches to manage rainwater on the one hand, and to create more space for the river on the other hand. In this work however, the focus is limited to the use of an open space for the retention of rainwater. As shown in Fig. 8 (aerial photo), the area selected for retention is an undeveloped space of about 6 ha enclosed by a drainage ditch. In Fig. 8, a concept to revaluate this area by turning it into a recreation space is schematically illustrated. Two playing fields with a size of approximately 0.5 ha each are created by lowering the ground by 0.5 m. They are hydraulically connected to each other and to the ditch system. Most of the time the two fields will be dry, while during heavy rainfall, the rainwater will flow into the first and subsequently into the second field, as shown in Fig. 8.

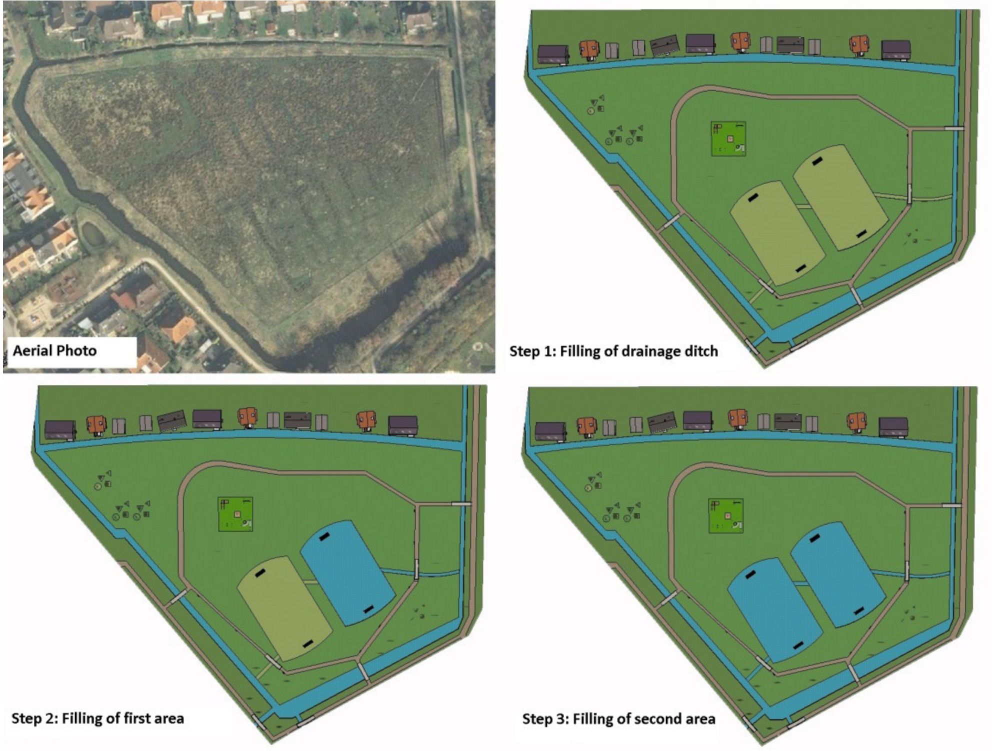

Fig. 8 Current aspect (aerial photo) and suggested improvement of the area with a concept for the management of rainwater in extreme events

To quantify the effect of this strategy, a hydrologic model was built including surrounding areas to finally represent a total size of about 180 ha. According to the topography, or eventually by creating some minor conveyance systems, the rainwater which is collected from the neighbour areas is conveyed toward the ditch system. When the water within the ditch reaches a certain level, a flow toward the first playing field starts. At this point, the availability of the second field for recreational purposes is still guaranteed.

The flow from the first to the second field starts only when the water level reaches 30 cm. Finally, when the water level in the second field reaches also 30 cm, the water flows further merging back into the ditch. Fig. 9 illustrates the result of a simulation carried for a hundred year event. The system shows the ability of absorbing completely the rainfall events previous and after day 7 and reduces the peak discharge by about 30%.

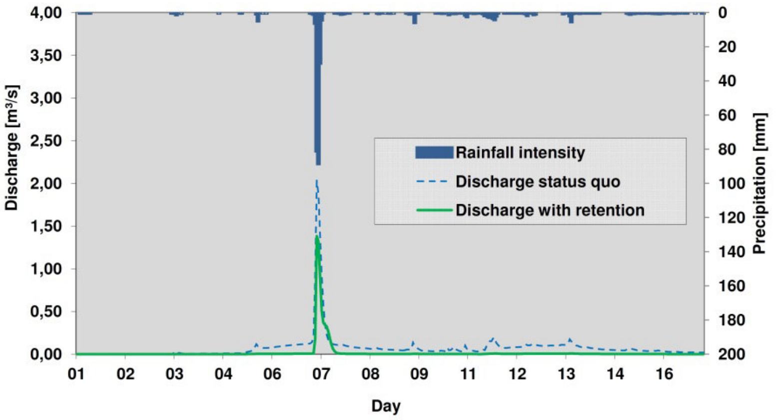

Fig. 9 Rainwater discharge versus precipitation during an extreme event with and without adaptation.

CONCLUSION

The novel hydrological modelling approach enables the detailed computation of a large number of spatially distributed SUDS in urban catchments and the redistribution of exceedance flow to larger-scale water retention areas. The enhanced module is part of the software product Kalypso for flood risk management planning. The application in the urban areas of Hamburg and Elmshorn offers a better understanding of the mitigation efficiency that can be reached using strategically placed, appropriate SUDS within an urban catchment. However, the uncertainties in nature and magnitude of climate change projections, urban growth scenarios as well as of impact modelling have to be investigated in a more detailed way to assess future flood risk in urban areas.

ACKNOWLEDGEMENT

The work described in this paper has been supported by a grant from the German Ministry for Education and Research (BMBF) as part of its KLIMZUG-Nord initiative.

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