MULTIPLE LINKED SUDS IN HYDROLOGICAL MODELLING FOR URBAN DRAINAGE AND FLOOD MANAGEMENT

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ABSTRACT

Assessing the performance of future urban drainage management practices requires novel hydrological modelling approaches that can handle a large number of spatially distributed measures, such as sustainable drainage systems (SUDS). SUDS are small-scale source-control structures that can drain surface water in a more natural way using infiltration, retention and storage devices in urban areas. Of particular concern is the control of exceedance flow in case of storm events that surpass the capacity of SUDS. A combination of SUDS measures and multipurpose spaces for water retention may provide an appropriate strategy to cope with the impacts of climate change and urban growth. 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 meso-scale retention spaces and the application of this model to an urban catchment. The objectives of the implemented model are the representation of SUDS as model elements with water re-distribution functionality as well as its possible integration into a flood risk mapping tool. We have applied the model to quantify the impacts of socio-economic and climate change in an urban catchment in Hamburg, Germany, under different future scenarios and combinations of SUDS. The results demonstrate the potential of SUDS and multipurpose retention spaces for flood mitigation.

KEYWORDS

Adaptation; climate change; urban growth; urban drainage management; urban flood modelling.

1. INTRODUCTION

The summer floods in 2002 and 2011 in Hamburg, Germany, together with the legislations of the EC Floods Directive (2007/60/EC) show the urgency to control and manage urban flooding. Considering the uncertainties of future land use development driven by rapid urbanization (UN, 2011) or climate change impacts (IPCC, 2012), urban drainage management should be handled within a dynamic framework. Strategies have to be able to perform in anticipation of increasing flood hazard and urban development. Further on, the EC Floods Directive (2007/60/EC) demands for, "sustainable land use practices, improvement of water retention as well as the controlled flooding of certain areas in the case of a flood event". To pursue these objectives, strategies are required which drain the water in a more natural way using infiltration, retention and storage devices in urban areas (Butler & Davies, 2011 and CIRIA, 2007). These measures are defined as Sustainable Urban Drainage Systems or SUstainable Drainage Systems (SUDS) in the UK (Butler & Davies, 2011) and can be described as small-scale source-control structures with a limited capacity. To enable the required control of exceedance flow in case of storm events that surpass the capacity of SUDS, a combination of SUDS measures and larger-scale retention areas (e.g. multipurpose spaces) may provide an appropriate strategy to cope with the impacts of climate change and urban growth.

This creates a research need for developing systems that convey surface overflow and strategies for integrating these into drainage management concepts (Woods-Ballard et al., 2007; Balmforth et al., 2006). It is the objective of this paper to describe the implementation of a new simulation tool enabling the detailed hydrological modelling of these drainage management strategies and to present modelling results of a case study. The following section describes the theoretical concept of the new model approach and its implementation based on the Kalypso simulation platform (http://sourceforge.net/projects/kalypso). By use of this model, we assessed the performance of small-scale SUDS measures and multipurpose spaces at the example of the Wandse catchment in the city of Hamburg, Germany. We further quantified the impacts of future land use and climate change scenarios on the peak discharge and inundated areas.
The enhanced model is part of the decision support tool Kalypso Planner Client for the process of flood risk management planning in the sense of the Floods Directive. The implementation of this tool is presented in the related paper Shaikh et al. (2013) and the process chain for the automated calculation of potential flood damages can be found in Kurzbach et al. (2013).

2. METHODOLOGY

2.1 Detailed Urban Development and Climate Change Modelling

In addition to the usual data required for a regular hydrological model set-up, i.e. watershed boundaries, land use, soil types, groundwater and the river network, the users may now define detailed maps of SUDS locations together with their type. The original land use coverage was based on land use classifications determining the fraction of impervious areas in each class. A sufficiently detailed land use map is now required matching the spatial detail of the SUDS distribution in the model area. The distribution of green roofs depends on the availability of building shapes, whereas the distribution of retention spaces and infiltration measures depends on the availability of free spaces. This demands for a modelling approach which can handle a large number of spatially distributed measures. For this purpose the numerical model KalypsoHydrology, a semi-distributed hydrological model for the simulation of the land-based water balances in river catchments and the river discharges (Pasche, 2003) has been enhanced with a tool to import overlays. Overlays are areas with additional information on soil profiles and drainage characteristics. It is possible to model groundwater recharge and vegetation in SUDS and larger-scale retention areas as overlays. In this way hydrological response units (hydrotops) are finally created by geometrically intersecting the land use, soil type, watershed and overlays. The areas with the same hydrologic characteristics are aggregated (see Figure 1).

![Figure 1: Spatial intersection and aggregation defines equal hydrological response units (hydrotops).](image)

Past and present-day greenhouse gas emissions will likely affect climate far into the future. Because of uncertainties in climate projections, meteorologists develop climate scenarios on the basis of different greenhouse gas emissions and other human factors. Based on these scenarios, numerical climate models simulate the climate in a reference period in the near past (e.g. the last 50 years) and continue simulation until 2100 (IPCC, 2012). Climate simulations enable long-term continuous simulations of climate impacts on the hydrological water balances in urban river catchments. Here, daily time steps are used as basis for the long term simulations of slow water balance processes like groundwater recharge, base flow and low water flow. For storm event simulations in urban catchments more temporally detailed data is required to model the fast flow processes (with a temporal resolution in the order of a few minutes). The model KalypsoHydrology enables both continuous long-term simulations and storm event simulations on the basis of continuous climate model data.

2.2 Semi-Distributed Hydrological SUDS Model

Based on previous work (Hellmers, 2010 and Pasche et al., 2009), the numerical core of KalypsoHydrology has been refined to enable the detailed simulation of the water balances and
drainage concentration in SUDS elements, such as green roofs and swale-filter-drain-systems. The interface of KalypsoHydrology has been extended so that the users can design SUDS measures of different types and constructions. These measures are subdivided into logical layers according to the attributes of their material and functionality, e.g. soil, storage and drainage characteristics. In Figure 2, the schematic designs of green roofs, swale-filter-drain-systems and swales are illustrated. For each layer, detailed continuous soil water balance calculations are done.

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

The enhanced methodology in the SUDS model 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. The drainage calculations are based on the mathematical approaches of Poleni, Darcy-Weisbach and Colebrook-White (Hellmers, 2010). The schematic diagram of a sample model net with SUDS is shown in Figure 3. When the design capacity of the elements on properties (e.g. green roofs, swales) is reached by a storm event (P) 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.

The model network used to describe the runoff concentration from upstream to downstream sections in a river system consists of sub-catchments, drainage strands and drainage nodes. With the new functionality to re-distribute water as exceedance flow among areas 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 hydrotops with the attributes of the imported overlays. During the computation these areas are transformed into additional small scale sub-catchments and an algorithm has been implemented in the model KalypsoHydrology to cross link these sub-catchments 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.
2.3 Integration in Urban Drainage and Flood Management

To assess the performance of multiple small-scale linked SUDS and larger-scale retention areas for flood mitigation the SUDS model was implemented as part of the decision support tool Kalypso Planner Client. This software tool connects hydrologic and hydrodynamic simulation models for use in flood risk management planning. The data processing in the Kalypso modelling framework is presented in Figure 4. Scenario simulations of future urban development projections can be derived from a calibrated basic model using overlay areas representing adaptation strategies like SUDS or retention areas. Before the computation, the original model network plan is updated with the overlay areas and their interconnections. Climate change projections are imported as continuous time series for long-term water balance and short-term flood peak simulations. Kalypso Planner Client computes steady-state non-uniform rivers hydraulics in the following step using a one-dimensional water surface profile model (KalypsoWSPM). Alternatively, unsteady and 1D-2D coupled surface flow can be simulated with the module Kalypso1D2D. In the post-processing phase, the inundated areas and flow depths can be computed based on digital terrain data using the module KalypsoFlood.
3. APPLICATION

The SUDS model has been applied to quantify the impacts of land use and climate change projections for 2050 in the Wandse catchment in Hamburg assuming adaptation strategies with small-scale SUDS measures and larger-scale retention areas (HCU, 2013). The river Wandse stretches over 21.5 km and drains a total catchment area of 88 km². The area upstream is mainly vegetated whereas downstream regions are more urbanised and have a higher fraction of impervious areas.

3.1 Climate Change Impacts

Based on two regional climate model (REMO) runs for the scenario A1B (Jacob et al., 2005 and 2009), we have simulated long-term water balance and flood peak events using a calibrated KalypsoHydrology model for a climate period from 2036 to 2065. The used climate data series comprise daily average temperature, sun duration, air humidity and wind speed data in a spatial resolution of 10 km. Of particular concern is the spatial and temporal distribution of precipitation for urban flood modelling. The regional climate model computes vertically falling precipitation for both A1B model runs. Additionally, this data has been post-processed with the information of wind drifted precipitation and the data has been bias-corrected. These three precipitation data sets span a range of six possible future projections. We evaluated the flood peak discharge results statistically to derive peak river discharges with defined return periods using the Log-Pearson III and Log-Normal III statistical distribution. The deviation between the results is illustrated in Figure 5. For events with return periods of 2 or 5 years, an increase of the peak river discharge of up to 27% and 20%, respectively, has been calculated. Three statistical results showed little to no climate change impact. For events with return periods of 10 or 30 years, there is no clear evidence of an increase in flood peak discharge. The largest variance has been found for events with return periods of up to 100 years. Here flood peak discharges are computed with up to 20% increase, but as well with 30% decrease. In order to assess the performance of SUDS under plausible climate change effects, we selected the following results as the basis for subsequent impact studies: (i) a high increase of flood peak discharge (+20%), (ii) a moderate increase of flood peak discharge (+10%) and (iii) no climate change impact.
3.2 Urban Growth and Adaptation Strategies

In the KLIMZUG-Nord project, socio-economic scenarios for 2050 have been defined (HCU, 2013). The first scenario (S1) assumes a decrease in population in the inner city, which means the people are moving into the suburbs. Because of less financial support, the buildings and infrastructure in the inner city remain more or less the same. 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 heavily subsidises the implementation of adaptation strategies like SUDS (green roofs, swales, swale-filter-drain systems) and larger water retention facilities in the city.

3.3 Results

The software module KalypsoHydrology has been applied to develop nine scenario models on the basis of three climate change impact assumptions (+20%, +10%, +/−0% change in flood peak discharge) and three urban growth assumptions (S1, S2, S3) including adaptation strategies for 2050. 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 in Figure 6 for the urban growth scenario S3. For a suburban area, an urban-suburban area and an urban area the results of the flood peak discharge simulations are depicted (Figure 6, right side).
In Suburban areas, in the upstream section of the river catchment, the impact by climate change cannot be compensated by the applied adaptation strategies, because only a minor spatial potential to implement SUDS is available. Further downstream, a larger tributary drains into the main river from urbanised areas where SUDS have been implemented. In the scenarios S2 and S3, a reduction of the flood peak discharge can be achieved (Figure 6, urban-suburban area). With the implemented adaptation measures in S3, the climate change impacts on the flood peak discharge can be compensated. The effectiveness is even higher in the downstream section of the river in the highly urbanised area (Figure 6, urban area).

Based on flood peak discharge results, the river hydraulics were computed with the one-dimensional water surface profile model KalypsoWSPM. And finally, the inundated areas and flow depth were calculated on the basis of digital terrain data with the module KalypsoFlood. The results of the inundated areas and water flow depths are illustrated in Figure 7 for the urbanised area, the urban-suburban area and the suburban area. For the climate change and urban growth scenarios, minor impacts on the inundated areas of a 100 year flood were calculated for the urban and urban-suburban area. The river topography with higher stream banks prevents flooding of the adjacent properties. In the upstream river section of the suburban area, the river topography is shallow. Here, the increased flood peak discharges by climate change impacts 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 mitigate these impacts, but cannot be compensated.
4. CONCLUSION

Of particular concern for flood management is the control of exceedance flow, when the storage capacity of small-scale SUDS measures is reached. The novel hydrological modelling approach enables the detailed computation of a large number of spatially distributed SUDS in urban catchments and the re-distribution of exceedance flow to larger-scale water retention areas. The enhanced model is part of the decision support tool Kalypso Planer Client, which is a framework to model the efficiency of drainage and flood management in urban catchments using a chain of numerical simulation models. The application in Hamburg 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 model simulations have to be investigated in a more detailed way to assess future flood risk in urban areas.

5. REFERENCES


