Quantification of climate change impacts on flood probability in urban areas and adaptation measures using climate model data with a high spatial resolution and a semi-distributed rainfall runoff modell

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Abstract:
The temporal and spatial resolution of climate data computed with the new generation of climate models opens new possibilities in the research of climate change impacts and their mitigation, including impacts on flood frequency and magnitude. In the presented study, climate model data and a semi-distributed hydrological model are used to develop a new concept, which is applied to assess the effectiveness of flood adaptation measures in urban areas. This research was performed within the joint project KLIMZUG-Nord for a case study within the metropolitan area of Hamburg.

Data of the regional climate model REMO *(*Jacob et al, 2006*)* were processed to quantify the impacts of climate change on flood probability using the conceptual, semi-distributed, deterministic, non-linear and detailed model Kalypso Hydrology. As this assessment implies a considerable level of uncertainty, adaptive measures for flood mitigation such as Sustainable Drainage Systems (SUDS) were considered to mitigate this uncertain future flood risk. The SUDS elements green roofs, swales and filter systems were modelled using the software Kalypso Hydrology in order to evaluate their effectiveness. The new developed tool enables a detailed and realistic simulation of the complex processes in SUDS-elements by dividing the measures in a sequence of layers built up with specific materials. The simulation displays a high level of physical soundness and level of detail and additional a spatial aggregation in the model is required to assess the effectiveness of SUDS for specific land use units in urban sub-catchments.

For the climate period 2041-2070 an increase of the frequency and magnitude of extreme events was calculated in the A1B-scenario. The consistency of the results of the hydrological processes in each SUDS-element was verified by analysing the water flow and the retention processes among all layers of the SUDS and therewith a detailed water balance calculation was possible.

In this research a new concept of linking regional climate model data with a semi-distributed rainfall runoff model is presented which was applied to quantify climate change impacts on the flood probability in urban areas. The hydrological model shows that a combination of SUDS elements (e.g. draining a green roof into a swale) leads to a higher potential for flood risk mitigation. Since the exceeding flow generated from one element is controlled by a subsequent one.

Introduction

Climate change impacts are already evident, which could affect as well a change in the magnitude and frequency of extreme rainfall, and in turn affect the flood risk in river catchments. The impacts due to flooding could be increased, where high sealing rate is present and the exposure to flooding is significant (WMO/GWP, 2008). Here, extreme rainfall events are the main drivers of pluvial flooding which could occur in combination with fluvial flooding from rivers, streams and drainage systems. For example in Hamburg, a thunderstorm in July 2002 caused serious flood problems with a total damage of more than 15 Million Euro (Pasche et al., 2008).

In research studies, a comprehensive methodology and a detailed data set to quantify the impacts of climate change on flood probability are required, especially for local scale and complex study areas such as small urban catchments (SUCAs). The IPCC-Scenarios (IPCC, 2000) serve as a basis for climate research studies and represent different worldwide economical and demographic development scenarios until 2100, whereas for the calculation of flood probability scenarios impact models are used.

To cope with the uncertain future impacts, traditional measures as enlarging storm water sewage pipes are not applicable (Pasche et al., 2008), but flexible and 'no-regret' solutions are required and in this context, sustainable drainage systems (SUDSs) have been identified as appropriate measures. In contrast to conventional drainage systems with the main purpose of draining rainfall as fast as possible to the nearest receiving watercourse, the main purpose of SUDSs is to reduce the surface runoff by retaining the rainfall water as close as possible to the source by infiltration techniques (e.g. filter drains, soakaways), source control measures (e.g. green roofs) and detention structures (e.g. ponds). Additionally, they can be combined in order to improve their efficiency, e.g. green roofs draining into swales with filter drains placed underneath.

In this paper, a theoretical approach for modelling SUDS elements and its implementation in a hydrological model is presented. The successful application of the tool was demonstrated for scenario studies in a river catchment, which is situated in the KLIMZUG-Nord project region.

Method

The methodology comprises the pre-processing of climate data series and their import into a hydrological model, which is outlined shortly. Strategies are defined for the processing of hydrological impact studies and the modelling of adaptation measures is described.

Pre-processing of data

For setting up the hydrological model a comprehensive data acquisition and pre-processing is necessary to assure qualitative results. For the simulations of climate scenarios, continuous data series (here: precipitation, temperature, evaporation) of the past and future have to be obtained. The available observed data series comprise data series from 1969 to 2004 of 5 rainfall gaging stations with a temporal resolution of 15 minutes and a spatial resolution of about 30 km². Computed data series with the regional climate model REMO *(*Jacob et al, 2006): first REMO model run*)* were post-processed on a regular geographical grid by the Service Group Adaptation (SGA) and comprise daily as well as hourly data series from 1961 to 2100 for the IPCC climate scenarios A1B, B1 and A2 with a temporal resolution on a grid of 11 km x 6,5 km.

Hydrological model structure

The applied model Kalypso Hydrology is part of the Open Source modelling suite Kalypso which comprises modules in the field of water management and hydraulic engineering. The core engine of Kalypso Hydrology is based on the computation concepts from the Institute of River and Coastal Engineering (www.tu-harburg.de/wb). It allows the simulation of the entire land-based part of the water balance on the basis of given precipitation, temperature as well as evaporation time series, and may be characterised as a conceptual, deterministic, non-linear, (semi-) distributed hydrological model (BWK, 2001). The user interface is illustrated in Fig 1.

Processing of hydrological impact studies

Computed climate data series describe the statistical sums and averages of weather phenomena (IPCC AR4, 2007), therefore different strategies have to be defined to quantify the overall changes of climate variables (precipitation, temperature and evaporation) and flood probabilities in climate periods (>30 years). In this study, average changes (e.g. yearly, seasonal, monthly) and the number of occurrence of values above thresholds were analysed additional to statistical analysis. A differentiation of seasons was done according to DIN 4049 for hydrological years: winter season from November to April; 01.11 – 30.04 and summer seasons from May to September; 01.05 – 31.10.

With the assumption of a systematic bias in climate model simulations (e.g. Frei et al., 2003), a correlation between the computed control scenario and the computed future scenarios can be defined. In this study two approaches were applied for calculating the magnitude of the projected climate change impacts of extreme rainfall and flood peaks: on the one hand the percentage change of extreme rainfall [mm/d] or flood peak [m³/s] and on the other hand the absolute value of change per return period and under climate change conditions was calculated. In both approaches the magnitude of change was referred to observed data series of the past to obtain the magnitude of a projected extreme event under climate change conditions (Hellmers, 2010).

Modelling adaptation measures

The theoretical approach for modelling SUDSs is based on the principle of hydrological response units (hydrotops), which are elements in sub-catchments representing the hydrological attributes of retention and horizontal as well as vertical water flow processes. For this purpose, SUDSs are divided into layers to simulate the specific infiltration, percolation, evaporation and storage processes for each layer.

A new software tool was developed to simulate SUDSs and was implemented in the core-engine of the semi-distributed rainfall runoff module Kalypso Hydrology. Green roof elements are subdivided into three main layers: the storage layer, the substrate layer and the filter layer (Fig. 2). The storage layer is indicated as the first layer in the theoretical approach, where vegetation can be planted. To prevent the overloading of the green roof, an overflow pipe is installed with the height (h_{ov}) and above the edge of the overflow pipe a freeboard is provided. The second layer is defined as a substrate layer with top soil. On the plane roof, a filter layer is constructed to drain the water to the down pipe and below this layer, a root protection and insulation fabric is placed to prevent leakage through the roof.

The change of the soil water content (Δsw) per time step (Δt) in the layers is calculated with the continuity equation (eq.1), which is applied for each layer with respective parameters.

$$\frac{\Delta sw(t)[l/m^2]}{\Delta t} = \frac{Inf(t)[l/m^2]\text{-}perk(t)[l/m^2]\text{-}ET_{a/p}(t)[l/m^2]}{\Delta t} - \frac{Q_{outflow}(t)}{A_{green\ roof}}\left[\frac{1}{m^2 * \Delta t}\right] \qquad \text{eq.1}$$

The potential inflow (Inf) into the layers is defined as the effective precipitation in the storage layer (L1) and as potential infiltration in the substrate (L2) and the filter layer (L3). The percolation (perk(3)) from the filter layer has to be set to zero with respect to the insulation layer on the roof. In the storage layer (L1) the potential evaporation ($E_p(1)$) from the stored water and in the soil layers, the actual evapo-transpiration ($ET_a(2)$) and ($ET_a(3)$) with respect to the vegetation are calculated respectively. Additionally, an outflow through the overflow pipe ($Q_{overflow}$) in the storage layer (L1) and the outflow through the rainfall down pipe in the filter layers ($Q_{Down\ pipe}$) reduces the retained water on the green roof.

The overflow from the storage layer is computed with two approaches. On the one hand the inflow into the pipe is calculated with the Poleni equation with the water level above the pipe (h_{ex}[mm]), the perimeter of the pipe (d_{pipe}[mm]) and the coefficient (μ = 0.480) according to the technical bulletin BWK (1999). On the other hand the flow is limited by the maximum capacity of the pipe which is calculated according to the Colebrook-White approach with the flow resistance (λ) (eq.2).

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

The drainage through the down pipe begins when free movable water is accumulated in the filter layer, which exceeds the field capacity of the soil layer. The effective flow through the down pipe is the minimal discharge calculated according to the Poleni equation by taking into account the soil porosity and the maximum capacity of the down pipe (cf. eq.2). For the Poleni equation in the drainage layer a coefficient of μ=0.577 is defined for overflow heights of zero according to BWK (1999).

A swale-filter-drain system is divided into four layers: the storage layer (L1), the colmation layer (L2), the filter layer (L3) and the base layer (L4) (cf. Fig. 3). The balance of the soil water content (sw) in the layers is based on a continuity equation as displayed for the green roof element, but the inflow (P_{inflow}) could include additionally the discharge from drained sealed areas and it is possible to drain the outflow from green roofs into swale elements.

For studying the hydrological effectiveness of the reduction of flood risk by SUDSs in the overall catchments, SUDS-elements of each type are aggregated and assigned to defined land use type areas in the sub-catchment in the data model, which are subsequently intersected with hydrogeological units. After the intersection, hydrotope areas with the attributes of SUDSs are created.

Application

The developed methodology and the implemented new software tool for simulating SUDSs were applied for climate change and adaptation scenarios in the Krückau catchment, which is located in the north-west of the Metropolitan Region of Hamburg. After a length of about 37 km, the river Krückau flows into the river Elbe and the modelled Krückau catchment area has a size of about 185 km². In the mainly rural Krückau catchment, the largest urban area is Elmshorn, which is located at the downstream section with sealing rates between 0.25% and 1.0% (Fig. 4).

Study Results

Changes in climate derived in the IPCC-scenarios for the Krückau catchment area were analysed with three approaches defined in the methodology. The average change in temperature, precipitation and evaporation were calculated and summarised in tables. For the studies of extreme rainfall events two approaches were used: first the number of occurrence of wet days (>25mm/d) for hydrological seasons were compared and thereafter short term extreme rainfall intensities (in [mm/h]) were analysed in more detail with statistical evaluations. An overview of all considered scenario study results and time periods in this paper are summarised in table 1.

The calculated climate changes are summarised in table 2, where a minimal average yearly temperature increase of 1.1°C and a maximal increase of 1.5°C were computed for the future time period 2041 to 2070 related to the control scenario (1971 to 2000). For winter periods a higher temperature increase of up to 1.9°C was calculated. The calculated max. changes in evaporation are less in summer periods (+5,6%) than in winter periods (+9,7%). The max. change in the sum of the precipitation in winter periods is calculated to be up to 18,5% in the A1B scenario, whereas for summer periods an increase of just 3,6% has been calculated. In contrast to the average precipitation changes in seasons the sum of days with a precipitation of more than 25mm/day (wet days) especially increases in summer periods. With these results it can be assumed that the winter gets warmer and wetter, but more extremes could occur in summers.

An increase of extreme summer rainfall events was calculated as well with statistical probability distribution curves. For summer rainfall events with high probabilities of occurrence, here: with return periods of once in a year (T=1a), a significant increase was calculated in the scenario A1B from 9,4mm/h to 15,4mm/h (+63.5%) in rainfall intensity (Table 3) and for lower probabilities of occurrence (T = 100a) an increase of the summer rainfall intensity from 24,6mm/h to 28,3mm/h (+15.2%) for the A1B scenario was computed. The calculated increase of hourly rainfall intensities for winter periods in the A1B scenario ranges between 7.8% for events with T=1a and 5.9% for events with T=100a (cf. table 3).

Flood hydrographs were simulated for specific river segments for each scenario of the climate change impact studies and seasonal differentiation. For this purpose fifteen statistical evaluations were worked out with the results of overall 750 short term flood peak simulations after respective long term simulations. The results of the climate scenario studies at the outlet node of the Krückau catchment are displayed in table 4 using the Log-Pearson III distribution and the percentage change approach.

The largest changes on the flood discharges were calculated for summer periods for the scenario A1B. For events with high probabilities of occurrence (T = 1a) an increase of the discharge peak from 6,0 m^3/s to 12,3 m^3/s and for 100-year-flood events an increase from 14,1 m^3/s to 19,2 m^3/s was calculated. Minor changes were calculated for the scenarios B1 and A2. The derived changes for flood events in winter periods are in all scenarios less then 1 m^3/s.

In comparison with the increase of the rainfall intensities, it can be stated that in the A1B scenario the summer flood peaks increase with a higher rate than the hourly summer rainfall intensities. Hence, the overall tendency of increase corresponds between the extreme rainfall and flood events, but the rate and magnitude of increase differs in the A1B scenario, which displayed the largest changes and is regarded as most important for the following discussion of the effectiveness of adaptation measures.

Testing and simulation results of adaptation measures

The new developed tool for simulating SUDS was tested with two approaches. On the one hand, the overall water balance comprising the inflow and the outflow components as well as the change of retained water in the SUDS elements was calculated. Secondly, the temporal dependency of the soil moisture formation in relation to the flow processes was analysed.

For the simulations an extensive green roof was modelled with a filter layer of 5cm, a substrate layer of 8 cm, an overflow height of 3.5cm and a free board of 10cm. For the filter layer an inorganic material with a pore volume of 30%, a coefficient of permeability of $2x10^{-5}$m/s and a field capacity of 25.5% was chosen. The material used for the substrate layer is made up of inorganic and organic matter which provide nutrients for the plants and also a appropriate storage capacity. Therefore a material with a maximal pore volume of 37.5%, a field capacity of 20% and a permeability coefficient lower than $4x10^{-6}$m/s was used to retain the water in the storage layer.

The simulation results of the design rainfall event show that the water level in the storage layer on the green roof reaches a maximum of 2.1cm (cf. Fig.5). The water stored on the green roof percolates into the substrate layer and when the soil moisture in the substrate layer reaches the field capacity (12 l/m^2), water percolates into the filter layer, but only as long as the soil moisture in the substrate layer is above the field capacity. The maximum soil moisture in the substrate layer reaches 20.8 l/m^2. When the soil moisture in the filter layer reaches the field capacity, free movable water is generated, which fills up the layer from the bottom and forms a water level. The maximum water level in the filter layer is 50mm which means that the filter layer is completely saturated. The free movable water volume drains into the down pipe of the green roof, where a maximum flow of $0.0491m^3/s$ is simulated.

The effectiveness of SUDSs to reduce the probability of floods in urban areas was simulated with single and combined measures in the urban areas of the Krückau catchment (cf. table 1). In this paper only the results at the downstream node of the city Elmshorn are presented. For floods with a return period of once in 50 years, the largest reduction of the peak discharge by separated SUDS measures is achieved by the assumption of turning 20% of sealed areas into green roofs followed by swales and unsealing (see Fig.6). A flood peak of 14,7m³/s under climate change conditions (0-A1B) is projected with a return period of once in 5 years. In the SUDS adaptation scenario with implemented green roofs, this flood peak is computed to occur only once in 50 years. With the combination of SUDS, the flood peak probability is even reduced below the status quo scenario 0. For example a flood peak with 11m³/s is calculated in the status quo scenario (0) to occur once in about 20 years, but it is projected to occur only once in 50 years in the SUDS combination scenario under climate change conditions (0-A1B) (cf. Fig. 6).

The SUDS combination scenario approximates the projected (climate change) natural state scenario as illustrated in the bar plot (Fig.6). The effectiveness of swales decreases with larger rainfall intensities, which points out, that the SUDS measures loose there effectiveness when the storage capacity is reached and an overflow of the systems is generated. This is less significant with the combined SUDS chain, where for example the overflow from green roofs drains into swales first and therewith the exceeding flow is reduced.

Conclusion and outlook

It has been illustrated in this study, that the spatial resolution of about 11 km x 6.5 km provided by the climate model REMO in the data stream D3 interpolated on a regular grid, is appropriate for the scenario studies in the Krückau catchment. But the applicability can not be generalised for other study areas. In mountainous or dense urban catchments a finer spatial resolution could be required and should be further analysed.

The restricted temporal resolution of data series provided by climate models was analysed in comparative studies (Hellmers, 2010). The results of discharge hydrographs with hourly and 15-minute simulation time steps were compared for a rural sub-catchment, an urban sub-catchment and a discharge node. The differences between these simulations are significant for the urban sub-catchments and therefore smaller time steps than hourly data series are required of climate model data series for flood probability simulations in SUCAs.

In the scenario studies it was found out that an overall corresponding tendency of changes in rainfall and flood events can be defined and that the increase of floods and extreme rainfall events in summer periods is higher than in winter periods.

The SUDS simulation results display acceptable differences in the water balance calculations of 0.1% to 0.01%. The developed approach enables a detailed simulation of complex hydrological vertical (e.g. infiltration, percolation, evaporation), horizontal as well as the storage processes of water in each layer of the SUDS element, where at the same time the effectiveness of SUDSs for the entire sub-catchment can be simulated in a comprehensive way. The effectiveness of SUDSs as flood probability reduction measures was successfully simulated with the new developed software tool. Especially the combination of SUDS with green roofs draining into swales plus unsealing plans displayed a large effectiveness, and therewith exceeding flow of SUDS measures due to the restricted storage capacity and the generation of overflow can be reduced in extreme events.

The presented methods and the software tool will be further developed within the KLIMZUG-Nord project and will be applied for the Wandse catchment area which is situated in the city of Hamburg. Additional perspectives for this study are the analysis of different REMO model runs, the calculation as well as application of bias-corrected climate model data series and the simulation of urban development scenarios, followed by the simulation of adaptation measures.

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About the authors

Prof.-Dr.-Ing Erik Pasche received his doctorate with a dissertation about the topic: „Turbulenzmechanismen in naturnahen Fließgewässern und ihre mathematische Modellierung“ with summa cum laude in 1984. Thereafter, he has been fellow partner as well as scientific consultant in the company Björnsen Consulting Engineers in Koblenz. Since 1998 he was the head of the Institute of River and Coastal Engineering (www.tu-harburg.de/wb) at the Technical University Hamburg Harburg till his sudden death in December 2010. In his fields of research: coastal protection, flood risk management and climate change impacts he received European wide recognition.

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Figures and Tables

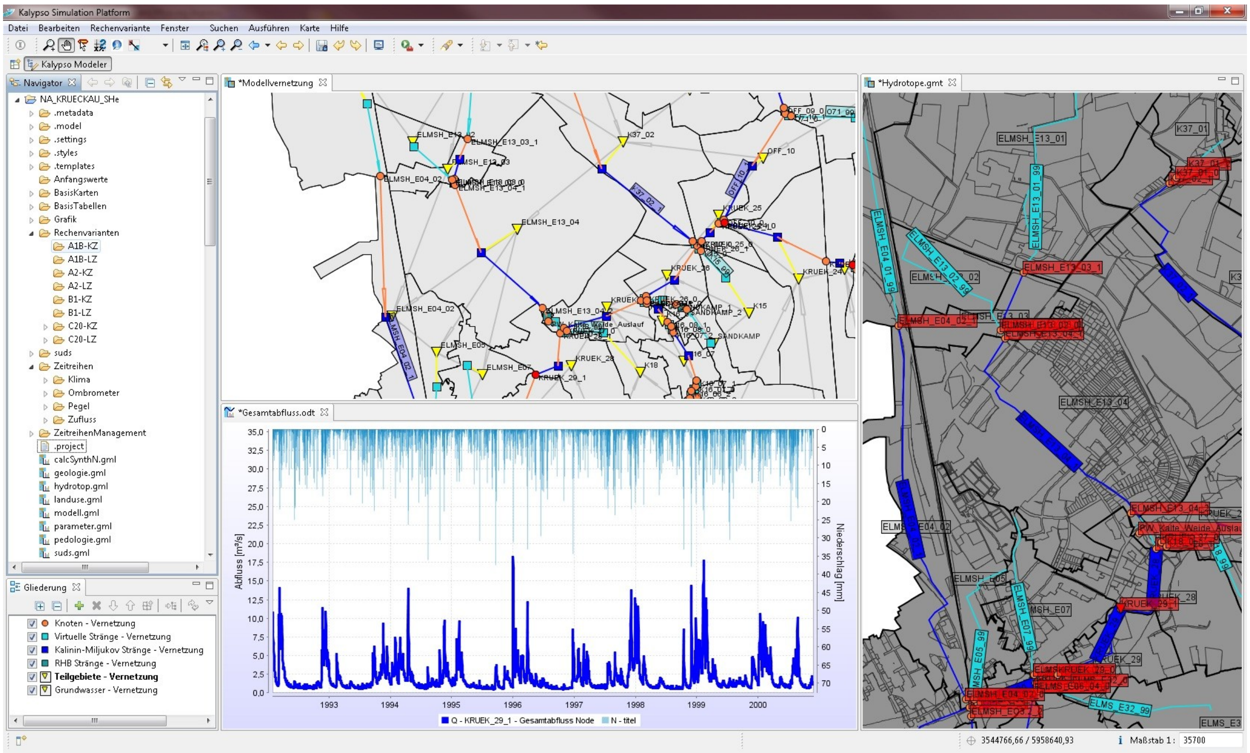


Fig. 1. User Interface Kalypso Hydrology (study: Krückau catchment)

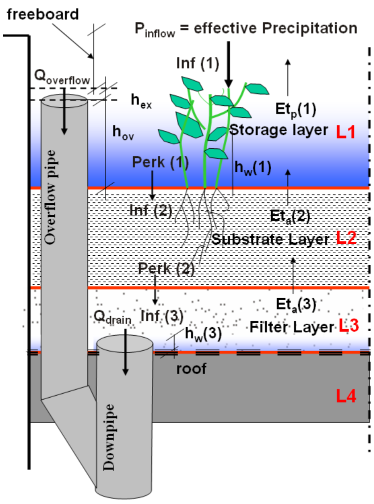


Fig. 3 Concept of the layer theory for green roofs

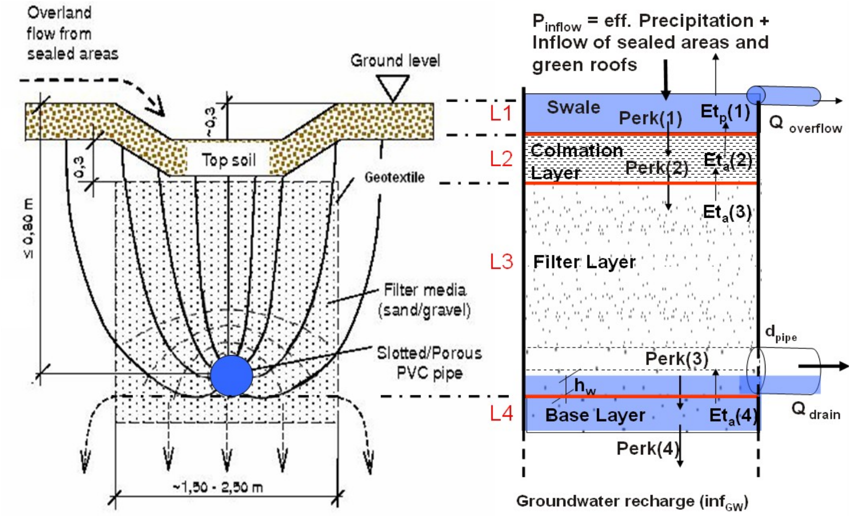


Fig. 2 Concept of the layer theory for swale-filter-drain systems

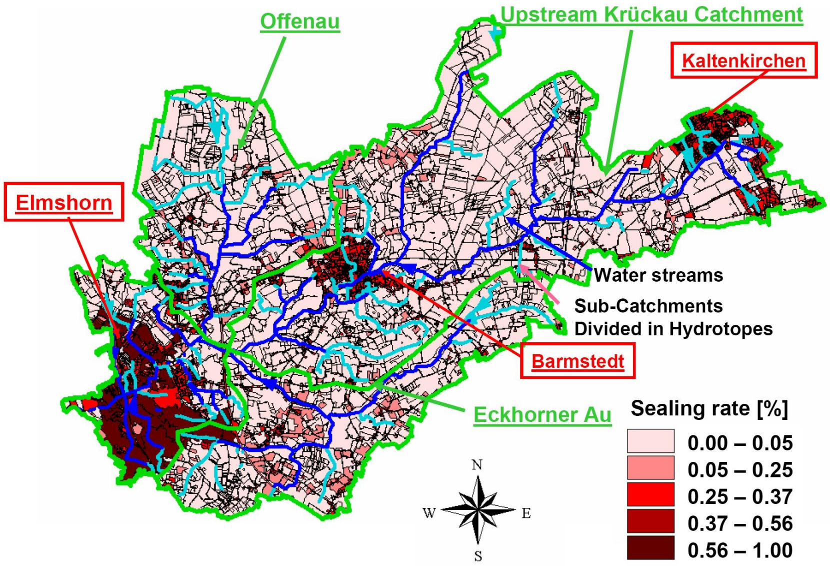


Fig. 4 Krückau catchment area with delineation of tributeries, urban areas (with sealing rates), water streams, sub-catchments and hydrotopes

Table.1 Overview of all scenario study results and covered time periods.

Scenario study results	**Climate period**	**Definitions and description**
Climate Change Impact Studies		
Status Quo (0)	[1971 – 2000]	Observed climate data series used for flood discharge simulations.
Scenario C20	[1971 – 2000]	Computed data series of the REMO model used for climate change studies and for the simulation of flood discharges with the hydrological model.
Scenario A1B	[2041 – 2070]	
Scenario B1	[2041 – 2070]	
Scenario A2	[2041 – 2070]	

Additional results and reference scenarios for flood probability studies		
Scenario 0-A1B,B1,A2	[2041 – 2070]	Referred statistical scenario results with the percentage change approach.
Natural State Scenario	[2041 – 2070]	Referred flood statistic scenario 0-A1B results with a land use of the whole catchment of 30%forests and 70% meadows.
Study of adaptation measures on the basis of the 0-A1B-scenario results		
Green roofs	[2041 – 2070]	Assumption of changing 20% of the sealed surfaces in the urban area into green roofs.
Swales	[2041 – 2070]	Assumption of changing 30% of the sealed surfaces in the urban area into swales.
unsealing	[2041 – 2070]	An unsealing with porous pavement has been assumed for 30% of the sealed areas (parking places, blind arrays, streets in residential areas).
Combination	[2041 – 2070]	Combination of measures: green roofs (20%) draining into swales (30%) and an unsealing of pavements (30%).

Table.2 Changes per hydrological season for all scenario study results and covered time periods.

		Temperature	Evaporation	Precipitation		
Seasonal Sequences	IPCC scenario	Average Percentage change [2041 to 2070]	Average Percentage change [2041 to 2070]	Average Percentage change [2041 to 2070]	Number of wet days [2041 to 2070]	
Changes in Summer Periods	B1	+ ~ 1,0 °C	+ ~ 3,6 %	+ ~ 2,9 %	C20: 41 days	+ ~ 2
	A1B	+ ~ 1,5 °C	+ ~ 4,0 %	+ ~ 3,6 %		+ ~ 25
	A2	+ ~ 1,2 °C	+ ~ 5,6 %	+ ~ 2,2 %		+ ~ 5
Changes in Winter Periods	B1	+ ~ 1,2 °C	+ ~ 4,8 %	+ ~ 12,7 %	C20: 24 days	+ ~ 2
	A1B	+ ~ 1,6 °C	+ ~ 9,7 %	+ ~ 18,5 %		+ ~ 6
	A2	+ ~ 1,9 °C	+ ~ 9,6 %	+ ~ 14,8 %		+ ~ -4
Changes in Yearly Periods	B1	+ ~ 1,1 °C	+ ~ 2,4 %	+ ~ 3,5 %	C20: 65 days	+ ~ 4
	A1B	+ ~ 1,5 °C	+ ~ 4,0 %	+ ~ 7,3 %		+ ~ 31
	A2	+ ~ 1,4 °C	+ ~ 5,2 %	+ ~ 0,8 %		+ ~ 1

Table 3 Hourly rainfall intensities [mm/h] for climate scenarios referred to the status quo scenario (0)

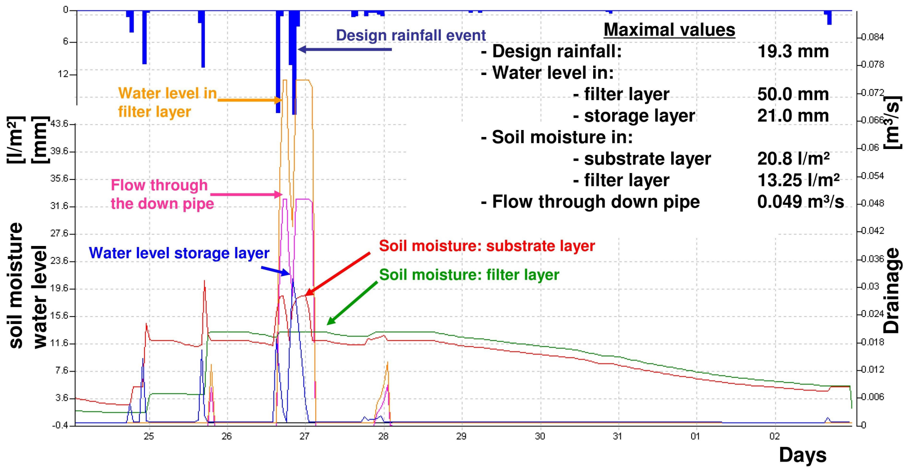
Scenario study	Return Period T [a]									
	1	2	3	5	10	20	30	50	100	a
Hourly summer rainfall intensities [mm/h] per return period T										
Status Quo (0)	9,4	11,7	13,0	14,7	17,0	19,3	20,6	22,3	24,6	mm/h
Scenario 0-A1B	15,4	16,9	17,9	19,3	21,3	23,4	24,6	26,2	28,3	mm/h
Scenario 0-B1	12,0	13,8	15,0	16,5	18,5	20,6	21,9	23,5	25,6	mm/h
Scenario 0-A2	12,2	13,4	14,3	15,5	17,2	18,9	20,0	21,3	23,0	mm/h
Hourly winter rainfall intensities [mm/h] per return period T										
Status Quo (0)	5,3	6,1	6,6	7,2	8,0	8,8	9,3	9,9	10,8	mm/h
Scenario 0-A1B	5,7	6,6	7,1	7,7	8,5	9,4	9,9	10,5	11,4	mm/h
Scenario 0-B1	5,7	6,4	6,9	7,4	8,2	8,9	9,3	9,9	10,7	mm/h
Scenario 0-A2	5,6	6,1	6,5	6,9	7,5	8,1	8,5	8,9	9,6	mm/h
Hourly rainfall intensities [mm/h] per return period T (statistical results both seasons)										
Status Quo (0)	9,4	11,6	12,9	14,6	16,8	19,1	20,4	22,0	24,2	mm/h
Scenario 0-A1B	14,1	15,6	16,7	18,0	19,9	21,8	23,0	24,4	26,4	mm/h
Scenario 0-B1	10,4	12,3	13,5	15,0	17,0	19,1	20,3	21,8	23,8	mm/h

Scenario 0-A2	10,1	11,7	12,7	13,9	15,7	17,4	18,5	19,8	21,6	mm/h

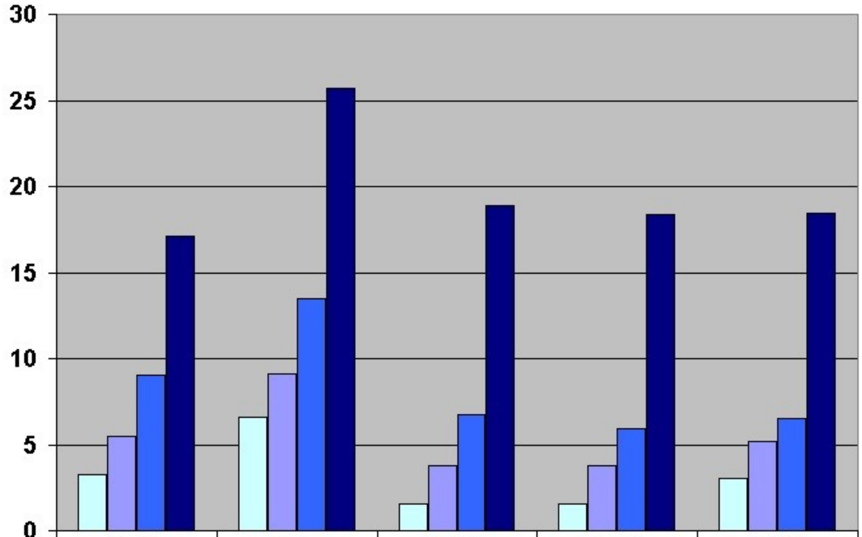
Table 4 Results of flood discharge statistics in [m³/s] at the outlet node of the Krückau catchment for climate scenarios referred to the status quo scenario (0)

Scenario study	Return Period T [a]									
	1	2	3	5	10	20	30	50	100	a
Summer flood discharges [m³/s] per return period T										
Status Quo (0)	6,0	7,4	8,1	9,0	10,1	11,3	11,9	12,7	14,1	m³/s
Scenario 0-A1B	12,3	13,3	13,9	14,7	15,7	16,6	17,2	17,9	19,2	m³/s
Scenario 0-B1	9,6	11,2	11,9	12,8	14,0	15,0	15,6	16,4	17,5	m³/s
Scenario 0-A2	8,3	9,1	9,6	10,3	11,1	11,9	12,4	13,0	14,0	m³/s
Winter flood discharges [m³/s] per return period T										
Status Quo (0)	9,0	10,9	11,9	13,2	14,9	16,7	17,7	19,1	21,6	m³/s
Scenario 0-A1B	10,1	12,0	13,0	14,2	15,8	17,5	18,5	19,7	22	m³/s
Scenario 0-B1	9,3	10,9	11,8	12,9	14,3	15,7	16,5	17,6	19,6	m³/s
Scenario 0-A2	9,0	10,8	11,9	13,2	14,9	16,7	17,8	19,2	21,8	m³/s
Flood discharges [m³/s] per return period T(statistical results both seasons)										
Status Quo (0)	9,3	11,0	11,9	13,1	14,7	16,4	17,4	19,2	20,9	m³/s
Scenario 0-A1B	12,0	13,8	14,8	16,0	17,7	19,5	20,5	22,4	24,0	m³/s
Scenario 0-B1	10,7	12,3	13,2	14,3	15,8	17,3	18,2	19,7	21,3	m³/s
Scenario 0-A2	10,0	11,5	12,4	13,5	15,1	16,6	17,5	19,1	20,7	m³/s

Fig **5**. *Water storage and flow processes in the green roof elements ['+'=inflow/'-'=outflow]*



Water balance	Water vol.
rainfall	+88,1 [l/m²]
evaporation	-18,7 [l/m²]
evapotranspiration	-18,7 [l/m²]
Drainage (down pipe)	-40,7 [l/m²]
Drainage (overflow)	- 0,0 [l/m²]
Change in soil moisture	-9,9 [l/m²]
Deviation in water balance	Δ=0,1 [l/m²]



	T=1a	T=5a	T=20a	T=50a	T=100a
Decreasing Sealing Rate [%]	3,2	6,6	1,6	1,6	3,0
Green Roofs [%]	5,5	9,1	3,8	3,8	5,2
Swales [%]	9,1	13,5	6,8	5,9	6,5
Combinations [%]	17,1	25,7	18,9	18,4	18,5

Fig. **6** *:Simulation results of flood discharges with adaptation measures.*