🏆 *reviewed paper*

The Current Use and Limitations of Water Related Digital Twins – a Practical View on Urban Climate Change Adaptation

Markus Groth, Steffen Bender, Thea Wübbelmann

(Dr. Markus Groth, Climate Service Center Germany (GERICS) – Helmholtz-Zentrum Hereon, Markus.Groth@hereon.de)
(Apl.-Prof. Dr. Steffen Bender, Climate Service Center Germany (GERICS) – Helmholtz-Zentrum Hereon)
(Thea Wübbelmann)

DOI: 10.48494/REALCORP2024.9023

1 ABSTRACT

Currently urban areas have to face many challenges. Overall, urbanization, demographic change, digitalization and climate change are main drivers that may directly or indirectly have an impact on the lifestyle and well-being of city dwellers. All drivers are interconnected and together with other sector-relevant drivers they form a complex network, that is often difficult to understand at first glance, and has many points of friction between different interests. For example, a growing urban population needs more space for housing areas which increases sealed surfaces and reduces natural groundwater recharge. Due to climate change, temperatures are rising (especially over sealed surfaces), also leading to an increasing water demand and rising evaporation rates. Both factors, besides others, influence the natural water cycle. In addition, in many places summer becomes drier, while more precipitation falls in winter times. The number and intensity of heavy rainfall events increases and dry periods are becoming longer. On the supply side, higher demand peaks in summer already pose greater challenges to water suppliers. Heavy rainfall can for example flood facility sites, parts of the critical infrastructure or cause power outages, which can lead to systemic interuptions.

In recent years, also a trend towards “smart cities” can be seen to improve the the quality of life for residents. The idea of the progressing digitalization is to transfer parts of the real word into virtual representatives. Some are referred to as digital twins. However, these digital twins differ in their technical structure, complexity, and target for which they were developed. For years, many city administrations partly already use hydrological or urban climatological models as one form of simplified digital twins.

Against this background, the paper presents and discusses the practical use, main results and lessons learned from case studies using two different hydrological models as digital twins in two German cities. Overall, the experiences from these case studies show that also the use of simplified digital models of a city – or parts of a city – without the need for big-data and monitoring information can be good planning tools to assess plausible results regarding possible future impacts based on climate change on a small scale. However, hydrological models currently are focussing on one or two challenges, only. But, due to the complexity of natural systems with a high number of connected processes, the whole story with interacting multiple drivers is not included totally. Depending on the modelling approach used, it is therefore possible to obtain different results with different models. Therefore, a better combination of several of such digital twins or the development of more powerful tools will be necessary, for example to transform an urban area towards being climate resilient and sustainable.

Keywords: digital twins, complex systems, climate change adaptation, model evaluation, city planning

2 INTRODUCTION

The importance of climate change and its impacts on municipalities (and urban areas) is still increasing (IPCC 2023; Jacob et al. 2021; Kahlenborn et al. 2021). For instance, precipitation patterns are changing across many regions in Germany, with increased winter rainfall and drier summers (Deutschländer and Mächel 2017). Climate change also rises the number and intensity of heavy rainfall events, which have already been observed in certain areas (Papalexiou and Montanari 2019; Fischer and Knutti 2016; Westra et al. 2014). In 2018, a year marked by prolonged periods of very low precipitation and high evaporation rates due to high temperatures, there was a notable increase in such events (Jacob et al. 2021). This trend is in line with the expected effect of rising atmospheric water vapor uptake on convective precipitation causing more intense heavy rainfall events in the future (Giorgi et al. 2019; Giorgi et al. 2011).

Climate change also has far-reaching economic consequences, with damage costs being one of the most significant impacts. In Germany, river floods, urban floods, and flash floods have been the most expensive extreme weather events to date. They have caused significant damage to buildings, critical infrastructures, and industries, including flooded production sites and disrupted supply chains. The total cost of damages incurred since 2000 is estimated to be more than 70 billion euros in Germany (Trenczek et al. 2022).

Considering the expected impacts and challenges of climate change, it is evident that there is a pressing need to prioritize climate mitigation, adaptation, and sustainability at all levels, especially with a stronger focus on regions and urban areas. This transformation is necessary to achieve a resource-efficient, sustainable, climate-neutral, and climate-adapted society (Jacob et al. 2021). For urban areas, in particular, spatial and urban planning can provide numerous opportunities to implement integrative approaches (Groth et al. 2023; Bender et al. 2022; Groth et al. 2021), which considers social, economic, and environmental aspects holistically to build sustainable and livable urban environments.

In recent years, also a trend towards “smart cities” can be seen as the velocity of data collection has increased. One goal here is the intelligent connection of municipal infrastructure to make city administrations more efficient in improving the quality of life for residents. The idea of the progressing digitalization is to transfer parts of the real word into virtual representatives. Some are referred to as digital twins. Digital twins have been found useful in manufacturing, construction, and maintenance. In contrast, a holistic digital twin of a city would have to cover many fields of action, including all associated technical and human interfaces. For this, extensive data collections and a better systemic understanding of linkages and feedback loops are necessary in advance. As a result, the final product would provide city administrations with a powerful tool. Positive first approaches of such digital twins can for example be found for the cities of Helsinki, Zurich and Vienna (Bender et al. 2023b).

To react proactively to future extreme weather events, many city administrations currently use hydrological or urban climatological models. By simulating different weather scenarios, decision makers get an idea which potential impacts can occur and which adaptation measures promise the greatest overall success. For this, regional climate projections provide a possible view, what and how many weather-related challenges can be expected in the future. Examples of this are the GERICS climate outlook for German administrative districts.[1]

To support municipalities in responding to urban floods resulting from heavy rainfall, the Climate Service Center Germany (GERICS) has conducted case studies in collaboration with stakeholders as part of the “GERICS Adaptation toolkit for cities” (Bender et al. 2017). One main objective of this approach is to demonstrate that also the use of simplified digital models based on a low number of information can serve as an effective planning tool for evaluating potential impacts of climate change for the entire municipality or specific sub-areas, highlighting present and future hot-spots on a local scale. This, in turn, can support the development of adaptation measures that can be planned, justified, and implemented within the context of urban development.

Against this background, the paper presents and discusses the practical use, main results and lessons learned from case studies using two different hydrological models as digital twins in two German cities. The freely available model “River Analysis System” (HEC-RAS), was used to simulate the heavy rainfall runoff behavior in the city of Geesthacht. The software platform “Tygron Engine” by the TAUW GmbH and “HEC-RAS” were applied for a specific hot-spot area in the city of Rostock.

The paper starts with a short overview of the current state of research on heavy rainfall-runoff modeling in chapter 3. The two following chapters describe case studies in the city of Geesthacht (chapter 4) and in the city of Rostock (chapter 5), whereby the Rostock case-study also includes a comparison of two different modeling approaches. Finally, in chapter 6, key findings are summarized and practical recommendations for action as well as further need for research are discussed.

3 THE CURRENT STATE OF RAINFALL-RUNOFF MODELLING

The expanding array and use of hydrological models reflect the diverse range of user requirements in terms of data prerequisites and practical usability. Broadly, these models diverge in their complexity, the extent of encompassed hydrological processes, computer performance, as well as spatial and temporal resolution of input and output parameters (Wagener et al. 2001). The availability of input data holds pivotal significance

---

[1] https://www.gerics.de/about/news_and_events/news/102260/index.php.en.

in the process of selecting an appropriate model (Clark et al. 2015). The accuracy of model results depends on the model's structure, the quality of input data, and the spatial-temporal precision it entails. Any simplification within the modeling approach inevitably results in a diminished accuracy in portraying processes across space and time (Wagener et al. 2001).

Hydrologic models can generally be classified in the following categories: i) conceptual models, ii) conceptual process-based (empirical) models, and iii) physically-based models (Lees et al. 2021; Guse et al. 2019). Conceptual models are based on straightforward model structures and simplified equations. Exchange of water in the atmosphere, hydrologic constituents, and storage capacities follows the water balance equation, omitting physical processes. Empirical models are based upon non-linear associations between input data and generated results. They are relatively simple in terms of process description, employing a modest number of input parameters. In contrast, physical models adhere to fundamental hydrological principles, integrating physical equations rooted in a profound comprehension of hydrologic processes. These models also account for temporal-spatial fluctuations and are suitable for smaller scales (Sitterson et al. 2017).

Furthermore, data-driven models can be used to simulate rainfall-runoff processes (Herath et al. 2021; Chadalawada et al. 2020; Reichstein et al. 2019; Le et al. 2019). In regions with poor data availability, conceptual models can yield commendable results even with a limited array of input parameters (Kumari et al. 2021). The choice of the model usually depends on the specific natural processes and scope under investigation, the site characteristics, and the spatial-temporal scales encompassed (Horton et al. 2021; Bach et al. 2014).

In most cases, comparative analyses up to now tend to concentrate on river basins (Flores et al. 2021; Lees et al. 2021). Such comparisons generally serve to highlight the advantages and disadvantages of distinct modeling approaches, laying the groundwork for their subsequent application in diverse contexts (Guse et al. 2019; Gao et al. 2016; Koch et al. 2016; Perrin 2001). Although there exist numerous cases of river system modeling, a scarcity of substantial efforts can be observed regarding the use of hydrological models to simulate heavy rainfall runoff in urban areas (Schütze et al. 2021; Wang et al. 2019).

The main challenges for running hydrological modeling in urban environments, are the anthropogenic impacts on the natural hydrological processes, such as soil sealing and compaction elevating surface runoff and reducing groundwater recharge (Cristiano et al. 2017). This leads to a complex system, whereas the exact extent of these interactions cannot always be quantified because they can change on a small scale (Wübbelmann 2023; Salvadore et al. 2015; Fletcher et al. 2013). Consequently, accurate representation of hydrologic processes at an urban scale for heavy rainfall events necessitates elevated spatial and temporal resolutions. In this context, rainfall-runoff models tailored for urban areas tend to segregate vertical and horizontal hydrologic processes, channeling their focus toward surface runoff dynamics.

4 THE GEESTHACHT CASE STUDY

4.1 General aspects – the HEC-RAS modelling approach

In an effort to simulate the runoff dynamics during specific heavy rainfall events within the city of Geesthacht, the "River Analysis System" (HEC-RAS), an open-access model conceived by the U.S. Army Corps of Engineers under the "Hydrologic Engineering Center," was used. Further model specific details can be found at Brunner (2016). During the model's setup, the preparatory phase mandates the organization of input data via a geographic information system – such as ESRI's ArcGIS Pro – enabling seamless integration of elements like buildings, levees, or other flow restrictions.

This distinctive modeling approach seeks to address three primary inquiries: i) identification of current flood-prone zones within the urban area which can be potentially be flooded after heavy rain events, pointing to the immediate need for adaptation strategies, ii) determination of areas within the city where construction measures, such as the densification of existing development, might exacerbate flood risks, and iii) clarifying the flow of surface runoff water during a heavy rainfall event. To this end, scenarios were integrated into the modeling process, varying in terms of spatial extent, the specific intensity of the analyzed rainfall events, and the hypothesized extent of built-up areas.

In close cooperation with project partners from the city administration of Geesthacht, two different scenarios were simulated for the main part of the urban area. The overarching objective was to capture and illustrate the temporal and spatial progression of urban flooding during and after a heavy rainfall event. Within the model framework, precipitation is uniformly distributed across the entire model area.

The first scenario "Historical heavy rainfall" is based on observation data to replicate the impacts of a weather event that happened in the past. Since there are no contemporaneous measurements or observation data available with the required temporal resolution nearby the city of Geesthacht, the remarkable heavy rainfall occurrence of June 15, 2007 – recorded at the closest Boizenburg/Elbe station – was used as a proxy. Throughout the totality of this precipitation episode, a substantial 92.5 mm of rainfall was registered, with the bulk of it (51.6 mm) falling within a single hour.

The second scenario "Severe extreme rainfall" (analog to the 2021 Ahr Valley heavy rainfall event) reflects the destructive power of an exceptional heavy rain event according to the catastrophic event happening in the Ahr Valley in Germany during July 2021, which caused devastation due to its unique topographical characteristics. During that period, 162 mm of precipitation flooded the region in a few hours.

4.2 Results

With respect to the scenario „Historical heavy rainfall" figure 1 (left) shows the surface flow in times of the precipitation peak. The map shows water accumulations of a few centimeters in height, extending over almost the entire road network and a considerable part of undeveloped terrains. Most of these accumulations, although widespread, can be rated as harmless. In particular, water accumulations on roads and steeper terrain segments in the central core of the model area are not continuous, attributable to the ongoing surface runoff. The water thus moves towards the west and southwest, depending on the prevailing topography. The animated temporal sequence clearly illustrates this run-off behavior. Two notable areas are covered on the southern edge of the map: the Elbe River and a reservoir. This results from the model's representation of water accumulations in these areas, although they do not exist in reality, because rainwater is diverted from the Elbe River and discharged into the reservoir, a phenomenon omitted from the model representation.

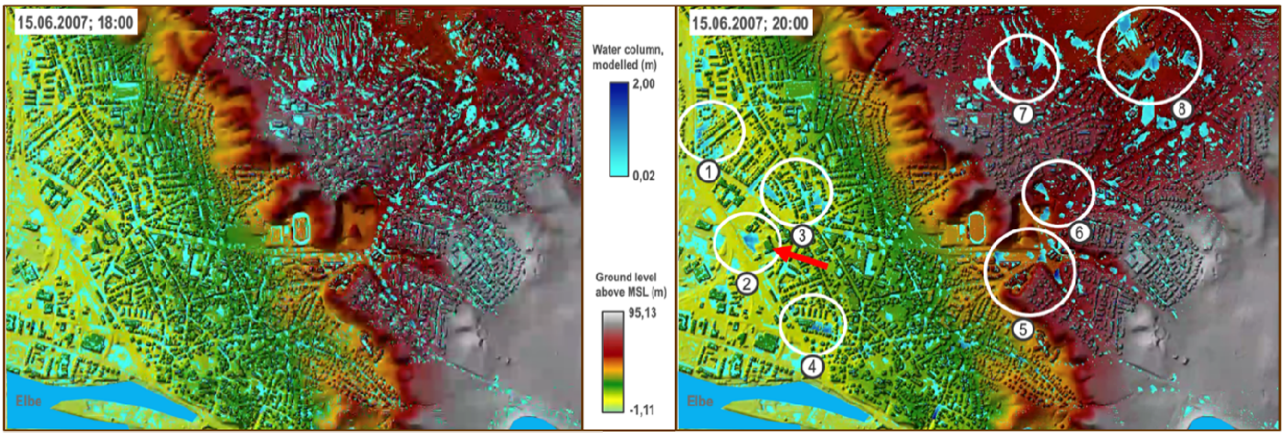

Fig. 1: Simulation results of the rain event "Historical heavy rainfall". The depicted phases encompass the heavy rainfall phase (left) and the subsequent runoff phase (right). Notably, the red arrow demarcates the precise location of the sports hall within the model.

Stormwater, unable to infiltrate the soil, follows roadways, flowing towards lower-lying areas, initially accumulating in depressions. The influence of the sewer system is not included in the model, because its potential effects during such an event are small, because its capacity to take rainwater becomes overloaded in a brief time span. Such a simplification is in line with the application of many hydrological models (Groth et al. 2020). Another reason for the usage of such a simplified model is the lack of precise data on the design of the sewer network, which makes comprehensive modelling challenging.

Based on the available DTM1 data, the current model does contain all operational road culverts or potential drainage pathways. Similarly, inaccessible sites, potentially obstructed by barriers or blockages like littered or clogged culverts, are not integrated into the dataset. In order to improve the model quality, and to enable not only qualitative but also quantitative assessments, an additional on-site mapping for the validation would be necessary. Despite these potential local limitations, the model results show eight potential accumulation zones (1 - 8) – distinctive circles indicate the flood-prone areas (figure 1, right). In the current version of the model, water depths of up to 2 meters can be seen in these areas, indicating an increased hazard potential.

In the second scenario with severe extreme rainfall, the amount of precipitation was increased to simulate the possible effects of an exceptionally extreme rainfall event. Notably, comparable amounts have been fallen in the summer of 2021 in the Ahr Valley showing that such events can also occur in Germany. Climate change will also increase the probability of such events. To explore potential floodlains within the city under such conditions, the historical precipitation amounts have been approximately tripled in comparison to the first scenario, which makes the temporal development similar to the Ahr Valley event.

The direct effects of more water in the urban area due to the higher precipitation is clearly visible (figure 2, left). In comparison to the first scenario, a larger expanse of water-covered areas emerges initially, while substantially larger volumes of water flow through the streets, towards the Elbe River. This escalation in precipitation quantities leads to more pronounced hydrological effects, increasing the potential for local flooding within the urban area.

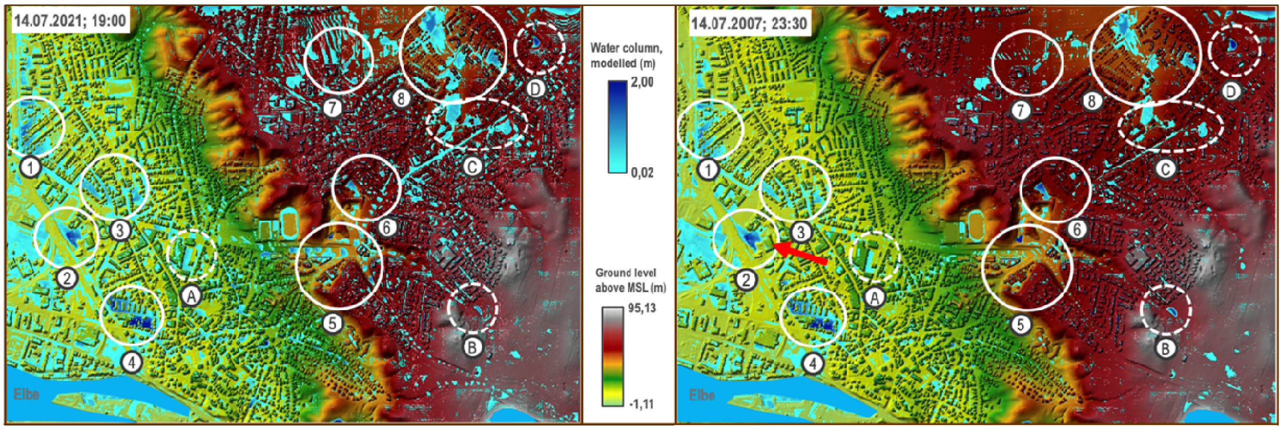

Fig. 2: Simulation of extreme heavy rainfall "Severe extreme rainfall". Phase during the heavy rain event (left) and the infiltration phase (right). The red arrow shows the location of the sports hall.

The flood-hotspots 1 to 8, which originally appeared in the first sceanrio, now become focal points for significantly larger water accumulations. These accumulations contribute to higher water levels or more extensive flooded regions within these hotspots. Moreover, four new hotspots (A - D) emerge, with water accumulations of about 1 meter (A, C), or localized zones with water depths reaching up to 2 meters (B, D) (figure 2, left). After the primary area precipitation has subsided, water heights of up to 2 meters remain at seven locations (figure 2, right).

Notably, two areas in the western sector of the model stand out, drawing particular attention. In area 2, water accumulation is relatively harmless according to the model, as the water naturally converges into a forested depression, and can gradually seep away without causing any damage. However, special attention should be paid to the sports hall on Grenzstraße (marked with a red arrow), as previous heavy rainfalls have induced moisture damage to its flooring.

Area 4 is an example where re-evaluation of the model is suggested, due to the high degreee of water accumulation. The mapping of missing road culverts and of surface conditions would facilitate a more accurate simulation of water flow directions and potential water quantities in this part of the city. Furthermore, it is advisable to investigate whether past flooding incidents have affected the area in the past.

In the context of this analysis, hotspot B, exclusively evident during the occurrence of the extreme heavy rain event, gives little cause for concern. Embedded in a forested area, it poses a minimal hazard potential. However, within the urban landscape, there are several zones where significant water accumulations can occur, both in terms of area coverage and water depth. Area 6, for instance, where an accumulation zone presently comprises a forested depression, offers the potential for future use as a temporary retention site. To realize this potential, it is crucial to ensure that flood drainage pathes are maintained to allow water flow into the swale. Meanwhile, sections of area 8 and the surroundings of hotpsot area C raise concerns, demanding a comprehensive review of promising adaptation measures, because the model results indicate an increased potential flood risk.

5 THE ROSTOCK CASE STUDY[2]

5.1 The Tygron engine modelling approach

5.1.1 General aspects

The Tygron Engine is as a 3D geodesign platform including cloud computing technology, offering diverse functionalities such as the dynamic computation and interactive visualization of flooding scenarios. The model takes into account a number of influencing factors, including i) infiltration dynamics, ii) evaporation kinetics, iii) groundwater flow phenomena, and iv) the interaction between constructed and natural hydraulic structures. For the Rostock case study, we used a digital terrain model DTM1, affording a grid width of 1 meter. With regard to the precipitation amounts, every cell is individually assigned with a water volume based on the comprehensive dataset from the KOSTRA Atlas German Weather Service (DWD) 2010R of the city of Warnemünde, incorporating the model rain type Euler Type II.

These cells are divided into groups, each assigned relevant parameters like infiltration behavior or roughness factor. The model simulates the interactions between neighboring cells in discrete time steps, taking into account water levels, surface heights, flow direction and other relevant parameters. A high degree of simulation accuracy is achieved through the use of small time steps and a finely gridded spatial layout. In an effort to follow an simplified approach adaptable for all municipalities – especially for municpalities without sufficient information of their sewage system – the sewer capacity was approximated using data according to experience values from other projects. Within the simulation, inflow into the sewer occurs when a grid cell both contains water and coincides with a surface sewer structure. This inflow persists until the sewer reaches its full capacity. Incorporating infiltration into the unsaturated soil zone introduces another option for mitigating surface water.

5.1.2 Results

As an example, we mainly consider a section of the map with the focus on the area around the Holbeinplatz, as illustrated in figure 3. These visualizations contain the essential map representations commonly used in Tygron Engine reports, effectively showing flood depths and flow directions. These representations reveal two vulnerable areas that are prone to flooding. One location is the Holbeinplatz, beneath a railroad bridge, while the other is north of the Werftstraße. In these depicted zones, the simulation shows flooded areas with water depths of up to 5 meters.

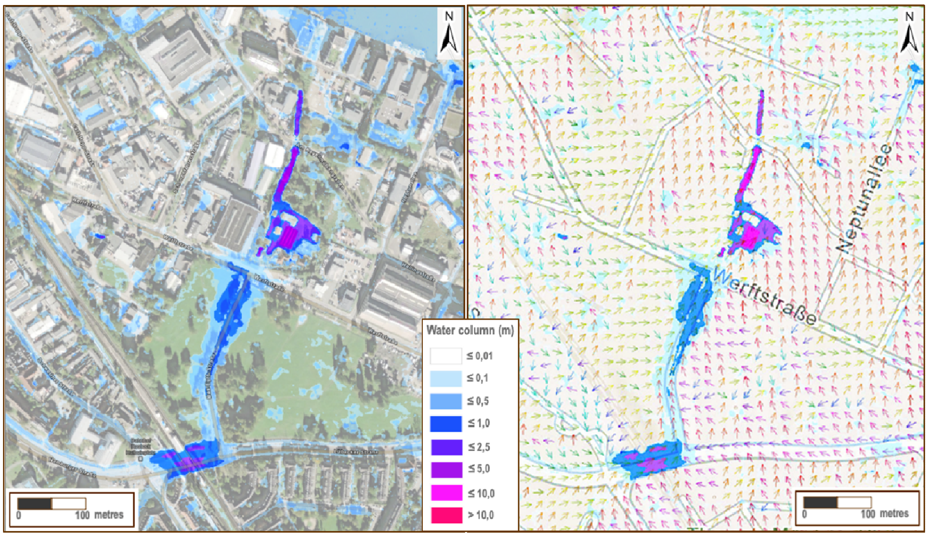

Fig. 3: Left: Flood depths near the Holbeinplatz and Werftstraße. Right: Flow directions of the surface runoff.

---

[2] The contents and visuals presented within this chapter have been taken from the conclusive reports developed by Tauw GmbH in collaboration with the Climate Service Center Germany (GERICS). These reports titled "Starkregengefahrenkarte Rostock: Studie zur Bewertung des Abflussverhaltens von Starkniederschlägen im Stadtgebiet Rostock mit der Software Tygron" (Tauw 2020) and "Modelloptimierung und alternative Modellansätze Rostock. Vergleich HEC-RAS – Tygron" (Tauw 2022) serve as key references. The contents have undergone modifications to ensure linguistic coherence and have been supplemented to enhance their comprehensiveness.

The modelled flow directions clearly show the dominant course leading toward topographic low points, signifying a likelihood for further water accumulation at these two locations during more intense precipitation episodes. The derived maps highlight the increased vulnerability of the Holbeinplatz, particularly during heavy rainfall events, as it plays a central role within public transportation. In light of the increasing frequency (Bender et al. 2019) and intensity (Dahm et al. 2020) of heavy rain events, proactive adaptation measures are strongly recommended for the Holbeinplatz, emphasizing the urgency of improving resilience.

Around the Werftstraße, the simulation also shows elevated water levels, but only with very local impacts, leading to limited disruptions and potential local damage. Notably, the model unveils water accumulations just north of the railroad bridge, spanning across Werftstraße and Neptunallee. This area's distinct hydrological dynamics are shaped by the presence of multiple road crossings – namely Werftstraße and Am Kayenmühlengraben. An on-site mapping is required to check the reasons for the modeled water columns. Topographical reasons, incorrect boundary conditions for the infiltration rates in the model, but also differences between existing road culverts missing in the model, are among the possible reasons for the modeled results. Independently of the potential need for model refinement, the results clearly indicate zones of increased flood risk. In view of this, it is of utmost importance to make neighboring property and land proprietors aware of these vulnerabilities. Proactive adaptation measures should be considered in this section, highlighting the importance of developing strategies for targeted discharge of surface water into temporary retention areas, where the water cannot cause any damage.

5.2 The HEC-RAS modelling approach

In order to carry out a direct model comparison between the models HEC-RAS and Tygron Engine, we chose a distinct area of the city of Rostock of approximately 4.5 km², using a grid of 5 x 5 m. To ensure consistency, both models are built with the same input data and without a detailed sewage system, as well as neither “missing” culverts nor pumps were considered. For the incorporation of infiltration, the curve-number (CN) method was applied, estimating the extent of infiltrated precipitation as a function of cumulative precipitation amount, soil sealing, land use, and soil moisture. In order to approximate the Courant criterion, calculation intervals were set at 2 seconds. Consequently, the computational iteration duration for HEC-RAS was about 10 minutes and 30 seconds per run, adhering to these specified parameters.

When performing simulations, time intervals can be set manually, serving as default settings for computations. The choice of these time steps, ranging from seconds to several minutes, depending on the processing capability of the computer and the time interval to be analysed. Despite maintaining identical model parameterization, the selection of time step length has a direct influence on the model outputs, whether in the form of map displays or chronological sequences presented as videos.

Figure 4 shows two snapshots from another project capturing the same point in time during the simulation of a heavy rainfall event. The only distinguishing feature between both approaches is the configuration of the time steps, set at 1 minute and 10 minutes, respectively. However, the visual representation differs significantly. In the model with 1-minute time steps, a lower water presence within the model areas is evident at first glance, with all water showing a lower extent. Furthermore, the identified hotspots have shallower water depths. Nonetheless, the accompanying scales illustrate that this scenario actually culminates in a higher peak for water depths when contrasted with the entire model area. In both cases, surface runoff is represented as fragmented non-contiguous flows, attributed to the Courant condition not being met. As a result, spatially restricted water accumulations occur.

This phenomenon – once again – highlights that model results should always be scrutinised, because depending on the model parameters selected, effects can occur – in this case flood heights – that are based only on mathematical boundary conditions. In this case such a phenomenon can be significantly improved by reducing the time steps to seconds.

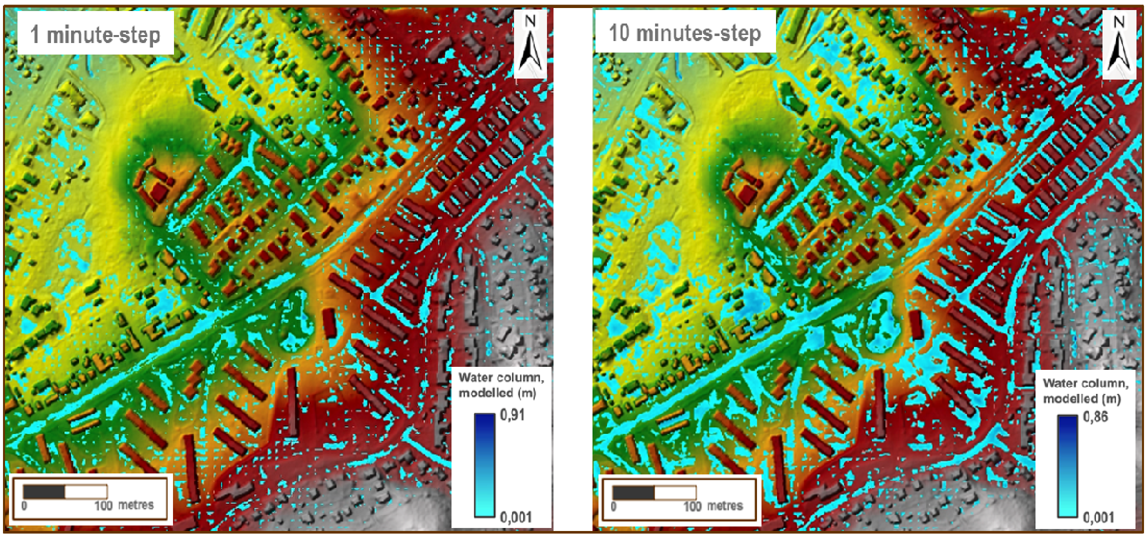

Fig. 4: HEC-RAS calculations with different time step configurations. Left: Time step 1 minute. Right: Time step 10 minutes.

5.3 Model comparison

In line with the increasing number of precipitation-runoff modeling efforts focused on heavy rainfall events, various map representations are available, depending on the specific modelling approach. As the interpretation of results is not always entrusted to modeling experts, this case study example presents the results of different models partly using identical input parameters. To enhance comparability, the modeling was conducted by the same experienced team, minimizing the influence of individual modelers as much as possible. Table 1 provides a summarizing comparison of the technical boundary conditions and key model input parameters. As an example we compare the modeled water depths in the Holbeinplatz and Werftstraße areas in Rostock (figure 5). In both model simulations, the primary flood-prone areas are observed around Holbeinplatz, particularly below the bridge, and south of Werftstraße. The spatial extent and water depths exhibit rough similarity, although the Tygron modeling indicates slightly larger water depths. The main differences are evident in areas somewhat distant from the primary hotspots.

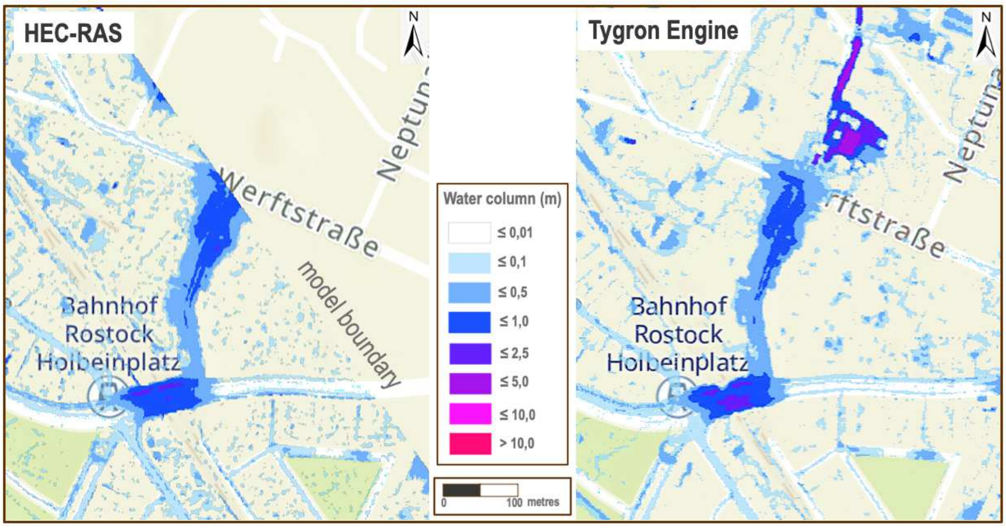

Fig. 5: Results from different model simulations. Left: HEC-RAS. Right: Tygron Engine.

The HEC-RAS result depicts a more “restless” scenario, characterized by numerous small delineated water accumulations. Conversely, the Tygron result shows larger continuous patches of water, attributed to its smaller time steps and the automatic stabilizer function. Overall, the Tygron modeling shows lower total water columns compared to HEC-RAS, particularly in areas with minor water accumulations, which is due to the incorporated channel capacity consideration. However, the model results also illustrate that in areas where this capacity is exceeded, Tygron exhibits higher water levels.

Input parameters and boundary conditions	**HEC-RAS (Rostock)**	**Tygron Engine (Rostock)**
Initial water levels	No	No
Hydraulic structures	No	No
Soil parameters	Yes	Yes
Roughness factor	Yes	Yes
Topography	Yes	Yes
Grid size	5x5 m, flexible mesh possible	1x1 m, only fixed mesh possible, 315 million cells
Total size	4,5 km²	9-10 km²
Boundary conditions	Adapted to road course	Adapted from the largest model
Infiltration	Calculation with the curve number method, where the land use determines the infiltration rate. Land use determines the infiltration rate; no further adjustments were made.	Dependent on the K-factors of the ground surface and the soil properties. In the RSAG area: Adjustment 0.06 m/d in the track area.
Sewer system	No	With averaged capacity of 10.82 mm/h under "street" cells
Evapotranspiration	No	Yes, minimal
Time step length	2 seconds	0,114 seconds
Rainfall event	43,5 mm/h	43,5 mm/h
Maximum discharge velocities	20 m/s	1-2,5 m/s
Computing time per run	10 min 30 sec	1 min
Flood heights	Up to 2,5 m	Up to 10 m
Surface runoff	In a chain of water accumulations.	In a chain of water accumulations.
Expected costs	0 to 10 k€ (including validation and one scenario)	15 to 25 k€ (including validation and one scenario)
Computer capacity	For modelling: Desktop PC or Laptop For use of results: Desktop PC or Laptop	For modelling: Access to supercomputer (proprietary) For use of results: Desktop PC or Laptop
Staff skill requirements	For modelling: Hydrological modelling skills; not required when modelling is done by a company. For interpretation: Basic hydrological understanding and modelling expertise would be an advantage	For modelling: not required. For interpretation: Basic hydrological understanding and modelling expertise would be an advantage

Table 1: Input parameters and boundary conditions.

Looking at the area southwest of the Schwanenteichpark in figure 6, the contrasting characteristics of the two model approaches are also evident. In the HEC-RAS modeling on the left, water accumulations are evenly distributed across the area, with generally shallow water columns of just a few centimeters. However, when using the Tygron model many of these water patches disappear, as the sewer model component removes a defined water volume from the surface. At first glance, this creates a smoother appearance. However, in places where water accumulates, higher water depths are observed despite the smaller time step. Moreover, new flood areas are formed compared to HEC-RAS, such as in the western region of Kuphalstraße. This divergence could be attributed to the fact that the analyzed area lies in close proximity to the model boundary of HEC-RAS, where hydraulic conditions are more strongly influenced by the given boundary conditions of the model. So it can happen at some points, that surface water is forced to flow out of the model. Therefore, when interpreting map representations, it is crucial to focus on areas located more in the central part of the model area whenever feasible to ensure reliable interpretations without impacts from the model architecture.

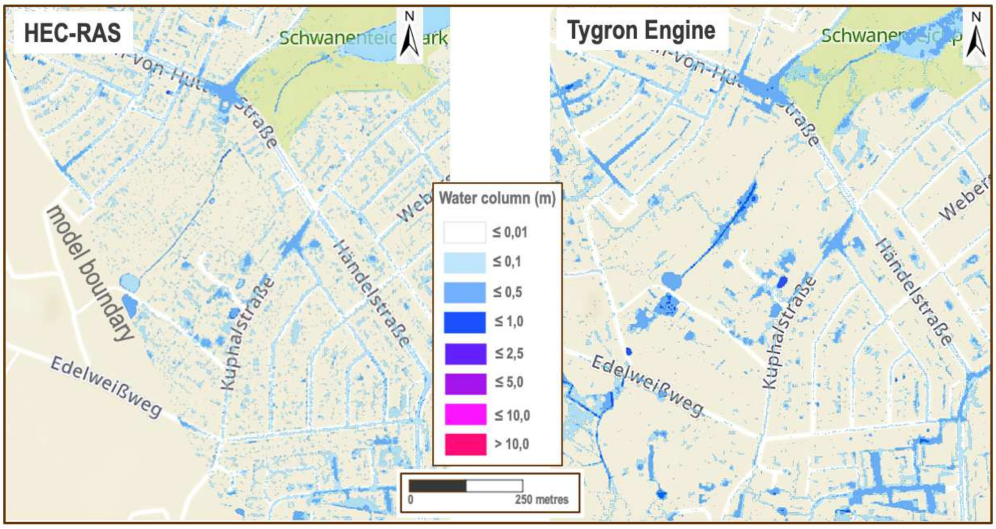

Fig. 6: Results from different model simulations. Left: HEC-RAS. Right: Tygron Engine.

6 CONCLUSION

The comparison between two hydrological models highlights their general usefulness in creating hazard maps for heavy rainfall events. Both approaches provide essential tools to identify areas that are potentially affected or at risk of flooding. Furthermore, these maps can be used to locate flow paths within urban areas, and to visualise significant hotspots.

Practical results and experience indicate that HEC-RAS offers a feasible way to quickly generate initial estimates of runoff behavior during heavy rainfall events (Wübbelmann 2023; Bender et al. 2023a). These calculations can be performed on a standard PC or laptop. With numerous customizable settings, the model can be tailored to individual requirements based on available data resources. It is ideally suited for the detailed analysis of small-scale areas and can also be applied to model smaller cities. Thanks to its relatively short computation times and hardware requirements, it enables rapid simulations of scenarios such as land use changes or the impact of new constructions on runoff behavior.

The commercial Tygron geodesign platform operated by engeneering companies stands out for its combination of fast computation and high-resolution output. The program automatically adjusts certain conditions to ensure robust numerical modeling, thereby achieving high-quality simulations, particularly in terms of surface water flow behavior. The model uses regional to local parameters and characteristics, such as soil types, for individual process calculations. However, it is not designed to account for small-scale processes like the influence of soil moisture on infiltration behavior. Due to its computing power, Tygron is also suitable for larger areas, including entire cities. Its 3D visualizations offer compelling materials for decision-makers to effectively raise public awareness about flooding issues.

In general, there is a need to optimize the process of “awarness creation – implementation of prevention measures – crisis communication”. This includes the improvement of early warning systems, for example due to a combination of regional climate information, data-collection from historcial events, and on-site monitoring using of sensors or satellites. There is also significant potential in providing comprehensive and area-wide digital models of municipalities, facilitating efficient heavy rainfall runoff modeling. However, it is important to also consider risk associated with digitization. Critical infrastructures, such as energy supply, information technology, and telecommunications, are expected to become increasingly vulnerable to the impacts of more frequent and intense extreme weather events (Groth et al. 2023). In order to take protective measures at an early stage, the hydrologcial models can also be used to check which components of the critical infrastruchture are – currently and in the future – located in vulnerable areas. However, in addition to the modelling activities also monitoring should be considered. This includes the regular updating of input parameters – e.g. land use or observed flooding – as well as the regular functionality check of components that affect runoff – such as blocked gullies or overgrown drainage ditches.

Overall, the experiences show that also the use of simplified digital models of a city – or parts of a city – without the need for big-data and monitoring information can be good planning tools to assess plausible results regarding possible impacts of climate change on a small scale. Based on this, first adaptation measures can be planned, tested in a simuation, justified, and implemented in the context of urban planning and development. Irrespective of the model results, preventive measures such as the large-scale unsealing of surfaces, increasing the proportion of green spaces and the creation of temporary retention areas and flood drainage paths have a positive influence on the flooding behaviour.

However, due to the complexity of natural systems with a high number of connected processes, the effects of such measures on the local scale and on the whole system can be answered – sometimes in parts, only – by the use of these models. Depending on the model used, local model results may vary, but the location of the most important hot spots is generally recognised. To increase the informative value of the models, either the results of different models can be combined or more complex models - which also require more input data - can be used, for example to transform an urban area towards being climate resilient and sustainable. Thereby also the possible implementation time and cost of adaptation measures (including the regular maintenance) as well as the cost of using different modelling approaches needs to be taken into account.

7 REFERENCES

Bach, P.M., Rauch, W., Mikkelsen, P.S., McCarthy, D.T. and Deletic, A. (2014): A critical review of integrated urban water modelling – Urban drainage and beyond. Environmental Modelling & Software, vol 54: 88–107.

Bender, S., Nolte, A., Wübbelmann, T., Baltruschat, S., Groth, M., Seipold, P. and Gehrke, J. (2023b): Building a digital city with several digital twins? – An exemplary view on water-related questions in urban areas. https://edition.pagesuite-professional.co.uk/html5/reader/production/default.aspx?pubname=&edid=6c7dc99e-5e88-4a68-9402-ffd093359632.

Bender, S., Groth, M., Wübbelmann, T. and Bockbreder, J. (2023a): Eine Starkregenmodellierung für zentrale Bereiche des Stadtgebiets Geesthacht unter Nutzung des Modells HEC-RAS. City Series 04. Climate Service Center Germany (GERICS), Helmholtz-Zentrum Hereon. https://doi.org/10.5281/zenodo.10656512.

Bender, S., Groth. M., Seipold, P. and Gehrke, J.M. (2022): Klimaschutz und Anpassung an die Folgen des Klimawandels – Synergien und Zielkonflikte im Rahmen kommunaler Konzepte und Strategen. Climate Service Center Germany (GERICS), Helmholtz-Zentrum Hereon. Helmholtz-Klima-Initiative (HI-CAM). https://www.gerics.de/imperia/md/assets/net_zero/dokumente/gerics_netto-null_report_anpassung_klimaschutz-final-screen.pdf.

Bender, S., Groth, M., Otto, J., Pfeifer, S. and Seipold, P. (2019): Regionale Klimainformationen für Rostock. City Series 03, Climate Service Center Germany (GERICS), Hamburg. https://www.gerics.de/imperia/md/content/csc/gerics_cityseries03.pdf.

Bender, S., Brune, M., Cortekar, J., Groth, M. and Remke, T. (2017): Anpassung an die Folgen des Klimawandels in der Stadtplanung und Stadtentwicklung – Der GERICS-Stadtbaukasten. GERICS-Report 31. Climate Service Center Germany (GERICS), Hamburg: https://www.gerics.de/imperia/md/content/csc/report31.pdf.

Brunner, G.W. (2016): HEC-RAS, River Analysis System Hydraulic Reference Manual. US Army Corps of Engineers. Hydrologic Engineering Center: https://www.hec.usace.army.mil/software/hec-ras/documentation/HEC-RAS%205.0%20Reference%20Manual.pdf.

Chadalawada, J., Herath, H., and Babovic, V. (2020): Hydrologically Informed Machine Learning for Rainfall-Runoff Modeling: A Genetic Programming-Based Toolkit for Automatic Model Induction. In: Water Resour. Res., 56, e2019WR026933, https://doi.org/10.1029/2019WR026933, 2020.

Clark, M.P., Nijssen, B., Lundquist, J.D., Kavetski, D., Rupp, D.E., Woods, R.A., Freer, J.E., Gutmann, E.D., Wood, A.W., Brekke, L.D., Arnold, J.R., Gochis, D.J. and Rasmussen, R.M. (2015): A unified approach for process-based hydrologic modeling: 1. Modeling concept. In: Water Resour. Res. 51/4, 2015): 2498–2514.

Cristiano, E., ten Veldhuis, M.-C. and van de Giesen, N. (2017): Spatial and temporal variability of rainfall and their effects on hydrological response in urban areas – a review. In: Hydrology and Earth System Sciences, vol 21: 3859–3878.

Dahm, R., Bhardwaj, A., Sperna Weiland, F., Corzo, G. and Bouwer, L.M. (2019): A Temperature-Scaling Approach for Projecting Changes in Short Duration Rainfall Extremes from GCM Data. In: Water 11, 313. doi: 10.3390/w11020313

Deutschländer, T. and Mächel, H. (2017): Temperatur inklusive Hitzewellen. In: Brasseur, G. P., D. Jacob, S. Schuck-Zöller (2017): Klimawandel in Deutschland. Entwicklung, Folgen, Risiken und Perspektiven: 48-56.

Fischer, E.M. und Knutti, R. (2016): Observed heavy precipitation increase confirms theory and early models. In: Nature Clim. Change 6: 986–991.

Fletcher, T. D., Andrieu, H. and Hamel, P. (2013): Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art. In: Advances in Water Resources, vol 51: 261–279.

Flores, N., Rodríguez, R., Yépez, S., Osores, V., Rau, P., Rivera, D. and Balocchi, F. (2021): Comparison of Three Daily Rainfall-Runoff Hydrological Models Using Four Evapotranspiration Models in Four Small Forested Watersheds with Different Land Cover in South-Central Chile. - Water 2021: 3191.

Gao, C., Yao, M.T., Wang, Y.J., Zhai, J.Q., Buda, S., Fischer, T., Zeng, X.F. and Wang, W.P. (2016): Hydrological Model Comparison and Assessment: Criteria from Catchment Scales and Temporal Resolution. In: Hydrol. Sci. J. 2016, 61: 1941–1951.

Giorgi, F., Raffaele, F. and Coppola, E. (2019): The response of precipitation characteristics to global warming from climate projections. In: Earth Syst. Dynam., 10: 73–89.

Giorgi, F., Im, E.-S., Coppola, E., Diffenbaugh, N.S., Gao, X.J., Mariotti, L. and Shi, Y. (2011): Higher Hydroclimatic Intensity with Global Warming. In: Journal of Climate, 24, 20: 5309–5324.

Groth, M., Bender, S., Olfert, A., Schauser, I. and Viktor, E. (2023): Kaskadeneffekte und kritische Infrastrukturen im Klimawandel. In: Brasseur, G, Jacob, D. und Schuck-Zöller, S. (Hrsg.) 2023: Klimawandel in Deutschland, 2. überarb. und erw. Auflage, Springer/Spektrum Heidelberg: 309-322.

Groth, M., Bender, S. and Groth, B.J. (2021): Rechtlicher Rahmen der Anpassung an die Folgen des Klimawandels im urbanen Raum. In: Zeitschrift für Umweltpolitik & Umweltrecht (ZfU), ZfU 4/2021: 385-414.

Groth, M., Bender, S. and Wübbelmann, T. (2020): Starkregen und Sturzfluten – Anwendung des GERICS-Stadtbaukasten in Bleckede. Report 34, Climate Service Center Germany (GERICS), Hamburg: https://www.climate-service-center.de/imperia/md/content/csc/report34.pdf.

Guse, B., Pilz, T., Stoelzle, M. and Borman, H. (2019): Charakterisierung und Analyse hydrologischer Modelle im deutschsprachigen Raum. In: Wasser und Abfall, 05: 43–52.

Herath, H.M.V.V., Chadalawada, J. and Babovic, V. (2021): Hydrologically informed machine learning for rainfall–runoff modelling: towards distributed modelling. In: Hydrol. Earth Syst. Sci., 25: 4373–4401.

Horton, P., Schaefli, B. and Kauzlaric, M. (2021): Why do we have so many different hydrologicla models? A review based on the case of Switzerland. In: Wires Water: 1–32.

IPCC (2023): Summary for Policymakers. In: Climate Change 2023: Synthesis Report. A Report of the Intergovernmental Panel on Climate Change. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.

Jacob, D., Görl, K., Groth, M., Haustein, K., Rechid, D., Sieck, K. und Wolff, W. (2021): Naturwissenschaftlicher Hintergrund der Erderwärmung: Wo stehen wir zurzeit? In: Wirtschaftsdienst – Zeitschrift für Wirtschaftspolitik, 101 (5): 330-334.

Kahlenborn, W., Porst, L., Voß, M., Fritsch, U., Renner, K., Zebisch, M., Wolf, M., Schönthaler, K. and Schauser, I. (2021): Klimawirkungs- und Risikoanalyse 2021 für Deutschland. Kurzfassung. UBA Climate Change 26/2021: https://www.umweltbundesamt.de/sites/default/files/medien/5750/publikationen/2021-06-10_cc_26-2021_kwra2021_kurzfassung.pdf.

Koch, J. Cornelissen, T. Fang, Z. Bogena, H. Diekkrüger, B. Kollet, S. and Stisen, S. (2016): Inter-Comparison of Three Distributed Hydrological Models with Respect to Seasonal Variability of Soil Moisture Patterns at a Small Forested Catchment. In: J. Hydrol. 533: 234–249.

Kumari, N., Srivastava, A., Sahoo, B., Raghuwanshi, N.S. and Bretreger, D. (2021): Identification of Suitable Hydrological Models for Streamflow Assessment in the Kangsabati River Basin, India, by Using Different Model Selection Scores. In: Nat. Resour. Res., 30: 4187–4205.

Kurganov, A. and Petrova, G. (2007): A second order well balanced positivity preserving centralupwind scheme for the Saint-Venant System.-Commun. In: Math. Sci., Vol. 5, No.1: 133-16.

Lees, T., Buechel, M., Anderson, B., Slater, L., Reece, S., Coxon, G. and Dadson, S.J. (2021): Benchmarking data-driven rainfall–runoff models in Great Britain: a comparison of long short-term memory (LSTM)-based models with four lumped conceptual models. – Hydrol. Earth Syst. Sci., 25, 5517–5534, 2021, https://doi.org/10.5194/hess-25-5517-2021

Le, X.-H., Ho, H. V., Lee, G. and Jung, S. (2019): Application of long short-term memory (LSTM) neural network for flood forecasting. In: Water, 11, 1387, https://doi.org/10.3390/w11071387, 2019.

Papalexiou, S.M. and Montanari, A. (2019): Global and Regional Increase of Precipitation Extremes under Global Warming. In: Water Resources Research, 55: 4901–491.

Perrin, C., Michel, C. and Andréassian, V. (2001): Does a Large Number of Parameters Enhance Model Performance? Comparative Assessment of Common Catchment Model Structures on 429 Catchments. In: J. Hydrol., 242: 275–301.

Reichstein, M., Camps-Valls, G., Stevens, B., Jung, M., Denzler, J., Carvalhais, N. and Prabhat (2019): Deep learning and process understanding for data-driven Earth system science, In: Nature, 566: 195–204.

Salvadore, E., Bronders, J. and Batelaan, O. (2015): Hydrological modelling of urbanized catchments: A review and future directions. In: Journal of Hydrology, 529: 62–81.

Schütze, A., Banning, A. and Bender S. (2021): Kartierung und Simulation von Überschwemmungsflächen in urbanen Räumen nach Starkregenereignissen. In: Grundwasser, 26(1): 87-97.

Sitterson, J., Knightes, C., Parmar, R., Wolfe, K., Munche, M. and Avant, B. (2017): An Overview of Rainfall-Runoff Model Types. Environmental Protection Agency (EPA). Athens (Georgia), United States.

Tauw (2022): Modelloptimierung und alternative Modellansätze Rostock – Vergleich HEC-RAS – Tygron. Abschlussbericht für das Climate Service Center Germany (GERICS).

Tauw (2020): Starkregengefahrenkarte Rostock: Studie zur Bewertung des Abflussverhaltens von Starkniederschlägen im Stadtgebiet Rostock mit der Software „Tygron“. Abschlussbericht für das Climate Service Center Germany (GERICS).

Trenczek, J., Lühr, O., Eiserbeck, L. and Leuschner, V. (2022): Schadenswirkungen von Überschwemmungen und Sturzfluten sowie Hitze und Dürre. Ein Vergleich der Extremereignistypen. Projektbericht „Kosten durch Klimawandelfolgen“: https://www.prognos.com/sites/default/files/2022-07/Prognos_KlimawandelfolgenDeutschland_Vergleich%20Flut%20und%20Hitze_AP2_3c.pdf.

Wagener, T., Boyle, D.P., Lees, M.J., Wheater, H.S., Gupta, H.V. and Sorooshian, S. (2001): A framework for development and application of hydrological models. In: Hydrol. Earth Syst. Sci. 5, 1: 13–26.

Wang, X., Kinsland, G., Poudel, D. and Fenech, A. (2019): Urban flood prediction under heavy precipitation. In: Journal of Hydrology, 577, 123984, https://doi.org/10.1016/j.jhydrol.2019.123984

Westra, S., Fowler, H.J., Evans, J.P., Alexander, L.V., Berg, P., Johnson, F., Kendon, E.J., Lenderik, G. and Roberts, N.M. (2019): Future Changes to the Intensity and Frequency of Short-Duration Extreme Rainfall. In: Rev. Geophys., 52: 522–555.

Wübbelmann, T. (2023): Dynamics of Flood-Regulating Ecosystem Services in Urban Areas Modelling Heavy Rainfall, Climate Change Impacts and Benefits of Nature-based Solutions. https://www.repo.uni-hannover.de/bitstream/handle/123456789/13724/Dissertation_TheaWuebbelmann_rev01.pdf?sequence=1&isAllowed=y.