

An integrated urban planning and simulation method to enforce spatial resilience towards flooding hazards

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ABSTRACT

Urban development projects in flood-prone areas are usually complex tasks where failures can cause disastrous outcomes. To tackle this problem, we introduce a toolbox (Spatial Resilience Toolbox – Flooding, short: SRTF) to integrate flooding related aspects into the planning process. This, so called toolbox enables stakeholders to assess risks, evaluate designs and identify possible mitigations of flood-related causes within the planning software environment Rhinoceros 3D and Grasshopper. The paper presents a convenient approach to integrate flooding simulation and analysis at various scales and abstractions into the planning process. The toolbox conducts physically based simulations to give the user feedback about the current state of flooding resilience within an urban fabric. It is possible to evaluate existing structures, ongoing developments as well as future plans. The toolbox is designed to handle structures in a building scale as well as entire neighborhood developments or cities. Urban designers can optimize the spatial layout according to flood resilience in an early phase of the planning process. In this way, the toolbox can help to minimize the risk of flooding and simultaneously reduces the cost arising from the implementation and maintenance of drainage infrastructure.

Author Keywords

Fluid dynamics; flood simulation; spatial resilience; Grasshopper for Rhino

ACM Classification Keywords

I.6.1 SIMULATION AND MODELING

1 INTRODUCTION

A modern city's ability to thrive is compromised by many factors. Flooding and insufficient storm drainage systems in combination with rapid urbanization can have disastrous effects to the inhabitants [6]. Flood modeling is adopted by stakeholders to enforce an integrated water management to

mitigate the risk of damage caused by flooding. A relatively new but promising approach in this field of research is flood resilience. A flood is typically a common event that needs to be considered as such. Furthermore, the number and severity of flooding events will increase: Experts from the United Nations University warn that due to climate change, deforestation, rising sea levels and population growth in flood-prone lands, the number of people vulnerable to a devastating flood will rise to two billion by 2050 [1,11]. Extreme natural disasters, such as tropical storms, are expected to become more frequent while rainfall events are predicted to become more intense. Modern planners and developers must adapt to new challenges in order to facilitate sustainable and resilience-focused urban planning. Conventional planning techniques are reaching their limits in such a context [9]. This paper demonstrates how the Spatial Resilience Toolbox – Flooding (SRTF) can be used as a flexible integrated urban planning and simulation framework to enforce flood resilience for urban developments. For this purpose, it evaluates any site plan regarding three different types of flood: (1) urban inundation, (2) tidal flooding and (3) river flooding. The toolbox then assesses the individual risks of a given spatial layout. During the planning process, it is possible to exclude insufficient proposals right at the beginning. As a result, the SRTF encourages stakeholders to develop the most suitable spatial solution for a specific area.

The toolbox combines several computer-generated processes such as physically based simulation and evaluation models to visualize the current state of flooding resilience. It is construed to facilitate an integrated urban development workflow with the focus on flooding resilience to mitigate flooding outcomes, to minimize damages and most important to improve the life of the inhabitants.

The SRTF is designed to provide valuable information about the status of resilience to support an integrated and

streamlined workflow. The main benefits of using the toolbox can be summarized with visibility and transparency, interactivity, flexibility and adaptability while using it during the urban design process. Thereby the most important outcome of the toolbox constitutes specific information pertaining to flood-resilience that allows the designer to rank different options of an urban development. To achieve this, we determined data visualization as one of the main goals of the toolbox. All necessary information is directly presented in the viewport as alphanumeric values and 3D scenario maps. Interactivity means it allows the user to directly work on the spatial layout, the terrain and the anti-flooding measures within the program to test out several options. Furthermore, the toolbox is construed to handle several scales, starting with for example simulating the risk of the rain-runoff inundation for one hospital to evaluating the tidal flooding risk for a whole city. Eventually, it is possible due to the program environment of Grasshopper to use the outcome of the SRTF to conduct other simulation and evaluation models.

2 STATE OF THE ART

Since the 1970s, the research community put systematic effort into developing and improving flood modeling techniques to forecast and to predict the outcome of flooding events for rural and urban contexts [4]. Two groups of methodologies emerged in the past century that are now the subject of ongoing research: Empirical methods and physically based hydrodynamic models [4]. Today, it is widely acknowledged that using physically based hydrodynamic models for predicting flood outcomes in an urban context constitutes the most realistic approach [8]. These models are well established in commercial packages. HEC-RAS [14], MIKE FLOOD [15] and Hydro-Bid [16] are amongst others, software tools to simulate, to present preceded flooding events or to present the probability of a flooding event for a specific location. These tools are mainly physically based, however, use different approaches to model urban flooding. Physical models are based on the understanding of the physics related to the hydrological processes [13]. They use physically-based equations to govern multiple parts of real hydrologic characteristics that represent realistic responses in the catchment area. The behavior is reproduced based on general physics laws and principles including water balance equations, conservation of mass and energy, momentum, and kinematics. Saint-Venant, Boussinesq, Darcy, and Richard have developed some of the equations that physical models utilize [8].

Spatial and temporal variations within the evaluation perimeter can be adopted by physical models. They are organized like the real-world system. One of the main advantages of a physical model is the interaction between model parameters and physical catchment characteristics. This approach leads to a more realistic scenario. Physical models produce accurate results when precise data are available and the physical properties of the hydrological processes are correctly understood and applied. To function

properly, the model requires the calibration of many individual physical and process parameters. Physical parameters are properties of the evaluation perimeter that can be measured; process parameters represent physical properties including average water storage capacity [8]. Therefore, physical models are site-specific. Most of them represent a three-dimensional system of the water exchange within the soil, surface, and air. Besides that, they are suitable to simulate groundwater movement, and the site's interactions with sediments, nutrients, and chemicals.

Logic dictates that the more advanced a model is, the more expensive it is in terms of data and computational resources. When physical data is hardly available, historical statistics in combination with simple black box models, such as hydrological models, can still produce valuable information. A 1D hydraulic model is helpful to understand and manage drainage networks in a relatively short amount of time (1 min to 1h) [3]. Therefore, these models are suitable for real-time applications. However, 1D models are not able to evaluate the effects when the network overflows and inundation is affecting the city surface. By contrast, two-dimensional hydrodynamic models have proven suitable and precise to simulate urban flooding. Due to the characteristics of urban areas and its inherent complexity, 2D models require long computation time (1h to several hours) [3], opposing real-time applications. Combining storm drainage systems and urban inundation requires a 1D-2D coupling. The computation time (1h to several hours) [3] of this model is not sufficient for real-time purposes.

Summarizing, there are very powerful tools (commercial and open source) available on the market. Most of them are characterized by a high level of accuracy and versatile configurations. Alongside with the great functionality comes an operation that demands profound knowledge and a detailed input of data. Besides that, the usage of 1D-2D models involves a substantial amount of computational time [3]. During the concept phase, where planners want to quickly compare a proposal with another, this is impracticable.

3 FLOODING SIMULATION

The objective of the SRTF is to offer an adaptable framework for stakeholders that are involved in a development project such as urban planners, investors, developers etc. to evaluate planning proposals according to its flooding resilience status. In the following, the methods that are used in the toolbox are explained based on a case study. The Toolbox was developed within the software environment of Rhinoceros3D and its Plugin Grasshopper for visual programming.

The flooding component forms the main part of the SRTF. It can be further divided into a simulation phase and an evaluation phase. The simulation phase consists of two simulations, the rain runoff simulation, and the tidal and river flooding simulation. When the simulations are completed, the output information of each simulation is then evaluated and visualized. This includes the rain-runoff inundation risk,

the rain-runoff erosion risk, and the tidal or river flooding risk for a specific level of water and the average risk value. The simulations can be conducted individually for example by evaluating only the urban inundation that is caused by rainfall. The evaluations in this paper are conducted for a newly planned neighborhood of a tropical town.

3.1 Rain Runoff Simulation

The rain runoff simulation is conducted with the help of the interactive physics/constraint solver Kangaroo for Grasshopper by Daniel Piker. The toolbox can represent a rainfall event by equipping particles with a certain mass and gravitation force. During the simulation, the particles are attracted by the external gravitational force, which results in runoff. Thereby, the particles search for ways downwards comparable to rain runoff. They behave as spherules running off the 3D geometry (Figure 1).

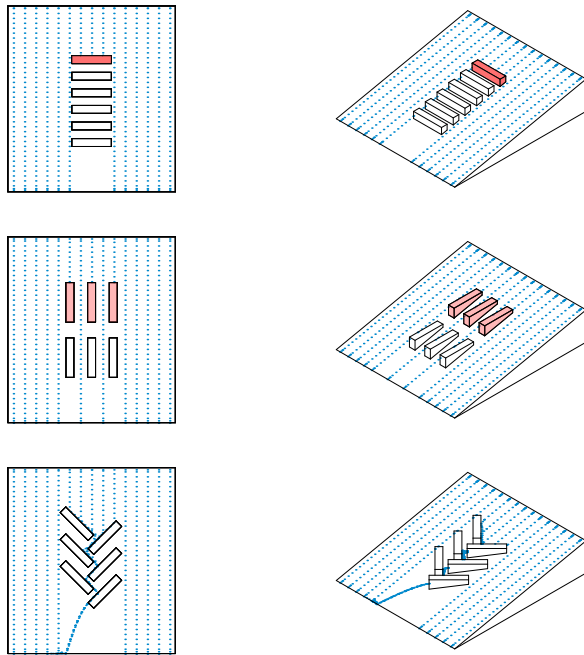


Figure 1. Using the rain-runoff simulation to compare different spatial configurations according to its behavior during rainfall

They pick up velocity when running unhindered and accumulate at bottlenecks or depressions. There are three parameters that can be set individually to match several different rainfall events: (1) the number of particles, (2) the size of particles and (3) the number of iterations. The simulation gets more realistic by increasing the number of particles and simultaneously decreasing the size of each particle. Obviously, a simulation with the number and size of actual raindrops constitutes the most realistic scenario. However, due the immense consumption of processing power for billions of particles, such an approach is not a realistic option for common users with limited technological possibilities. The rain runoff inundation simulation for the case study was conducted with 10,000 particles with a

diameter of 30 centimeters for each particle. The value of 30 centimeters is used to reach the same volume with spherules as around four liters of water per square meter. This amount reflects approximately one hour of rain during a day with excessive rainfall (> 100 mm per day). For comparison, in February 2015, during an excessive rainfall event, the city of Jakarta (c. 450km from Semarang) recorded a precipitation of 277 mm on one day [12].

The number of iterations is based on the situation that is being evaluated. A smaller amount of iterations represents the situation during a rainfall event and shows bottlenecks within the urban layout whereas more iterations are used to evaluate local inundation that appears after a rainfall event. The simulation in this paper is carried out with 3000 iterations. The most accurate practice for inundation would be achieved by letting the simulation run as long as there is movement in the scene. The results of further attempts had shown that in this case, the results are very similar after 3000 iterations. During the simulation, the toolbox saves the locations for each particle after every 10 iterations. These locations are then being connected with curves to show the flow paths. Additionally, it saves a screenshot after 10 iterations that can be merged afterward into a video, which shows the course of the simulation. The interval between iterations can be adjusted as needed. The value that is used in this paper is explained in the section of the erosion risk since it is also dependent on the number of flow-path segments.

3.2 Rain Runoff Evaluation

The risk assessment of the rain runoff inundation is conducted based on the location of each particle after the simulation. The toolbox counts the number of particles that are in a specific range within every building. The range is set to two meters by default. This allows to compromise the rating of a building in a negative way when it is surrounded by water under pressure. The value of the range distinguishes water that is running along the housing units from water that accumulates and pushes against buildings. Then the number is divided by the footprint area of each building. The higher the value the greater the risk of damages through flooding. This means that the density of particles near or at the buildings is responsible for the outcome of the evaluation. Buildings with a high risk of inundation are always characterized by an accumulation of particles nearby. The street network is treated similarly. Each street is further divided into segments at junctions or bends. Then the number of particles measured that are within a specific range near each street segment. The value is the same that is used for the housing units. The number is then divided by the area of the range. Now each building and each street segment is assigned with specific risk value. The information is visualized with color gradation in the viewport (Figure 2).

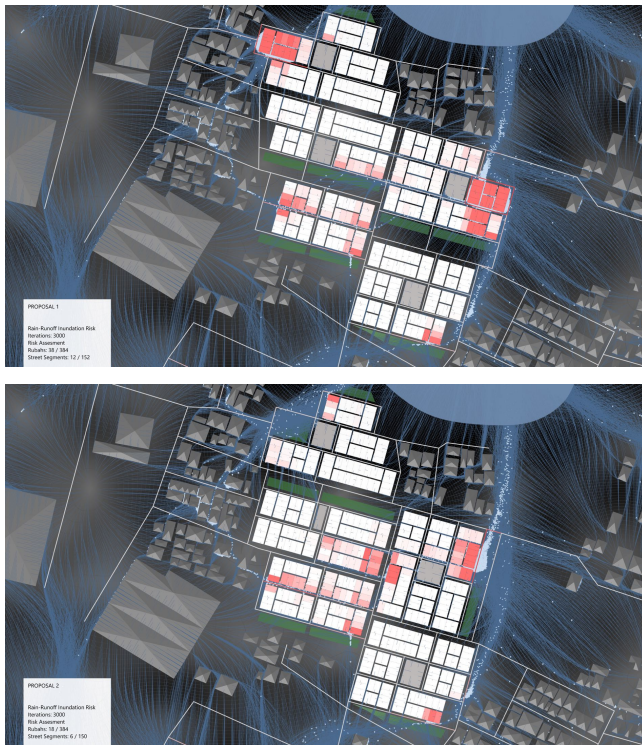


Figure 2. Comparing two proposals from the case study according to the rain-runoff inundation risk after 3000 iterations. Red buildings are considered flooded; proposal I - 38 vs. proposal II - 18

The darker the tone, the higher is the risk of inundation for a specific home. Furthermore, there is a legend in the viewport that indicates the number of housing units and street segments affected by flooding (Figure 2 and Figure 3, bottom left). With the outcome of the rain runoff simulation, one can also conduct the rain runoff erosion risk evaluation (Figure 3). Hereby the path of each particle is used to evaluate the runoff erosion risk. The toolbox creates the paths by recording the locations of the particles after a given amount of iterations. For the case study, the interpolation between locations is set to 10. So, the simulation with 3000 iterations produces paths with 300 segments for each particle. The value of the recording can be changed as needed. A smaller number constitutes a more accurate representation of reality. Nevertheless, it also affects the processing time in a negative way.

In the next step, the toolbox measures the distance of each segment. This distance gives information about the velocity of each particle at a specific location. It is possible to cull segments with a low value, so the outcome shows only places that are subject to the risk of erosion. The algorithm automatically culls those paths where the travel distance is lower than a given value. For the presented case study, the value is set to 1.5 m. This means that only those paths are visible in the evaluation where its particles traveled with a velocity of 1.5 m or higher per 10 iterations. This procedure ensures a clear picture of the situation because there are

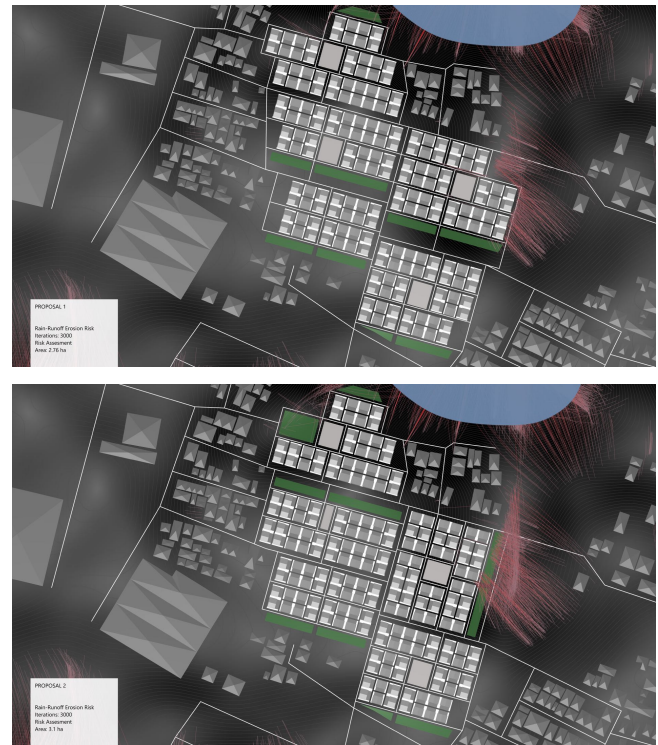


Figure 3. Comparing two proposals from the case study according to the rain-runoff erosion risk after 3000 iterations. Red flow paths mark areas that are likely to face erosion; proposal I – 2.76 ha vs. proposal II – 3.1 ha

3.000.000 flow-path segments in the scene. The remaining paths are displayed in the viewport with a gradient that shows the risk level of erosion caused by runoff (Figure 3). The algorithm also measures the area that is affected by the risk of runoff erosion. Therefore, it groups several flow-paths that are near each other with a given density threshold into a patch. The threshold is set to 1.5 m. Then it uses the segments located on the edge of the patch to span an area. This area is then measured and rated as prone to erosion.

3.3 Tidal and River Flooding Simulation

The second simulation the toolbox is capable of is the tidal and river flooding simulation. It illustrates and evaluates the impact of different water levels in the area. To measure the inundation, a plane is moved from a given altitude up to a predetermined value. The plane is considered as the surface area of a river, lake or the sea. To get precise information about which part of the geometry is flooded, the toolbox calculates the intersection between the plane and the surroundings (Figure 4).

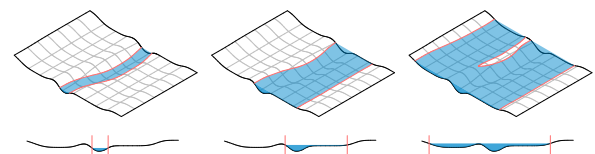


Figure 4. Using the tidal & river flooding simulation to compare three different water levels for a river flooding scenario

Everything inside the intersection area is perceived as flooded. Hereby, the toolbox culls areas that are not directly connected to the original surface. In this way, it is possible to evaluate the impact of, for example, dams where the terrain behind it can be lower than the level of water (Figure 5). The simulation computes several water levels one after the other according to the input parameters. The altitude of the water level indicates the peak.

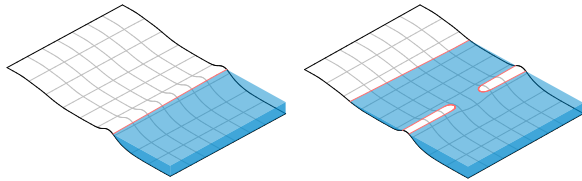


Figure 5. Using the tidal & river flooding simulation to evaluate the outcome of an open dam for the same water level

The frame count states the number of iterations between the lowest and the highest value. This case study was evaluated within a range from zero to eight meters. Although it is very uncommon in this region, this scenario is comparable to an intense storm surge like the one the hurricane Katrina produced in August 2005 [2].

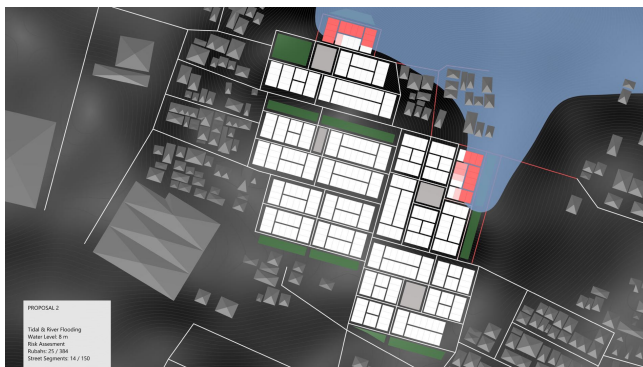
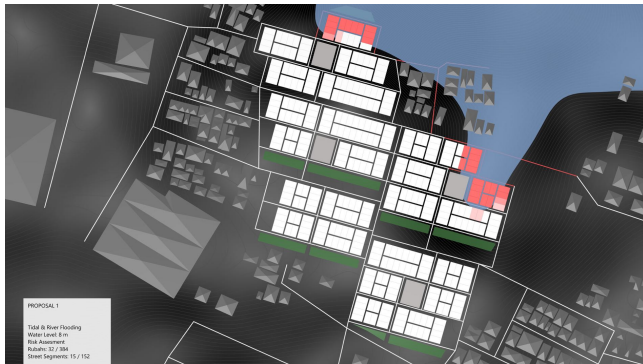


Figure 6. Comparing two proposals from the case study according to the tidal & river flooding simulation for a level of water of 8 m. Red buildings are considered flooded; proposal I - 32 vs. proposal II - 25

3.4 Tidal and River Flooding Evaluation

During the simulation, the risk assessment for the houses and the street network is presented in Figure 6. The legend (Figure 6, bottom left) provides details about the number of affected buildings and street segments. When the water level reaches the top of a platform of a building, it is marked with a red color. The toolbox applies a darker tone of red according to the depth of water. The depth is computed by iteration so each frame represents a depth of eight centimeters. It counts the number of iterations after a building is considered as flooded. In this case, the water levels that are deeper than 24 centimeters are considered equal. The values can be adjusted as needed. For this case study, the value is set to balance imprecisions and to match the threshold of lasting damages. The same methodology for assessing the risk applies to the city network. Hereby the lowest point of the street segment is evaluated. When the water reaches it, it is marked with a red color in the same manner as the risk assessment for the buildings.

The last part of the evaluation phase is called the mean risk assessment (Figure 7). It is related to the tidal and river flooding simulation and gives an understanding of the risk distribution in the area. Whereas the prior evaluation is useful for evaluating the site for specific water levels, the mean risk assessment shows the risk of all scenarios combined.

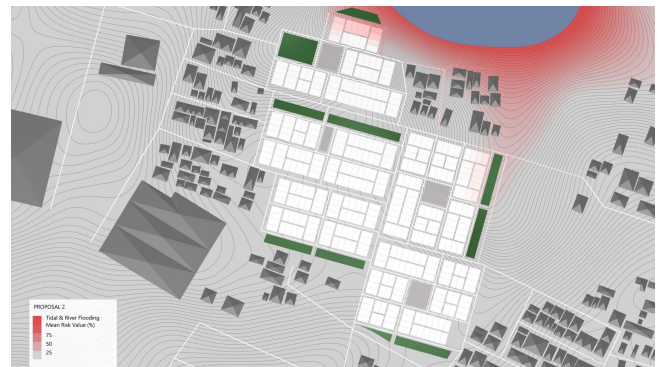
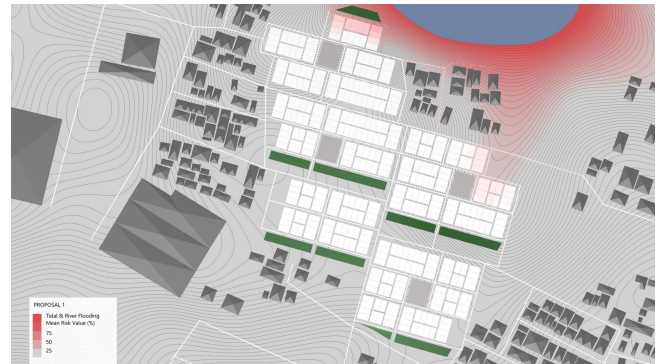


Figure 7. Evaluating the mean risk of two proposals from the case study according to the tidal & river flooding simulation. The color gradient reaches from red (high risk) to grey (low risk).

In this case, every single state of the tidal and river flooding simulation is recorded to compute the mean value. The toolbox then colors all affected buildings and street segments according to its mean associated risk from low to high (Figure 7). The algorithm behind that works as follows: Every building in the area is reduced to one point. As in the evaluation before the point is located on the foundation of a building. This point marks the threshold that distinguishes vulnerable from not vulnerable. The space above the point is considered vulnerable. To measure the mean risk, the algorithm counts every iteration when the point is flooded. In the end, this number is divided by the number of iterations that are used to conduct the simulation to get the mean risk. The same methodology applies to the street network and the terrain. Therefore, the terrain is interpolated to a grid, in this case, approximately three by three meters (the value is set by default but can be adjusted as needed). The surface consists now of several faces with one center point. The center point is used to define the risk value with the method explained above. The value of the center point is used for the corresponding face. Finally, the information is visualized by means of a gradient that shows the mean risk level of flooding (Figure 7).

4 RESULTS & DISCUSSION

In the presented case study, several parameters have been analyzed that affect the outcome of the SRTF. First, the accuracy of the results depends on the accuracy of the input data. A more detailed terrain surface can produce a more realistic rainfall runoff outcome than a less detailed surface. Furthermore, the accuracy can be increased by raising the level of complexity of the simulations. Technically, there are no limits to the richness of detail, e.g. the number of particles, or building geometry. However, the complexity goes along with processing power and time. The 3000 frames of the rain runoff simulation used in this case study take about two minutes to finish with a customary computer (i7, 4.0GHz). If one would increase the number of particles to get more accurate results, the simulation would take longer. The number of particles exponentially increases the processing time of the evaluations as well. Therefore, it is important to find the right balance between accuracy and speed. At least when the toolbox is used in a form finding process where fast feedback is essential for evaluating many different options. Nevertheless, on the same hand, it makes sense to increase the level of complexity for the simulation when the variety of proposals has shrunk.

Another aspect one needs to consider is the size of the investigated area. To get precise results one may use a terrain that is larger than the actual site. In fact, the results become more accurate by increasing the investigated area. The surroundings have a direct impact on the investigated design (see Figure 2; the blue flow-paths are directed along the terrain and the layout of the buildings). Terrain and other solid geometry like buildings channel the runoff into a certain direction and therefore affect everything beneath. For

the case study, we used a terrain that is about 80% larger than the design proposal.

As it is commonly known, water is a fluid. For the evaluation of the rain-runoff inundation, this means that the situation is always changing until it settles. To represent reality, it would be necessary to evaluate every stage. Since this approach would take too long, one must find the balance between time and accuracy. As stated above, we used two stages to evaluate the proposals of the case study. The simulation is executed with 1000 respectively 3000 iterations to perceive the conditions after two different periods of time. After 1000 iterations, the toolbox presents the situation during a rainfall event. After 3000 iterations, the simulation has progressed so far to represent the situation after a rainfall event.

Comparing the two planning proposals described above in more detail, the major shortfall of the second proposal can be found at the T-junction in the middle of the neighborhood (Figure 8). It is evident, that the arrangement of the buildings in the first proposal is more convenient at this place because the excess water can runoff along the street.

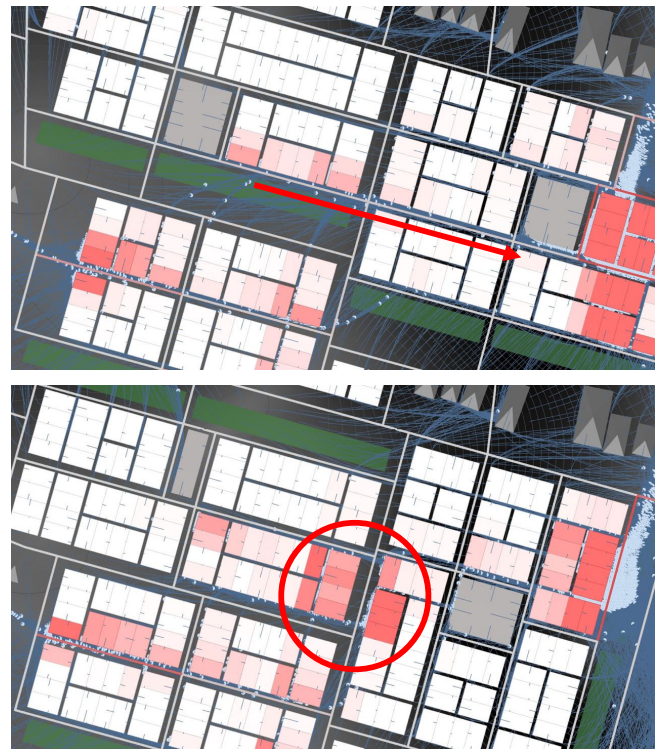


Figure 8. Comparing two identical extracts of the two proposals (presented in Figure 6) according to the rain-runoff simulation. The figure shows the situation amid the neighborhood. In the first proposal, the water runs downwards to east along within the street network (see arrow). In the second proposal, the water accumulates amid the neighborhood because it is blocked by the housing units (see circle).

Therefore, to ensure the discharge of rainwater, planners can adopt the layout of the first proposal because it provides a better drainage in this area.

Both examples prove that the SRTF provides information about the status of flooding-resilience for urban inundation. Combined with the evaluation of the street network one can assess the functional capacity of a city's infrastructure. In the viewport, it is visible, which parts of the neighborhood are cut off due to inundation. This information is essential to evaluate the resilience status of a city since the street network facilitates its operability. Moreover, the toolbox reflects the situation on site and provides feedback about the spatial layout. The outcome of the rain-runoff inundation evaluation constitutes essential information for further planning intentions.

Besides urban inundation, the toolbox is also developed to evaluate the risk of erosion due to rain-runoff. This helps to mitigate fast runoff and therefore the risk of damages caused by erosion, debris, and landslides. Urban planners can take this information into account when developing buildings, neighborhoods or cities. The toolbox visualizes the evaluation by means of the flow paths. Combined with the description of the velocity the user gets profound data for the area. For example, at first sight, the situation looks in favor of the first concept when comparing the proposals about the rain runoff erosion risk. Hereby, the first concept seems to perform better because the affected area is smaller. But as it is visible in Figure 3, the runoff in the east gets slowed down by the green space in front of the houses. That means that the buildings are not harmed by the debris. By contrast, in the first proposal, the overall area at risk is less but the buildings that are affected are hit directly by the fast runoff.

Additionally, Figures 6-7 depict the outcome of the tidal & river flooding simulation. The legend in Figure 6 states, that the first concept hosts its housing units in a way that during a high tide of 8 meters, there are 32 buildings flooded. At the same water level, there are only 25 buildings at stake in the second concept. This means that 7 homes can be saved from severe damages due to flooding by changing the spatial layout. Combined with the results of the mean risk assessment, the findings demonstrate that the second concept is not perfect but more suitable a tropical town in case of a tidal flooding event.

5 CONCLUSION

The SRTF provides information about the status of flooding-resilience for urban inundation, tidal and river flooding. The rain-runoff simulation provides information about the status of inundation and the level of erosion in the area. On the one hand, this information is valuable because it enables the user to foresee the properties of a specific spatial layout during or after a rainfall event. One benefit is obvious: In order to eradicate insufficiencies within an urban system, it is necessary to detect them. The toolbox presents all necessary information visually so the user can get an exact image of the advantages and deficiencies of a design concept. In the same manner, the user is provided with information that allows rating certain layouts according to its characteristics towards rain-runoff. As shown in the case study, the second layout is

more suitable for the area regarding the rain-runoff inundation risk. As it is shown in the images (Figure 2), the second neighborhood would suffer less during a heavy rainfall event. After 3000 iterations, the number of housing units that encounter a risk of inundation decreases about 20. A similar discrepancy applies to the street network. There are 6 segments fewer affected in the second proposal. Hence, by choosing the second proposal over the first one, the damage caused by a heavy rainfall event could be reduced by more than 50 percent. It also indicates that the effort of implementing stormwater infrastructure is higher in the first concept because there are more insufficiencies within the urban system.

We want to clarify that the approach that is presented in this paper is not intended and able to replace the actions carried out by hydraulic engineers but instead it should assist the urban designer or other non-hydrologists to analyze a site plan quickly and effectively or to implement measures for enforcing resilience during an early phase of the planning process. This means that urban designers can develop a concept with a realistic focus on flooding hazards.

The findings that are presented in this paper prove that the SRTF is construed to support decision making during the planning process of an urban development. It enables decision-makers to foresee the impact in advance which gives them the means to act when it is still possible. For example, the mean risk evaluation provides useful information about locations that are not endangered by flooding and therefore suitable for e.g. housing units. Alongside comes the ability to divide a plot into parcels with different functions. For example, locations with a high risk of inundation are not suitable for housing or commercial estates but rather can be used for green spaces or public spaces with mobile structures such as markets. With the SRTF, it is easy and fast to locate such places.

In conclusion, it can be said planning in flood-prone areas is a complex task. There are many issues that need to be taken into account in order to plan a site effectively. One crucial factor hereby constitutes the orientation and the arrangement of the buildings. Conventional planning techniques without computational assistance are reaching their limits in such a context. The SRTF overcomes this issue. The findings prove, that its usage provides a convenient approach that assists users to enforce flooding resilience for future urban developments.

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Further information and videos of the simulations can be found at:

<https://toolbox.decodingspaces.net/spatial-resilience-towards-flooding-hazards>

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16. <http://hydrobidlac.org>