



Urban SIS

D441.6.2.2 Use case urban flooding: Stockholm

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Table of Contents

| | |
|--|-----------|
| 1. Purpose of the study | 5 |
| 2. Method | 5 |
| 2.1 Design of method | 5 |
| 2.1.1 Model comparison setup | 5 |
| 2.1.2 Temporal and spatial resolution | 6 |
| 2.2 Data requirements from Urban SIS | 7 |
| 2.2.1 Essential Climate Variables (ECVs) | 7 |
| 2.3 Additional input data | 8 |
| 2.4 Data adaption | 8 |
| 3. Result | 11 |
| 3.1 Demonstration of urban runoff modelling using the hydraulic model | 11 |
| 3.2 Modelling of historic rainfall over entire Stockholm | 12 |
| 3.3 Consequences of spatially non-uniform rainstorms | 13 |
| 3.4 Modelling of future rainfall using scaling factors | 16 |
| 4. Discussion and recommendations | 17 |
| 4.1 Accuracy | 17 |
| 4.2 Delimitations | 18 |
| 4.3 Assumptions | 19 |
| 4.4 Suggestions for further studies | 19 |
| 4.5 Area of use for an advanced end user | 20 |
| 4.6 Area of use for a non-technical end user | 20 |
| 5. Conclusion | 21 |
| 6. References | 21 |



1. Purpose of the study

The Urban SIS case study for Stockholm city is a modelling demonstration of using spatially and temporally distributed rainfall inputs to urban flooding modeling. The outcomes include urban flooding modelling using downscaled, high-resolution precipitation data for historical time series, as well as information regarding precipitation patterns in future climate conditions. The high temporal and spatial resolution of the precipitation data in the Urban SIS web portal (<http://urbansis.climate.copernicus.eu/>) provides information regarding how rainfall patterns vary in space and time, which provides extensive information regarding how to choose and generalize rainfall data for dimensioning purposes – even though these matters require more method development.

The decision support that we as advanced end-users need, is high-resolution precipitation data, which pedagogically demonstrate some of the complexities related to rainfall/runoff modelling – but we also need rational, scientifically based methodologies for how to generalize these heterogeneous rain events. The main purpose of this study is to investigate how to select the rain events for which to adapt the infrastructure and build cities that are safe and reliable in the present as well as the future climate. A secondary objective is to assess how to move between the high-resolution Urban SIS data and standardized rain descriptions e.g. block rains and/or CDS-rains.

The temporal and spatial scale presently used by end-users (eg. municipalities, county boards etc.) is generally less detailed than the data provided in the Urban SIS project, for example block rains and/or CDS rains. For these types of users, applying the Urban SIS data explicitly may not be a feasible way forward to model specific rains. Our study is a first step towards investigating if the high-resolution Urban SIS data can be used as a better, scientifically based basis for how to choose appropriate dimensioning rain events (block rains and/or CDS rains).

2. Method

2.1 Design of method

2.1.1 Model comparison setup

The rains that have been modelled to generate flowpaths and flooding maps over Stockholm have been chosen in various manners. Apart from modelling a “large rain” over entire Stockholm City from the historical time series, the main efforts have been put on how to derive general dimensioning precipitation events from high-resolution data, and how to translate these into future conditions.

- Modelling of historic rainfall for the rain event of Aug 23rd 2006 for the entire geographical entity of Stockholm City, to investigate the consequences of a rainfall event with large magnitude and short duration, which influenced a large proportion of the modelled domain



of Stockholm City. The rainfall event used occurred on August 23rd 2006, with a peak at 09:00 (07:00 GMT + 2 hours).

- Modelling of future rainfall using generic scaling factors - the presently recommended factor in sewer system design 1,25 (Svenskt Vatten, 2016) as well as a more extreme coefficient of 1,5 chosen in collaboration with SMHI (based on general differences between rainfall statistics from the Urban SIS data of historic and future climates, respectively). The upscaling was made to, in a generalized way, represent more extreme future precipitation conditions), the purpose being to demonstrate possible effects in term of urban flooding, caused by increased precipitation due to climate change. The main focus is put on end-user applicability and how to possibly improve/update the current practices as a result of the outcomes of the Urban SIS project.
- Comparing rainfall events from the historical periods to precipitation measurements, with the goal to develop a methodology of how to characterize and describe rains in terms of return periods and durations. The purpose of this has been to facilitate and clarify some characteristics like e.g. return period, to be used for dimensioning purposes (in present as well as future climates).
- Investigate consequences of having rainfall events that vary spatially, compared to the common practice of using spatially uniform rains (with “peak intensity”) over the entire modelling domain – a methodology which often overestimates total rainfall as rainstorms in reality generally are highly non-uniform spatially.

2.1.2 Temporal and spatial resolution

The supplied precipitation data is presented in 15 minute intervals, which is a higher temporal resolution than what generally is available for rainfall modelling.

The geographical domain included in the Stockholm case study is delimited by the borders of Stockholm City (Stockholm Stad), see red delineation in Figure 1. The geographical resolution of the modelled raster cells is 4 x 4 m². The precipitation input data is however supplied in grids of 1 x 1 km², which implies that the spatial resolution of the land cover and the urban hydraulic flooding model has an even denser spatial resolution. The total modelled area for the Stockholm use case is about 220 km², and comprises about 13 million raster cells (in the 4 x 4 m² resolution).

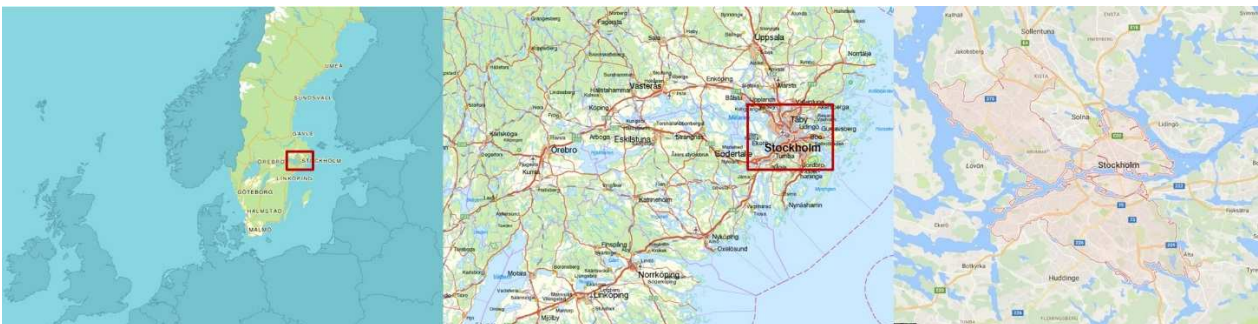


Figure 1 - The location and delineation (in red) of the modelled area in Stockholm City.

To be able to perform several different modelling scenarios despite time constraints, the latter part of the modelling task was made for a smaller geographical domain, specifically for two sub-catchments within the inner city of Stockholm. Both catchments - Rålambshovsparken (0,41 km²) and Berzelii Park (1,83 km²) - were chosen as they are located in low points close to the sea surface and that they are well-known areas for inhabitants of Stockholm as well as visitors, where many people often are gathered. The locations of these two sub-catchments are displayed in Figure 2.

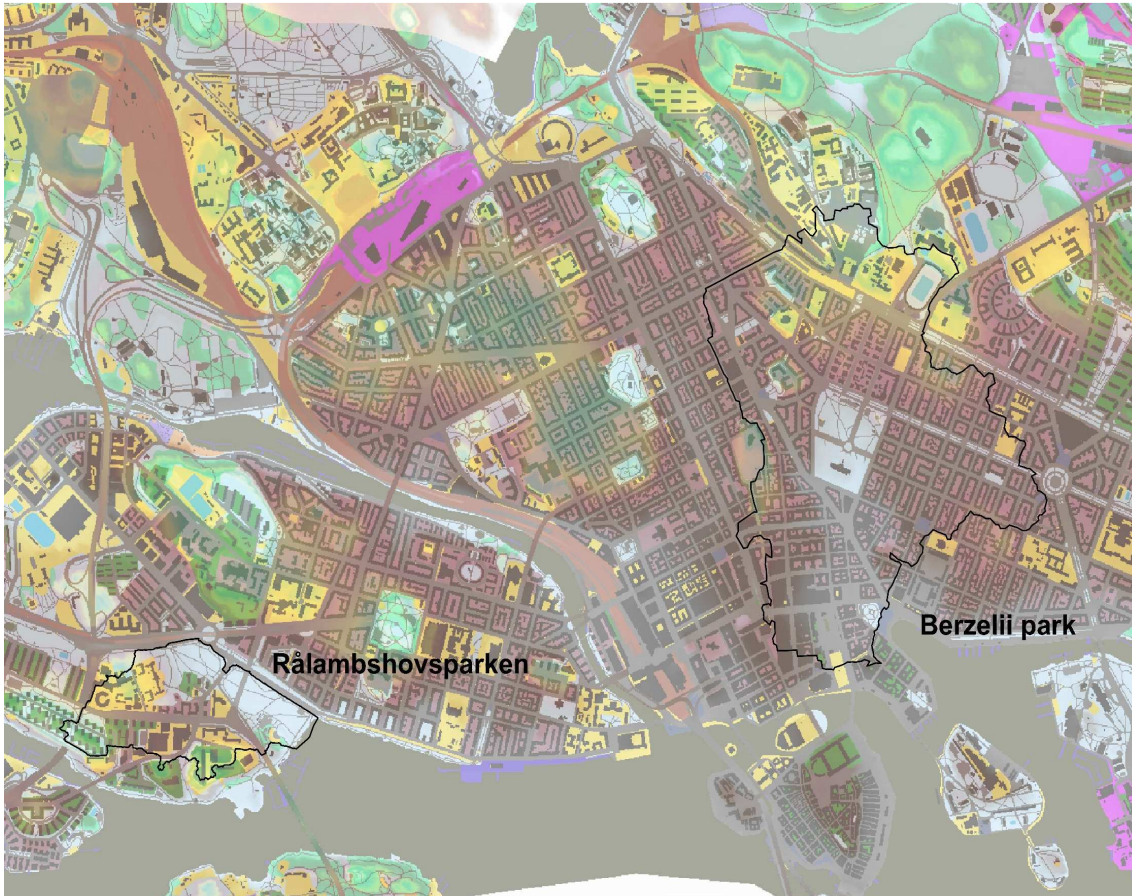


Figure 2 - The location and delineation of the two subcatchments in Stockholm City modelled for several scenarios, Rålambshovsparken (west) and Berzelii Park (east).

2.2 Data requirements from Urban SIS

2.2.1 Essential Climate Variables (ECVs)

The only ECV used for the urban flooding modelling case is the precipitation data from the Urban SIS web portal. Several rainfall events were chosen to represent “large rains” with different properties and characteristics. Initially, there was an intention to also use the high-resolution soil moisture data from the Urban SIS portal, however, this was not applied in this project due to time constraints and limited previous knowledge on how to combine this information with the modelling strategy of the MIKE model (section 2.4).



2.3 Additional input data

Additional input data required to run the urban flooding model include data from a land use map supplied by Stockholm City (*Stockholm Stads stadskarta*), and a terrain model based on Lidar data with a resolution of $1 \times 1 \text{ m}^2$. A runoff coefficient (Stockholm Vatten, 2015) is assigned to each land use class, and by combining the land use map with the general runoff coefficient, the infiltration capacity can be determined in each cell.

To be able to draw conclusions regarding statistical characteristics of the studied rain events in terms of recurrence intervals and durations, the Urban SIS precipitation events were compared to statistics of measured rainfall in the region of southeastern Sweden.

2.4 Data adaption

The precipitation data over the Stockholm City area was adapted in several ways to become the desired input data to the surface runoff model. The precipitation, given in grids of $1 \times 1 \text{ km}^2$ was downscaled further to a spatial scale of grids of the size $4 \times 4 \text{ m}^2$. On the spatial scale of the input data to the model, runoff coefficients were assigned according to the land use type as provided by Stockholm City (*Stockholm Stads stadskarta*).

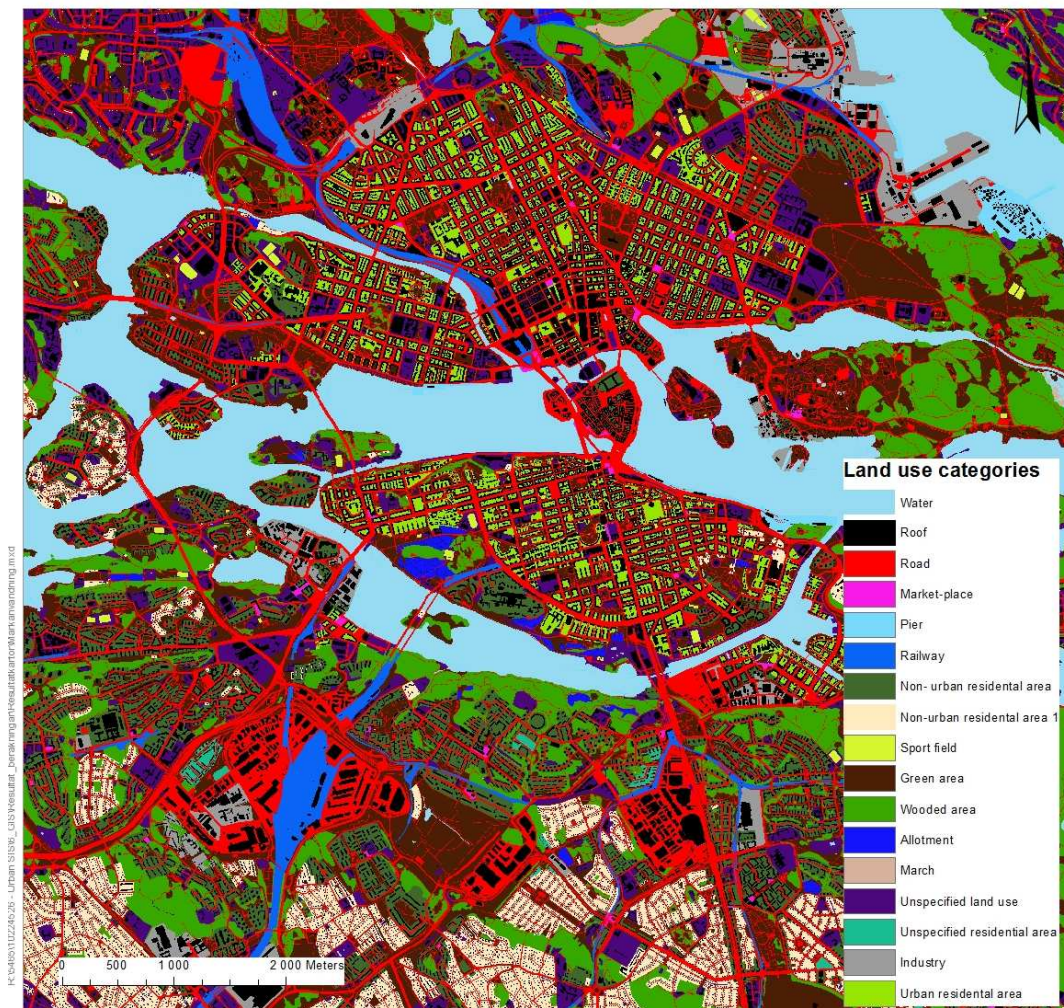


Figure 3 - Land use distribution (giving rise to different runoff coefficients) within central Stockholm City as used as inputs to determine infiltration capacity and roughness for the respective types of land use (source: the land use map supplied by Lantmäteriet combined with runoff coefficients as described by Stockholm Vatten, 2015).

The precipitation data from the Urban SIS web portal has been downloaded as a raster grid for every timestep and imported into a GIS system where the major part of the data processing was made.

The precipitation data is combined with infiltration capacity, so that only excess water contributing to surface flow is entered into the hydraulic model MIKE21. Additional losses due to the filling of the stormwater network are also subtracted from the precipitation in quantities corresponding to a rain event with a 5-year return period. By multiplying the precipitation in each grid with the runoff coefficient of each of the 4 x 4 m² grids, the precipitation lost as infiltration is quantified in each grid, and the remaining excess precipitation is entered into the hydraulic model. The used hydraulic model has previously been set up in a project performed with Stockholm City, and the model is used with the permission of Stockholm City.



The input data used in the MIKE21 model is the precipitation from the Urban SIS portal, in a gridded resolution of 1 x 1 km², using timesteps of 15 min. This fine resolution in both space and time is much higher than in the types of urban flood modelling that are commonly made for Swedish conditions.

3. Result

The modelling of the surface runoff as a consequence of the rain event of Aug 23rd 2006 was made for entire Stockholm City (figure 5). All other modelling scenarios were made for two smaller sub-catchments in central Stockholm – Berzelii Park and Rålambshovsparken (figure 2). As the general behavior, as well as the land use characteristics (the ratio of parks, buildings etc.) of the two catchments were similar, only one of these are presented further in this report - Berzelii Park.

3.1 Demonstration of urban runoff modelling using the hydraulic model

In figure 4, a detail from the hydraulic MIKE model is displayed to demonstrate how the urban runoff is modelled. Here, an example comprising parts of the Berzelii Park subcatchment is used.

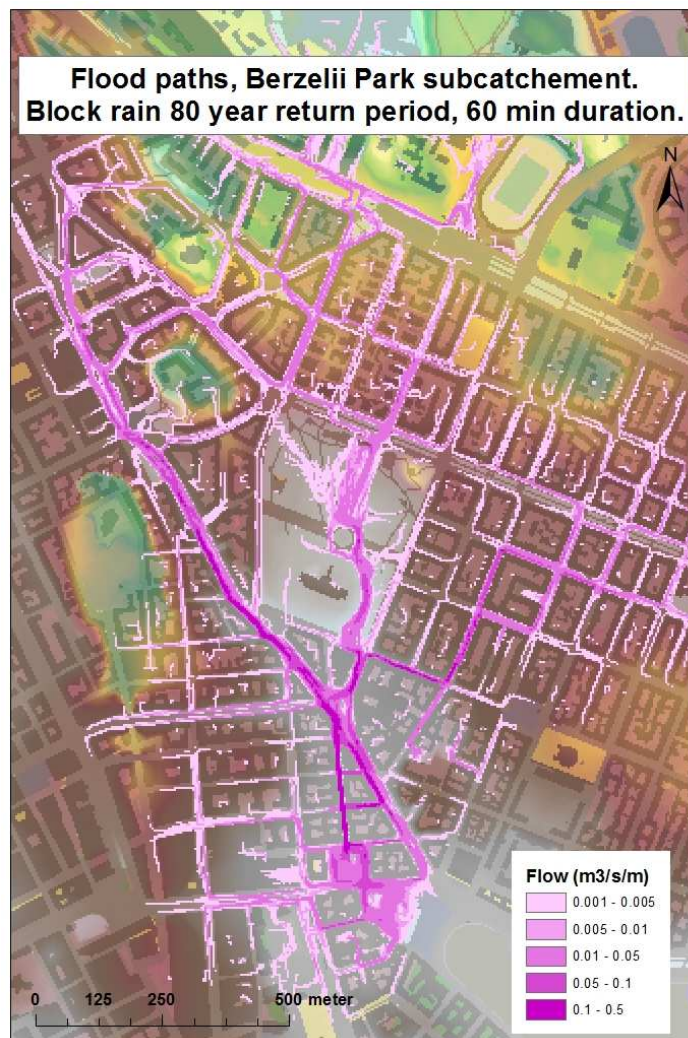


Figure 4 - Urban flooding modelling demonstration for the Berzelii Park subcatchment in the Stockholm City Centre.

3.2 Modelling of historic rainfall over entire Stockholm

The historical rainfall event chosen for the modelling demonstration has a duration of little more than two hours, and to simulate the runoff event in its entirety, the model is run for several hours after the time when precipitation ceases. The flooding maps over Stockholm City are presented for the rain event of August 23rd 2006 (figure 5), showing urban flooding with the most profound flooding effects shown in depressions/low points.

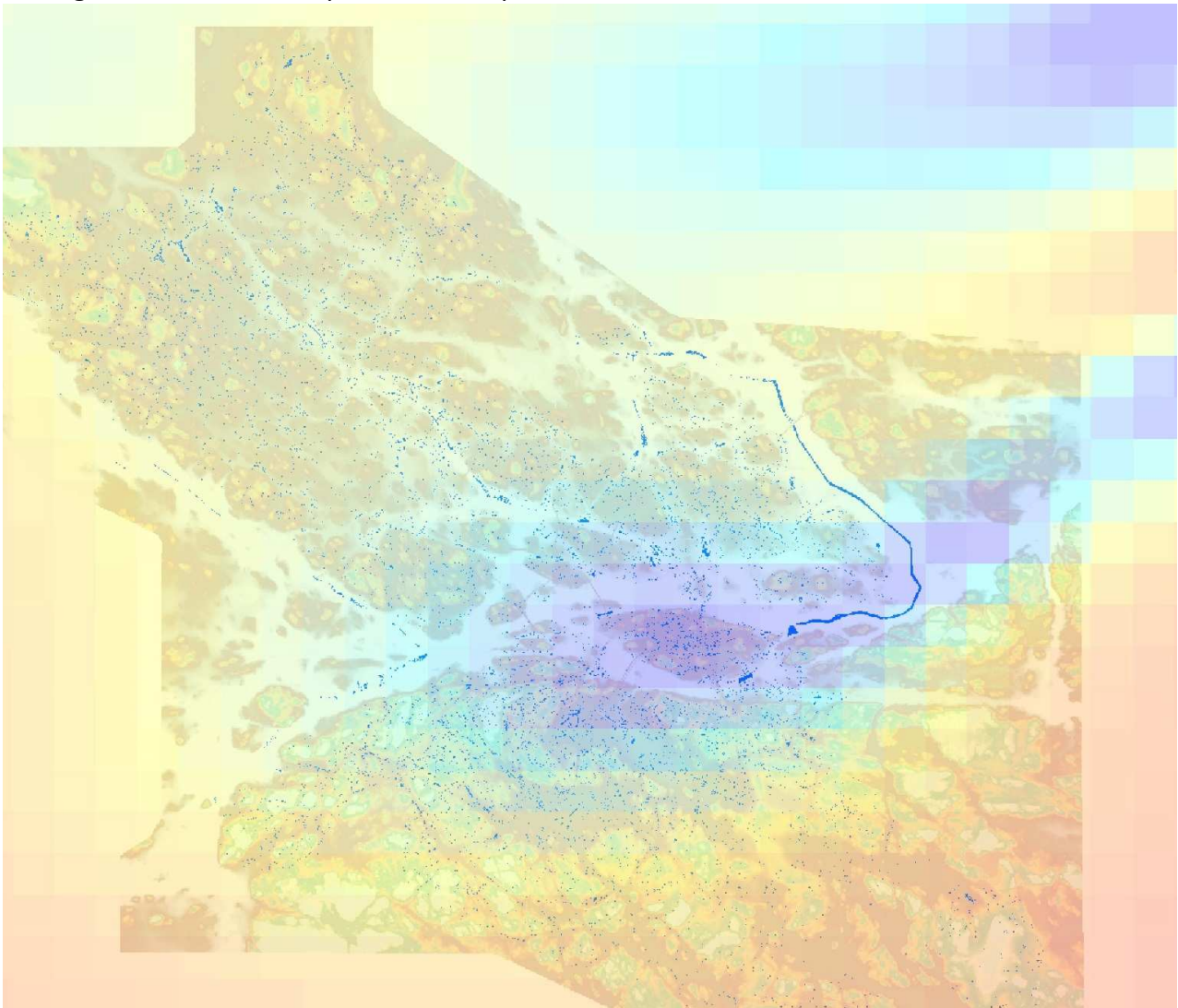


Figure 5 - Urban flooding modelling for the entire spatial domain of Stockholm City (figure 1) using the Urban SIS rain event of August 23rd 2006. The coarser color grid shows the Urban SIS precipitation data for one of the modelled timesteps, where blue grids demonstrate the largest amount of rainfall. The gridded precipitation data is in an overlay layer over a topographic map where brown areas corresponds to a higher area and where green areas represent areas close to sea level. The blue “dots” are the results of the hydraulic modelling, showing flooded areas on a very fine topographical scale (4x4 m²). The reason that blue fields are sometimes seen in the waters of Lake Mälaren and the Baltic Sea is due to boundary effects and the model setup.

3.3 Consequences of spatially non-uniform rainstorms

Comparisons were made between spatially non-uniform rainstorms from Urban SIS and uniform rainstorms using similar characteristics (regarding duration and recurrence intervals). This was done in several ways: by using the precipitation Urban SIS rain event of August 23rd 2006 and comparing this to a spatially uniform rain event in the same duration (i.e. the same amount of precipitation falling over the same time period but in a spatially uniform rain as a block rain). The urban flooding effects of this comparison for the low point of the Berzelii Park sub-catchment are shown in figure 6. These results show a larger degree of flooding using the Urban SIS rain as input data, as the high-resolution rainfall data has a maxima in this area. Correspondingly, the Urban SIS rain would give smaller flooding effects than when using the averaged block rain input, in other parts of the city. This modelling exercise gives an example of the risks of using averaged block rains for modelling of urban flooding – that rainfall undoubtedly will be underestimated in parts of the geographical domain, while overestimated in others. Parts of the differences in flooding extent may also be a factor of the different temporal distributions of the two compared rainfall scenarios.

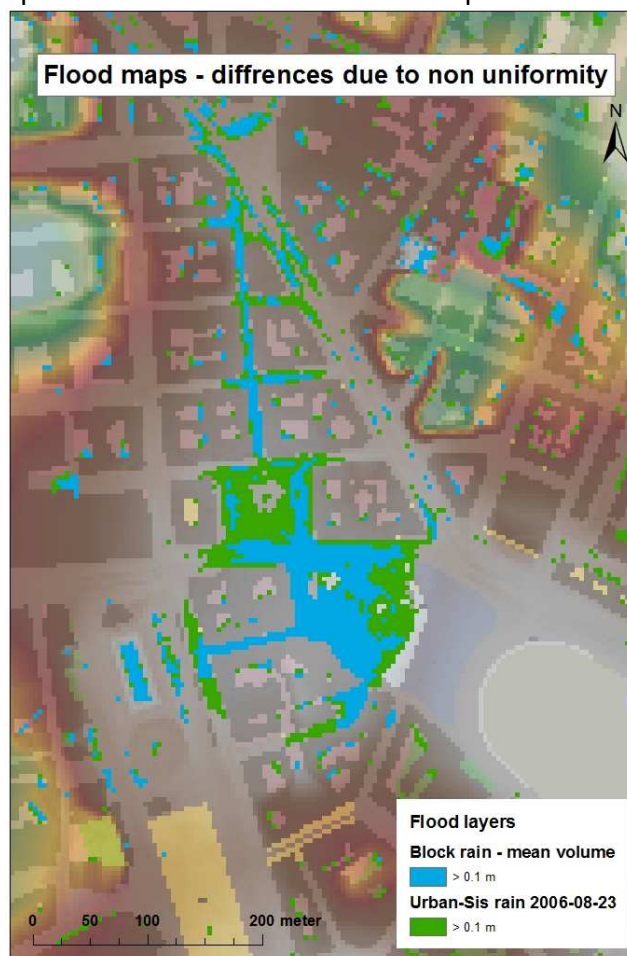


Figure 6 - Urban flooding effects in parts of the Berzelii Park using the Urban SIS rain event of August 23rd 2006 (green) and a block rain (blue) which over the entire Stockholm area gives the same precipitation volume. The blue layer is displayed on top of the green layer, and all blue-colored areas are also flooded for the green scenario – implying that the flooding is always equal or less for the blue scenario than for the green scenario in this particular area.



However, the non-uniformity in time and space of actual rainfall – as demonstrated by the Urban SIS data, poses difficulties for the end-users when trying to decide on which rains to use for dimensioning purposes. By comparing the Urban SIS data for the rain of August 23rd 2006 to precipitation measurements in the region of southeastern Sweden, it was shown that the rainfall in the 1 x 1 km² grid cell that has the “worst” rainfall corresponds to a rain with a return period of 80 years and having a duration of 60 minutes. When looking at other durations (eg. 15 min, 30 min and 2h) of the chosen rain event, and comparing the rainfall in the grid that for the chosen duration received the most rainfall to rainfall statistics, the recurrence times for the other investigated durations were shorter than for the maximum 60 min rain (80 years).

Another modelling scenario was carried out for the two smaller sub-catchments to compare the flooding effects Urban SIS rain to a block rain (over the entire domain) with a return period of 80 years and a duration of 60 minutes. As this recurrence interval and duration is valid for the grid having the most extreme precipitation, this thus implies that the rainfall will be overestimated in all other grid cells.

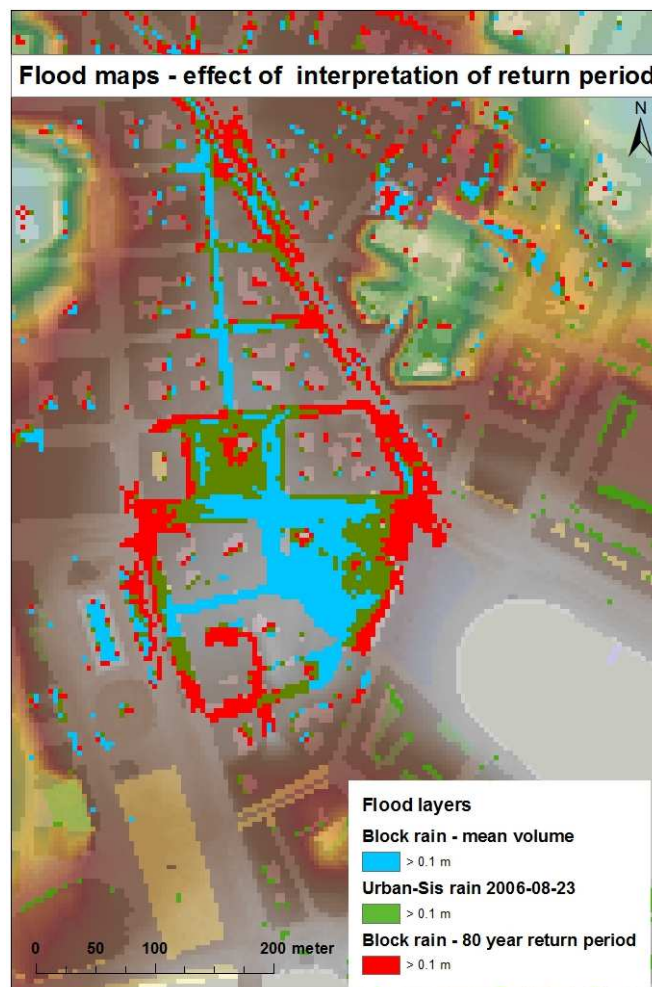


Figure 7 - Urban flooding effects in parts of the Berzelii Park using the Urban SIS rain event of August 23rd 2006 (green) and a block rain (blue) which over the entire Stockholm area gives the same precipitation volume, as well as a block rain having the same characteristics as the grid receiving the most precipitation (red).

This demonstration (figure 7), as well as the results of figure 6 demonstrates the difficulties when moving from the high-resolution precipitation data to more standardized rains (for example block rains and/or CDS rains) which are usually used for dimensioning purposes.

Commonly, it is assumed that a rain with a certain *local* recurrence interval (often 100-year-rain) falls over the entire city (/model domain) – an assumption that the Urban SIS data shows is extremely unlikely and which will most probable lead to severe overestimations of flooding. The cause of the discrepancies shown in figures 6 and 7 is of course that the Urban SIS data (as well as real rains) is very heterogenous in time and space, as also demonstrated in figure 8, where the rain event of August 23rd 2006 moving over Stockholm is shown.

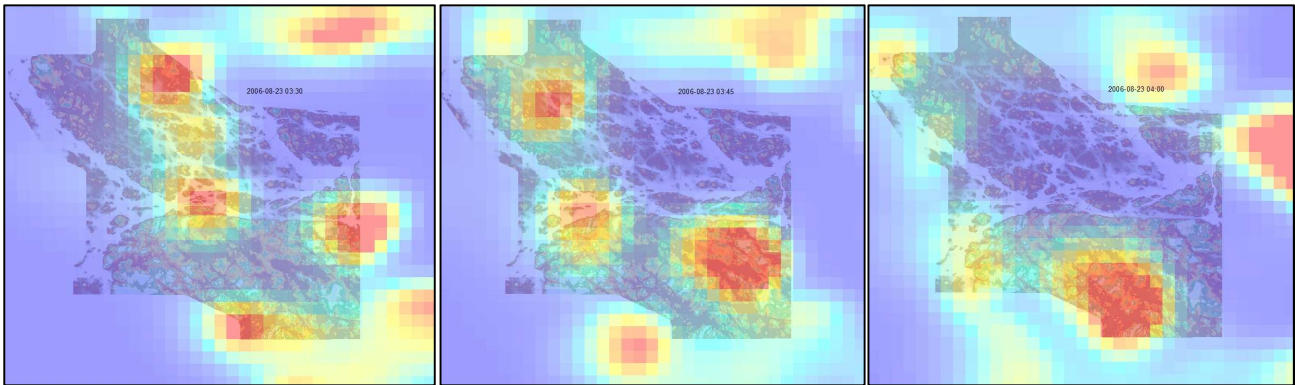


Figure 8 - A visualization of the heterogeneity in space and time for parts (three consecutive 15-min timesteps out of the total ten) of the Urban SIS rain event of August 23rd 2006 (03:30 to 04:00).

When summarizing the rain of August 23rd 2013 for each grid cell and over all ten timesteps, a geographical distribution as shown in figure 9 appears. The figure shows clearly that the sum of rain that falls during this rain is also highly heterogeneous. Averaging the rain over the entire domain gives that the mean rainfall in every cell is 20.7 mm. As a comparison, the cell that receives the most rainfall receives 41.1 mm.

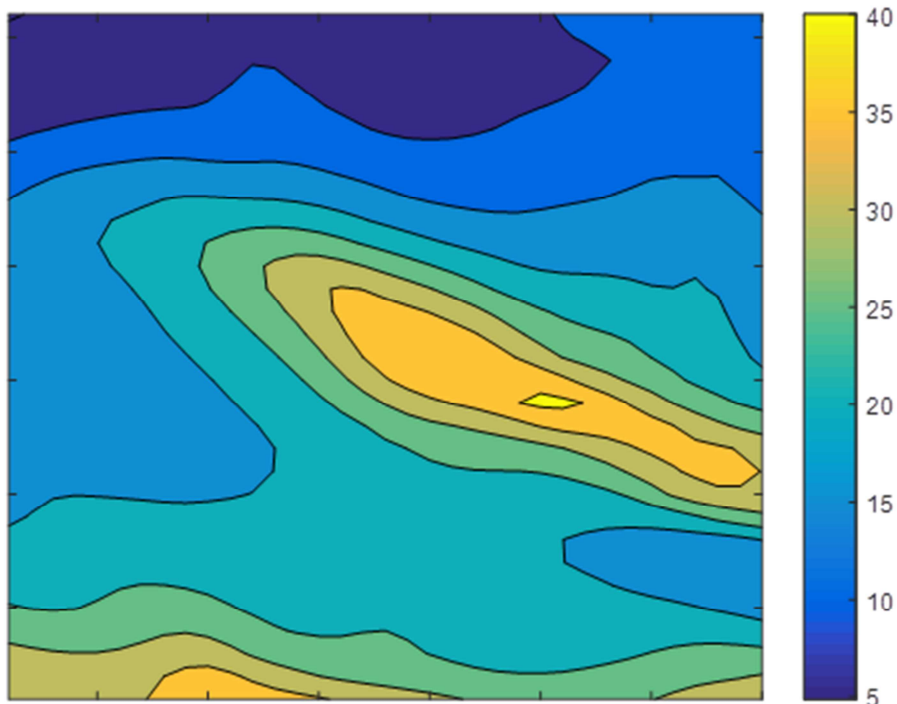


Figure 9 - The sum of rainfall over Stockholm for the Urban SIS rain event of August 23rd 2006, showing large spatial heterogeneities.

3.4 Modelling of future rainfall using scaling factors

To be able, in a generalized manner, to use the Urban SIS data to compare flooding effects in present and future climates, one would need a more developed methodology to be able to make the coupling between present day rains and recurrence (/duration) statistics and future rains having the same properties as the present rains, but for the future climate. As this is not easily done, and furthermore require more method development and statistical analyses than feasible within this project, modelling representative conditions in a future climate was done by scaling the Urban SIS rain of August 23rd 2006 using climate factors of 1,25 (as common current Swedish practice) and 1,5 (representing a more extreme scenario, as indicated by the Urban SIS projection, see D441.3.6). The results of these different modelled scenarios are shown in figure 10. As the runoff/infiltration is modelled linearly using a coefficient, the resulted flooded volume will be directly proportional to the used climate factor.

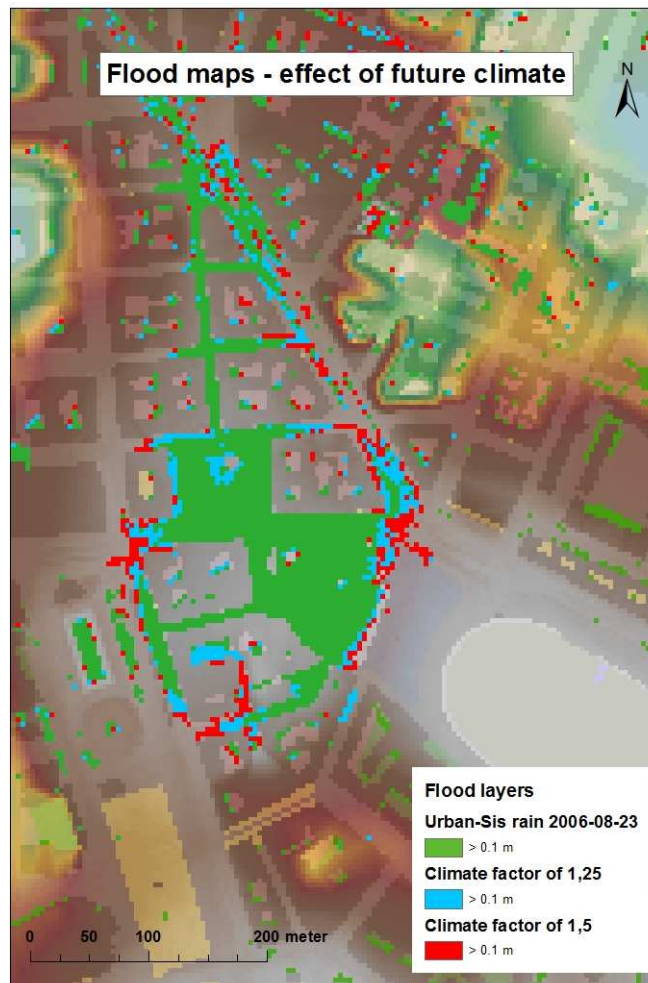


Figure 10 - Urban flooding effects in parts of the Berzelii Park using the Urban SIS rain event of August 23rd 2006 (green) and climate factors of 1,25 (blue) and 1,5 (red) respectively. For this modelling demonstration, the differences regarding the resulting flooding are evident but not major.

4. Discussion and recommendations

4.1 Accuracy

The accuracy of the urban flooding model depends on the quality of all the input data, as well as the assumptions being made. The high-resolution precipitation data from the Urban SIS portal provides detailed knowledge regarding precipitation, however, with little knowledge about accuracy (however, another parallel deliverable D441.5.4.2 will discuss visualization of uncertainties in Urban SIS data). Other input data used is land use (one land use type assigned to each of the 4 x 4 m² grids), and general runoff capacities assigned to each of the land use classes.

The runoff capacities used are based on generic values based on values assigned in the publication P110 (Svenskt Vatten, 2016) which may be associated with some uncertainties. Also, the stormwater system has not been explicitly included in the model, however – the losses of surface runoff due to stormwater drainage in pipes has been generically described as a loss. Reduction of



the water volumes due to infiltration as well as stormwater system are made in a relatively coarse way and could be made more sophisticated. This could for example be made by allowing for time-dependencies, e.g. that the infiltration capacity of the surface decreases over the course of a rain, which is not included in the current model setup (which assumes uniform losses throughout the entire rain).

The digital elevation model (DEM) being used to determine gradients and flow paths is based on Lidar data with a resolution of $1 \times 1 \text{ m}^2$ provided from Stockholm city (when WSP created the MIKE 21 model of Stockholm city in 2014-2015).

Given that the model was run for the urban area of Stockholm City, where lots of construction and re-construction works are being made, the data regarding land use and the DEM – both held constant - may not have been entirely up-to-date and accurate over time. This, together with the assumptions related to the infiltration capacities as well as inaccuracies when quantifying the losses of surface runoff due to the stormwater systems below ground, may lead to inaccuracies on the detailed scale. Also, the resolution of the terrain model ($4 \times 4 \text{ m}^2$) implies that not all topographical structures that may influence the surface water flow paths may be included.

These are all reasons that the results of this urban flooding modelling should only be used for general flood analysis and not for detailed urban planning.

4.2 Delimitations

The delimitations regarding the urban flooding modelling have mainly been due to time constraints as the simulations are highly time consuming. To be able to run several different scenarios, the initial modelling domain of entire Stockholm city was reduced into two main sub-catchments (Berzelii Park and Råambshovsparken) for which several different scenarios were modelled.

A main constraint has been the limited methodology regarding high-resolution precipitation data – that no rainstorm is identical to another one. This implies that the idealistic thought of finding “two similar rains” (in historic and future conditions respectively) is not possible. This difficulty lead to us focusing on i) the differences in flooding effects when using uniform and non-uniform rains respectively, as well as ii) strategies regarding how to characterize rainstorms that are non-uniform in time and space, i.e. “how do you determine the recurrence time of a particular rain event?”.

Another delimitation regarding urban flooding conditions, apart from how to choose an appropriate rain event, is that the outcome in terms of flood mapping is also a function of initial conditions and other factors. This implies that ideally a multitude of scenarios should ideally be modelled. Again, the modelling time is a constraint here, as modelling of a multitude of different scenarios for an entire city is generally not possible.



4.3 Assumptions

Assumptions made while modelling are primarily related how to quantify the losses of water, i.e. determining the quantities of the precipitation which do not contribute to the surface runoff. This comprise that the effects of stormwater systems has been included implicitly as a general loss (quantified as a rain event with a 5-year return period), and that the runoff coefficient is constant over time, i.e. that it does not diminish through the course of the rain.

As no possible calibration of the hydraulic (flooding) model has been made, the model outcomes should be interpreted on a general rather than detailed level.

4.4 Suggestions for further studies

Throughout the project, several suggestions for further studies have been identified, comprising:

- More information regarding statistics of high-resolution rainfall in historic and future climate to provide basis to general climate compensation methodology. For example by using precipitation scaling coefficients which may vary with for example spatial scale, duration as well as geographical location. For comparison, in Sweden – a generalized climate compensation factor is usually used, which rescales the rain increasing the total precipitation with the factor 1,25 (Svenskt Vatten, 2016).
- Development on formalized methodologies on how to characterize high-resolution rain events in terms of recurrence intervals and duration. The recurrence interval varies from cell-to-cell, which for a normal end user provides too much information – instead, a classification system to make a condensed classification of an entire rain (over many grid cells) is desirable. A desired result of these studies could for example be to determine a specific dimensioning rainstorm event for Stockholm with a return period of 100 years.
- Improved development of methodologies for end users regarding how to choose appropriate dimensioning precipitation events.
- Improved flooding modelling using more detailed descriptions of infiltration and soil moisture for example: non-uniformity in time, allowing for runoff calculations as functions of rainfall intensity and duration. Also, how to implement other high-resolution data from the Urban SIS portal, such as for example soil moisture, into the urban flooding modelling routines.
- Improved flooding modelling using more detailed descriptions of stormwater network.
- Further modelling, investigating the effects of differences in infiltration capacity due to other soil moisture conditions in a future climate.
- Effects on total urban runoff/flooding of different rainstorm properties, for example – are there general differences to be found that can be coupled to the direction and velocity of the passing rainstorms?



4.5 Area of use for an advanced end user

Advanced end users (such as for example WSP consultants who have performed this sub-part of the Urban SIS project, the Swedish Civil Contingencies Agency (MSB), stormwater specialists and risk managers at municipalities and County boards etc.) can benefit from Urban SIS data mainly by offering more detailed information regarding characteristics of “large rains”, on a fine spatial and temporal scale. This provides additional information as a complement to (and further development of) the generally derived rains that now commonly are modelled.

Data from Urban SIS could also be used for model calibration/validation for occasions for where there are historic measurements of water levels etc. in Stockholm City.

A potential further use is being able to run many modelling scenarios, using a catalogue of rains from Urban SIS data, to determine “worst probable” conditions. This type of extended scenario analyses can be of use to make quantitative assessments regarding the likelihood of several areas in a city/municipality to be affected by flooding at the same time. This in turn can be of great use for contingency planning, and vulnerability analysis of Stockholm City; for example “what is the risk of all major hospitals to be inaccessible due to urban flooding at the same time”?

4.6 Area of use for a non-technical end user

For the non-technical end-user (e.g. non-specialists at municipalities, administrative/government authorities, county boards etc.), the entirety of the governing factors behind urban flooding are generally very complex to grasp, which gives the expert/consultant performing the analysis a pedagogical challenge in how to simplify the problem and formulate it into a context that is understandable even for a non-specialist. This is one of the reasons that translations of the high-resolution data into more standardized descriptions such as uniform (constant intensity) block rains and/or CDS-rains became a focus point in this project.

The Urban SIS web portal gives a clear and pedagogical view that/how rainfall can vary substantially even on small spatial scales, which makes a clear illustration of some of the complexities of urban flooding.

Information that these end-users can get from the increased spatial resolution of the climate data over urban centers includes more site-specific information regarding how likely the city is to be influenced by a rainstorm. Modelling urban flooding using the Urban SIS data, especially when being able to model a range of rainfall events, also gives indications regarding where in the city there are limiting structures/bottlenecks, which can give information regarding where it is most crucial to perform more detailed studies and investigate solutions to reduce negative consequences of flooding. When having a reliable hydraulic model, flood mitigation measures can also be evaluated - i.e. to optimize flood protection solutions, by e.g. infrastructure and/or by allowing certain areas to be flooded during extreme conditions.



Looking at the historic and future data also provides a good explanation that the commonly used climate factor (adding 25% of the rain to represent precipitation in a future climate (Svenskt Vatten, 2013) is an approximation that should be used with some caution.

5. Conclusion

The demonstrations in the case study have both methodological and practical benefits. For the end user Stockholm City, the identification of vulnerable areas prone to flooding after intense rainfall is of course a result. With simulations with an Urban SIS rain event the city gets a more accurate evaluated risk (compared to conventional modelling using block rains and/or CDS rains that are uniform over the entire domain). This, as the Urban SIS data represents an actual (albeit non-validated) rain and not a rain only used for dimensioning. The results from the flooding model can thereby be compared to measured flood data (water levels and/or velocities) for calibration of the model so that that the hydraulic model becomes more accurate, and its results more reliable.

The performed study demonstrates the difficulties when moving from the high-resolution precipitation data to more standardized rains (for example block rains and/or CDS rains) which are usually used for dimensioning purposes. A main constraint has been limited methodology regarding high-resolution precipitation data – that no rainstorm is identical as another one. This implies that the idealistic thought of finding “two similar rains” (in historic and future conditions respectively) is not possible.

The Urban SIS data, for historical as well as future precipitation data forms, a scientific basis for improving dimensioning practices by finding and applying rains that can be said to be dimensioning events for a specific location (such as Stockholm City). Statistics comparing historical and future Urban SIS precipitation data can lead to scientifically based climate scaling coefficients for the Stockholm area, which vary with duration as well as with spatial scale of the particular modelled (sub-)catchment.

6. References

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