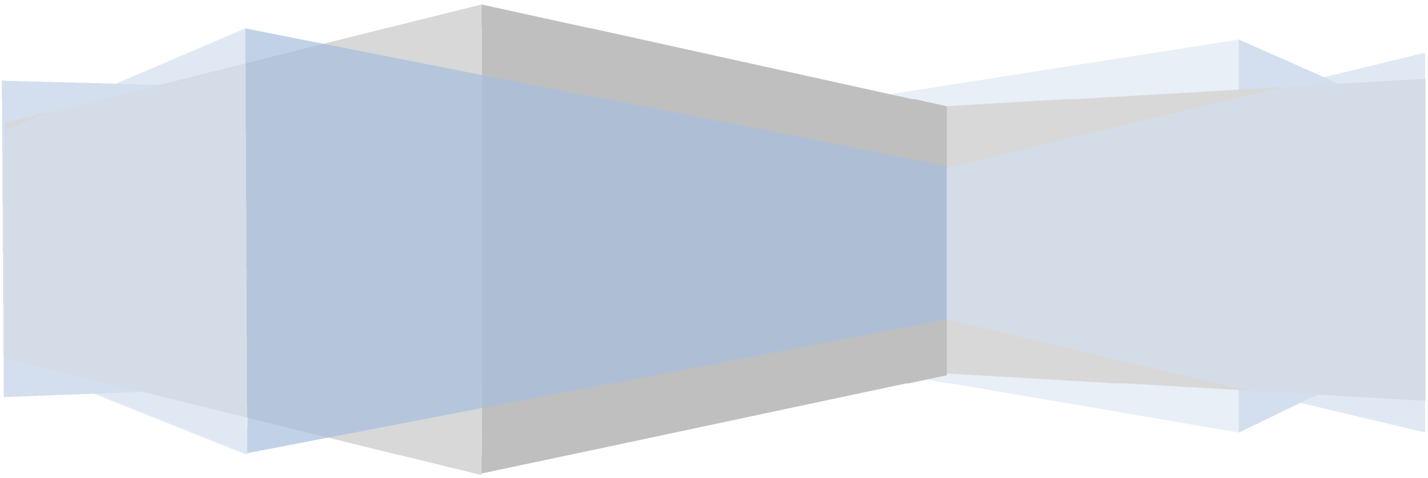
Water Challenges for a Changing World
Joint Programming Initiative

Report on
Flood model development

Work package 4: Urban flood forecasting

MUFFIN: Multi-scale Urban Flood Forecasting



MUFFIN: Multi-scale Urban Flood Forecasting

Editor of this report: Søren Thorndahl, Aalborg University
Authors: Jonas Olsson (SMHI), Rasmus Nielsen (AAU), Søren Thorndahl (AAU), Teemu Kokkonen (AALTO), Tero Niemi (AALTO), Marc Schleiss (TUD), Marie-Claire ten Veldhuis (TUD)

Date of submission: 01-15-2018

E-mail: st@civil.aau.dk

Project Website: http://www.muffin-project.eu/
Project code: WaterWorks2014-MUFFIN

Table of Contents

1. Introduction 3
2. The “large-scale” development (SMHI) 4
    2.1. The HYPE model 4
    2.2. Development in MUFFIN 4
    2.3. The forecasts 5
3. The joint case studies 7
    3.1. Aalborg (AAU) 10
        3.1.1. Case study area characteristics 10
        3.1.2. Precipitation data 12
        3.1.3. Hydrological data 13
        3.1.4. Model developments 14
    3.2. Rotterdam 16
        3.2.1. Experiments: 17
        3.2.2. Hydrological observations and studies: 17
        3.2.3. Rainfall sources: 19
    3.3. Helsinki 20
        3.3.1. Catchment descriptions 20
        3.3.2. Hydro-meteorological data 21
        3.3.3. Model development 23
4. References 25

1. Introduction

This report provides an overview of the flood modelling development of Work Package 4 of the MUFFIN - Multi-scale Urban Flood Forecasting project.

Multi scale flood forecasting experiments are set up, tested and compared across different case study catchments, spatial and temporal scales, and with different input and forcing data, catchment characteristics, etc. The main objective is to evaluate large scale flood forecasting against local fine scale catchment flood forecasting through joint case studies. By comparing accuracy and uncertainty in critical runoff/discharge, predicted flood prone areas, potential lead-time, etc. the two model scales (hereafter referred to at the two Hydro-models) are evaluated with regards to the resolution required of inputs and outputs and their potential in real time flood forecasting in urban areas.

The flood forecasting experiments are divided in two overall scales:

1. A large scale catchment setup of the rainfall-runoff routing model HYPE on local catchments. This setup will be customized to operate in high resolution for urban areas in the three case study catchments in Helsinki, Rotterdam, and Aalborg. In MUFFIN the HYPE model will be updated with a higher resolution and detail compared to the present setup of the pan-European E-HYPE model and the Swedish S-HYPE. This means a 1h temporal resolution, a higher level of detail with regards to surface elevation based on high resolution digital elevation models (DEM), as well as detailed description of land-use in urban areas in order to improve the prediction of runoff in urban areas. The setup of the HYPE model is described in detail in section 2.

2. A local catchment setup of local flood models. These setups are customized hydraulic distributed (2D) local flood models which includes relevant hydrological processes which are necessary to predict urban flooding in a high level of detail. The models will thus account for the urban drainage system, preferential water ways (roads, channels etc.), infiltration/runoff processes, etc. to a larger degree than in the large scale setup. In each case different existing models will be applied (Helsinki: SWMM, Rotterdam: 3Di, Aalborg: MIKE) in combination with local customization and add-on’s to the existing models. The three local flood model developments are described in section 3.

2. The “large-scale” development (SMHI)

SMHI intends to set up “high-resolution” HYPE models in each study catchment, in order to investigate if/how high-resolution hydrology can provide an added value in an urban flood forecasting context.

2.1. The HYPE model

HYPE (Hydrological Processes for the Environment) is an open source dynamic integrated rainfall-runoff and nutrient transfer model developed and maintained by the Swedish Meteorological and Hydrological Institute (SMHI). HYPE simulates water flow and substances on their way from precipitation through soil, river and lakes to the river outlet in a catchment. The catchment is divided into sub-basins which in turn are divided into classes (calculation units) depending on land use, soil type and elevation (Figure 1). A general description of the model can be found at http://www.smhi.se/en/research/research-departments/hydrology/hype-1.7994) and the full model documentation is available at http://www.smhi.net/hype/wiki/doku.php.

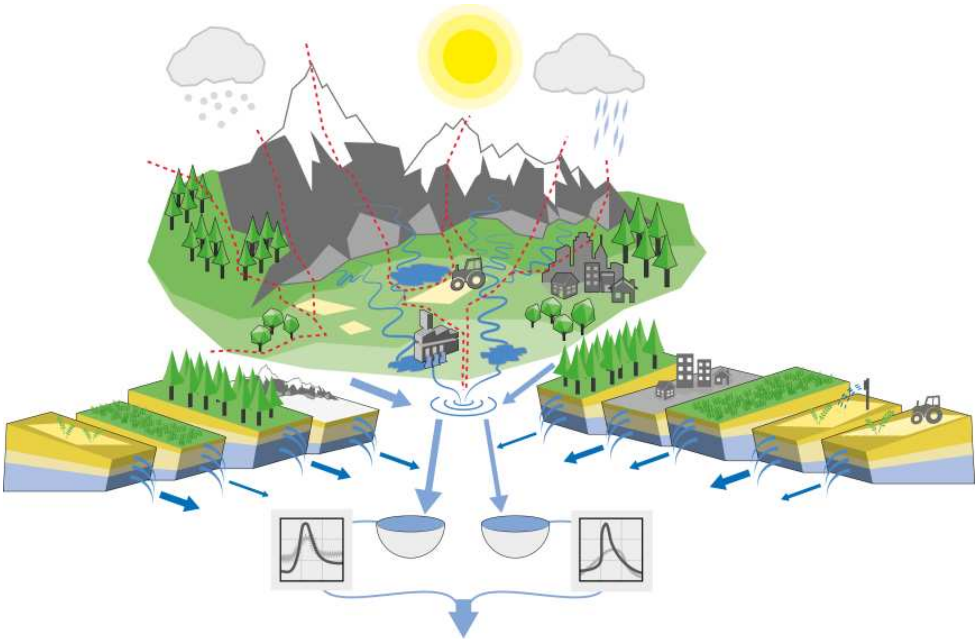


Figure 1 *Schematic of the HYPE model.*

The HYPE model has been set up for different parts of the world, see http://hypeweb.smhi.se/, and in MUFFIN we will use the set-ups for Sweden (S-HYPE) and Europe (E-HYPE) as starting point. In S-HYPE, the country is divided into ~40 000 sub-basins with a mean size of ~10 km². This model is used operationally to make 10-day discharge forecasts in all sub-basins (http://vattenwebb.smhi.se/hydronu/). In E-HYPE, the mean sub-basin size is ~250 km² and in both set-ups the time step is 1 day (http://hypeweb.smhi.se/europehype/long-term-means/).

2.2. Development in MUFFIN

In MUFFIN we will develop the HYPE model for applications at higher resolutions.

- *Temporal resolution:* In MUFFIN we will develop the HYPE model for a time step of 1 h. Generally, this time step is strictly not sufficient for pluvial flooding, which may involve a very rapid runoff increase that requires a time step in the order of 1 min to be accurately described. However, it is a substantial improvement compared with today's daily time step and it is likely to contribute to meaningful support in urban flood events even though small time scale flood developments cannot be discretized directly. Further, 1 h is a suitable choice with respect to available high-resolution forcing data (observations and forecasts). The development will include evaluation of the "time-step sensitivity" of process descriptions and parameters, adjustments if required, and finally calibration and validation for different urban or semi-urban sub-basins.
- *Spatial resolution:* In MUFFIN we will explore different ways to provide a more detailed and realistic representation of the urban environment than what is currently available. This includes e.g. using more detailed land-use data such as EEA Urban Atlas (http://www.eea.europa.eu/data-and-maps/data/urban-atlas). By using the most recently released DEM (Digital Elevation Model) data available it may be possible to decrease the sub-basin size in urban areas. It will be attempted to include descriptions of technical modifications of the natural flow paths in HYPE, e.g. sewer systems and pumping stations. Further, by using land-use specific runoff, rather than just the lumped basin outflow that is normally considered, a more spatially resolved result may be obtained.

2.3. The forecasts

HYPE forecasts and warnings are generally based on the following procedures:

- Calibration of the model to the extent possible.
- Simulation of runoff/discharge (R/Q) by using observed precipitation (P) and temperature (T) over an as long as possible historical period.
- Estimation of R/Q warning levels corresponding to return periods of e.g. 2, 10 and 50 years.
- Production of successive R/Q forecasts by 1/ initializing the model using the most recent meteorological observations and 2/ forcing the model by meteorological forecasts
- If the R/Q forecasts exceed the warning levels, warnings should be issued.

Output can be in the form of R/Q time series with warning levels marked (Figure 2) or maps with colors representing the estimated R/Q return period (Figure 3). Figure 3a shows an example from today's operational system, on sub-basin level, and Figure 3b is an illustration of how results for specific land-uses inside sub-basins may be provided after the development described above. The intention in MUFFIN is to be able to provide this information at 1-h and "land-use" scale.

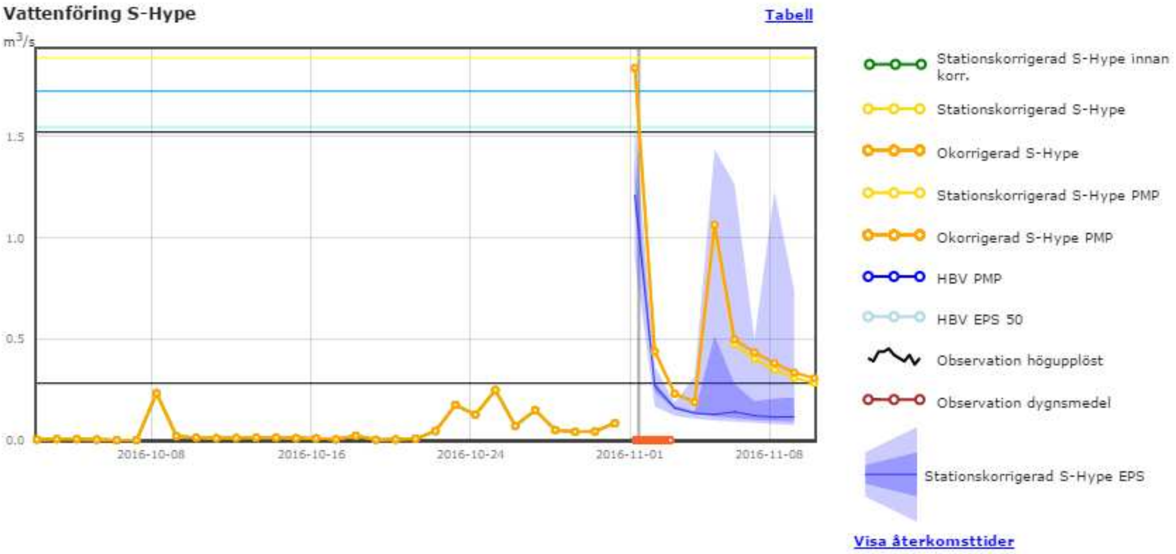


Figure 2 *Example of forecast hydrograph with warning levels (light blue: 2 years; blue: 5 years; yellow: 10 years) and ensemble forecasts.¨*

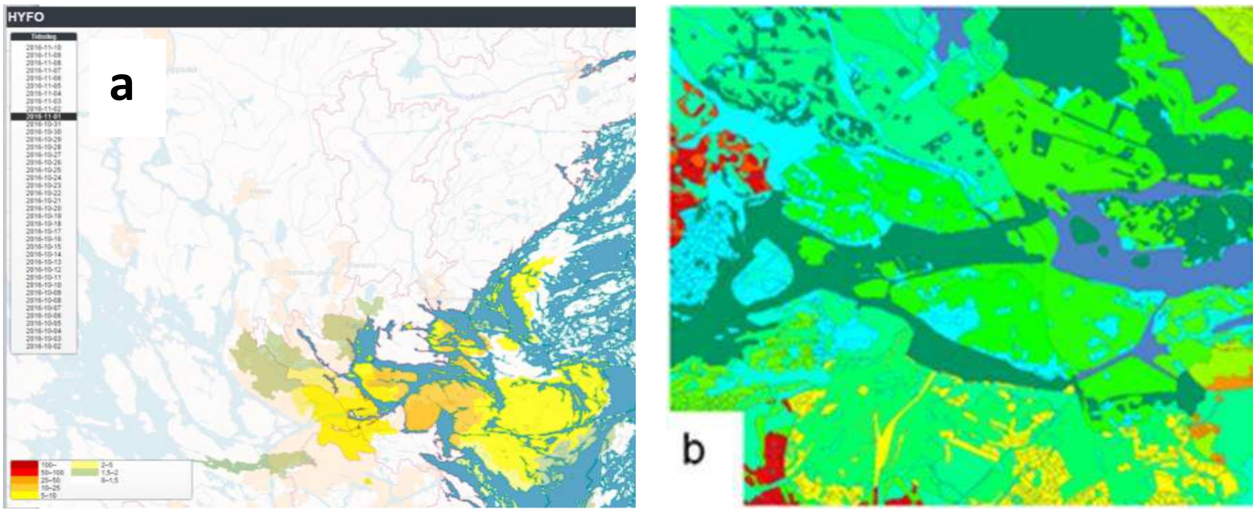


Figure 3 *Example of forecast maps: current design in the web tool (a) and illustration of the increased spatial resolution potentially available in the high-resolution HYPE (b).*

3. The joint case studies

The basic concept is to set up a local high-resolution HYPE sub-model for each of the study basins, in which there is already a local (hydraulic) model available. Then run both hydro-models in parallel, in order to explore how their output relates to each other, and/or coupled, in order to explore any added gain of such coupling. The intention will be to have two HYPE sub-models in each study basin; one optimized using local information and one entirely based on open Pan-European data.

There are a number of potential "dimensions" to explore, e.g.:

- The precipitation input is naturally a key aspect, and different products (representing e.g. different scale/resolution or different observational sensors or different forecasting methodology) should be used. At least one set of precipitation inputs (observations and forecasts) should be identical for both hydro-models, then other products may be tested for each model separately in order to assess the different aspects.
- With respect to observations, a key issue is how different observational products affect the initial state of the hydro-models and, in turn, how this initial state affects the forecast performance.
- Application of a common long-term forcing dataset (precipitation and temperature) as model inputs to large scale and local scale catchment models, in order to compare flood simulation results across scales and catchments.
- With respect to forecasts, an ensemble approach should be the main option although also deterministic forecasts may be used.
- It may be considered to divide the forecasting experiments into "theoretical" and "operational", where the former aims at assessing "optimal performance" (e.g. by using data that are not (yet) available operationally in real time) and the latter "practically attainable performance" (by using data that are available operationally in real time).
- One aspect of a multi-scale approach is the scale of the weather systems – their representation in the input data as well as their relation to flood risk, this should be assessed.

In Table 1 specifications of each case study catchment is given along with specifications of local experiments.

Table 1 *Overall plan for the joint experiments (H: historical, R: real-time).*

	Rotterdam	**Helsinki**	**Aalborg**
Large scale catchment (HYPE setup)	Delfland (410 km^2) Catchment type: Rural/urban	Haaganpuro (11km^2) Catchment type: Urban	Østerå catchment (150 km^2) Catchment type: Rural/urban
Local scale catchment	Rotterdam Centre (4.9 km^2) Model: 3Di Catchment type: Urban	Länsi-Pakila (1 km^2) Model: SWMM Catchment type: Urban	Kærby (1 km^2) Model: MIKE Catchment type: Urban (industrial and residential)
Hydrological forcing data for calibration and validation	- Water level sensors (H+R) - Flow and pump data from drainage system (H+R)	- Flow measurements at both catchments (H)	- Water level gauges (H+R) - Ground water level gauges (R) - Combined sewer over flow registrations (H) - Pump data (H)
Rainfall observations	- Rain gauges (H+R) - Citizen weather stations - KNMI C-band radar data(H+R) - Rotterdam X-band radar (H+R)	- Rain gauges (H+R) - University of Helsinki composite radar data (H) - FMI radar data (R)	- SVK Rain gauge network (H) - Local rain gauges + disdrometer (H+R) - DMI C-band radar (H+R) - AAU X- band radars (R)
Rainfall forecasts	- KNMI national C-band radar nowcasts (H+R) - HARMONIE forecasts (H+R) - WRF simulations (H+R) - Stochastic rainfall simulator (H)	- Aalto radar nowcast (H+R) - FMI HIRLAM (H+R) - HARMONIE? (H+R)	- AAU ensemble nowcast on X-band radar (R) - AAU ensemble nowcast on C-band radar (H+R) - DMI-HIRLAM (H) - SMHI MEPS (H+R) - GLAMEPS (H+R)
Special focus experiments	- Spatial and temporal resolutions of models and inputs - Evaluation of accuracy between different rainfall products and forecast products - Display of flood risk maps - Detailed investigation of relationship between rainfall and flood response using citizen reports	- Predictive skills of large scale model at local catchment - Impacts of land-use in flooding - Impacts of temporal resolution on small catchment simulations.	- Space/ resolutions of models and inputs - Comparisons of return periods of rainfall and flood response - Predictive skills of large scale model local catchment - Use of HYPE model as boundary condition for local model - Development of fast and distributed flood model based on pre-simulated multiple system states

In addition to the local data, which is described in more detail in the following sections, a common forcing dataset is produced. The purpose of a common dataset, which is not linked to specific location/case study is to:

- Assess whether there is any connection between "high-resolution hydrological warning level" from HYPE and urban flooding estimated from the local models with regards to long term /extreme statistics
- Identification of events/sequences in the forcing data that have generated discharge or runoff associated with high return periods.
- Investigate the impact of basin characteristics (and possibly hydraulic model) across the different case study areas
- Investigate impacts of spatial and temporal resolution across models and case study areas

The common dataset will help to provide knowledge the behaviour on models and study areas with regards to flooding before moving towards forecasting.

The common precipitation forcing dataset is produced on the basis of rain gauge data from the network of the Danish water pollution committee. A total number of 73 gauges cover an area of 65 km x 40 km (Figure 4). 15 of the gauges have precipitation records from 1979 to present.

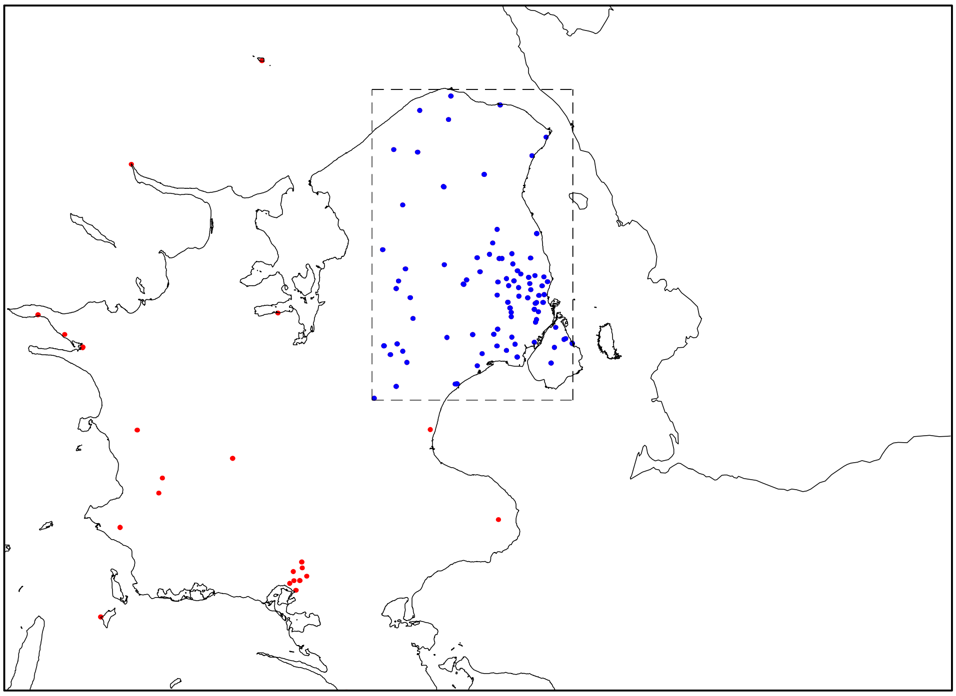


Figure 4 Rain gauges (blue dots) applied in common forcing dataset covering an area of 65 km 40 km over Sealand and greater Copenhagen in Denmark.

3.1. Aalborg (AAU)

The overall objective of the Aalborg case study is to develop an operational real-time flood model for Aalborg, Denmark. Based on the overall objective the following research questions are formulated:

- How does the hydrological cycle affect urban flooding, and what are the key hydrological processes?
- What is the optimal spatial and temporal resolution for input data and urban flood forecasting models, and how does that relate to practical use, model execution time, and end-user specifications?
- Can complex urban flood models be simplified without compromising accuracy and scales in order to reduce computation time and thus provide models which can operate in real-time.
- How is the uncertainty of urban flood forecasting models best described, and how can uncertainty be quantified in a meaningful way to the end-users?

3.1.1. Case study area characteristics

For the Aalborg case, the Østerå river catchment is applied on the large scale setup (Figure 5, Table 2). This river system flows north towards the city center og Aalborg and discharges into the Limfjord. Through parts of the city Østerå flows in open and closed channels. Upstream the channel system two minor streams, Østre Landgrøft and Vestre Landgrøft discharge into Østerå. These streams are heavily polluted by combined sewer overflows. Østerå and the two streams enclose the areas Kærby and Håndværkerkvarteret (Figure 6, Table 2) which are subject to the local scale setup of the Aalborg case experiments. This area is selected for the development of flood forecasting models since it has prior been prone to flooding from both urban drainage system, overflowing streams, and in low areas flooding due to a high groundwater table. Moreover the catchment has benefits in a close location to Aalborg University, good coverage of radar observations and other hydrological observations.

Table 2: Characteristics for the Aalborg case

	Østerå-catchment	**Kærby**	**Håndværkerkvarteret**
Catchment type	Rural and urban	Urban (residential)	Urban (industry)
Total area (km2)	150	0.60	0.38
Impervious area (%)		40	88
Inhabitants		2100	~80

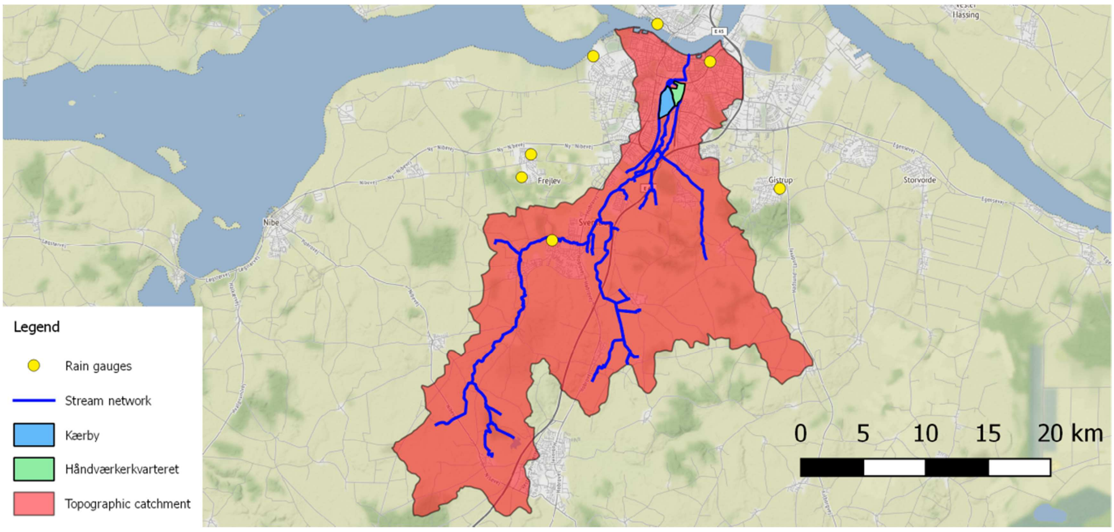
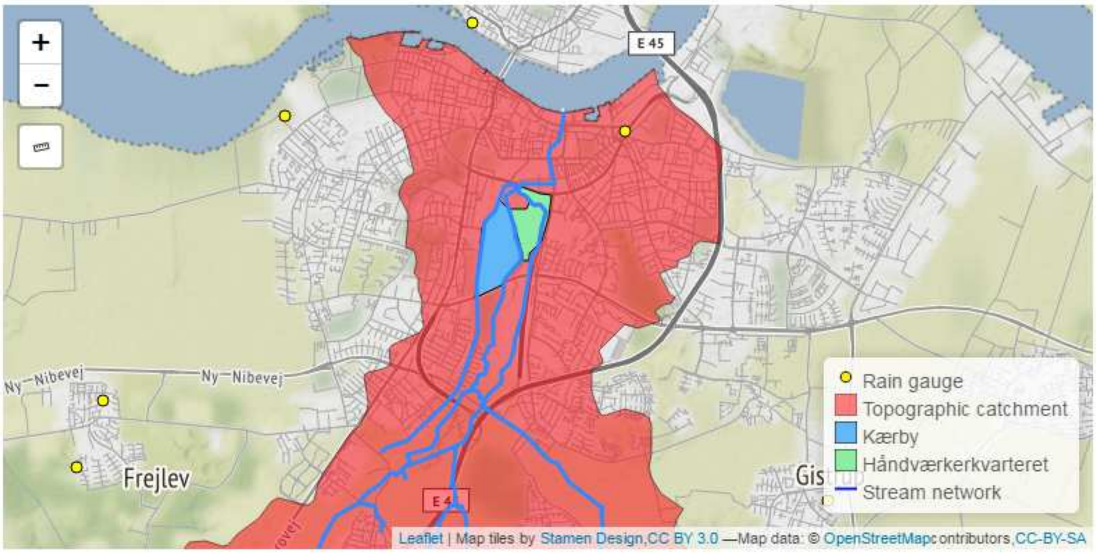


Figure 5: Østerå Catchment



Leaflet | Map tiles by Stamen Design,CC BY 3.0 —Map data: © OpenStreetMap contributors,CC-BY-SA

Figure 6: Catchments applied in the Aalborg Case. The Topographic catchment (in red) will be modelled with the HYPE-model, and the urban areas (in green and blue) with MIKE URBAN.

The interaction between streams, drainage system, groundwater, and variability in rainfall is examined using Kærby and the Håndværkerkvarteret as two linked case studies. Even though both study sites are heavily influenced by each other, different conditions cause urban flooding in each area. High groundwater table, low elevation level, and the fact that Kærby is enclosed by two streams, makes Kærby an ideal case-study for studying the effects of integrating the complete hydrological cycle in respect to urban flood forecasting. Håndværkerkvarteret consists of mostly impermeable areas with a few open grass areas. As such the urban flooding is more likely linked to the hydraulic capacity of the outgoing streams.

Kærby and Håndværkerkvarteret are located in a low elevation between two higher elevated hills to the east and west. Figure 7 shows digital elevation model (DEM) visualization of the Østerå catchment with a resolution of 10x10 meters.

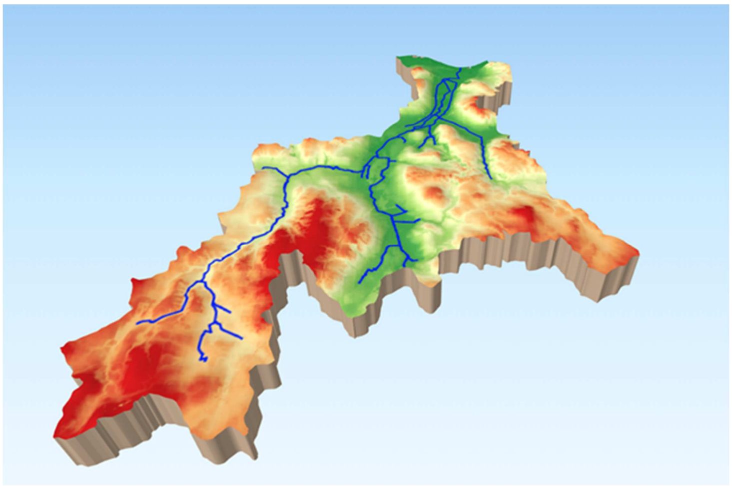


Figure 7. 3D-visualisation of elevation in the Østerå catchment . The vertical height is exaggerated by a factor of 10.

It is believed that different conditions in weather, soil characteristics (both saturated and unsaturated zone), sewage system capacity, and stream network capacity may cause urban flooding in both areas. However, both drainage systems discharge to the Østerå stream network, and the capacity of this network is observed to be limiting during rainfall events. However, each location has its unique problems listed below:

Kærby:

- Low elevation and high groundwater level
- Limited soil infiltration capacity
- Limited hydraulic capacity of older combined sewer system
- Limited hydraulic capacity of stream network

Håndværkerkvarteret

- Little to no infiltration of surface water to groundwater
- All surface water is discharged directly into the stream network with no retention

3.1.2. Precipitation data

Precipitation data is available from several sources, including rain gauges, disdrometers, radar and radar nowcasts, and numerical weather models. The Danish rain gauge network of the Water pollution committee (e.g. Madsen et al., 2009),(Figure 5), covers the topographic catchment with 7 rain gauges with historical data back to the late 1990's.

Approximately 1.7 km from the project area in the BEWARE project, where a parking lot equipped with a disdrometer and 9 tipping bucket rain gauges with real-time data transmission and historical data back to 2013 (Ahm and Rasmussen, 2017, http://vejrradar.dk/beware/)

In collaboration with Aalborg Water Utilities, Aalborg University operate two dual polarimetric X-band doppler radars (Furuno WR-2100, Nielsen et al., 2017), Figure 8. Aalborg university has developed quality controlled and bias adjusted QPE and QPF products, which are available in real-time for both both the Østerå and Kærby catchments.

Furthermore, DMI operates a dual polarimetric C-band doppler radar located approx. 50 km north of Aalborg. This has the benefit of a much larger range (240 km), but also a coarser resolution. In MUFFIN this radar will in combination with X-band radars be used to provide nowcasts with a lead time of up to two hours.

Numerical weather prediction model data are available from DMI and SMHI as high resolution ensembles: MEPS, GLAMEPS.

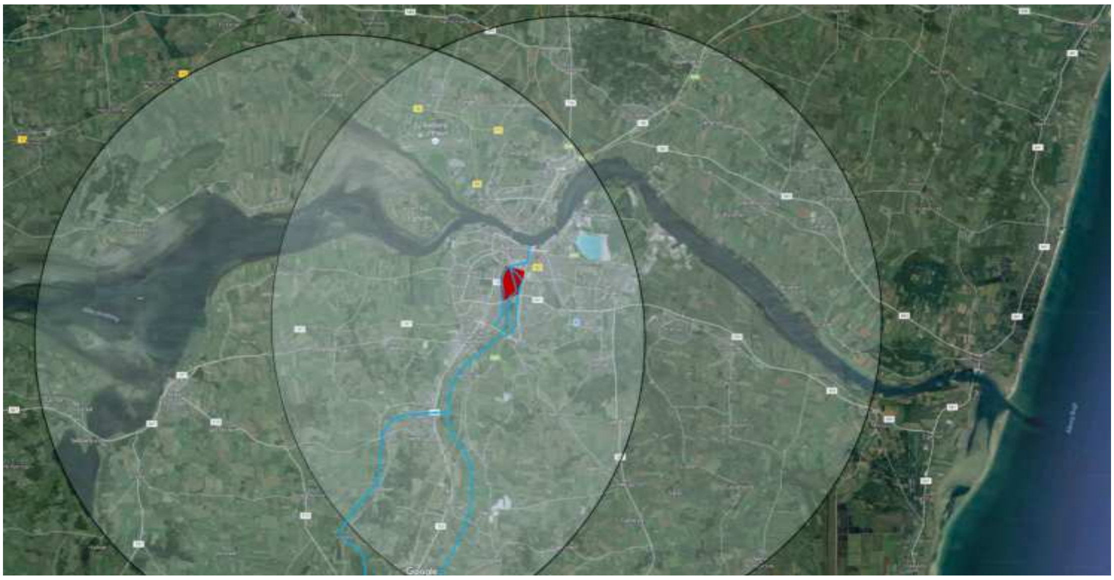


Figure 8 Radar coverage with a 15 km range. The total range of each radar is 50 km.

3.1.3. *Hydrological data*

Historical water level data from the Østerå river system is available for a period from 2007 to present.

In order to provide better hydrological data from the MUFFIN project an extensive monitoring campaign is established in Kærby and Håndværkerkvarteret. The goal of this monitoring campaign is to identify the conditions that cause flooding in both areas and to provide the necessary in- and output data in order to validate the hydrological models. A local experimental setup is developed to inquire knowledge of stream water level and flow, groundwater level, and overflow discharge from the sewer system. The data transmission system is automated using GSM modules sending data feedback to an FTP server once a day. Later on this automated data logging system will be used for real-time hydrological flood modelling and forecasting with much higher frequencies of data transmission. (Nielsen and Thorndahl, 2017)

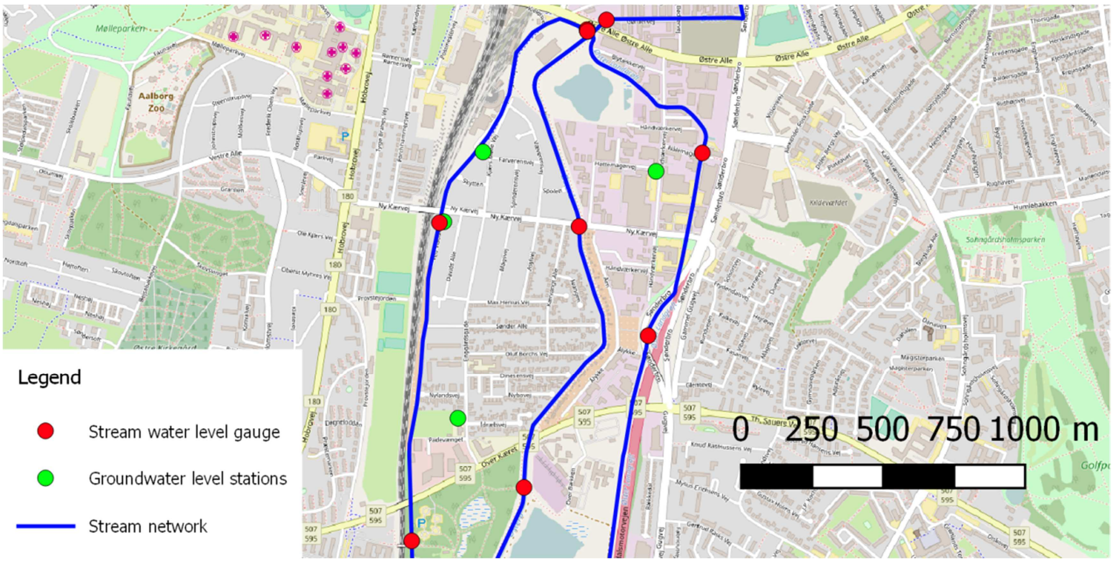


Figure 9 Locations of stream water level and ground water level monitoring in Kærby and Håndværkerkvarteret.

3.1.4. *Model developments*

Four main modelling experiments are conceived:

1. Setup of the large scale HYPE model for the Østerå catchment with impervious fractions for the urban areas. This model is operated in order to provide flood warnings if water levels exceeds thresholds corresponding to different return periods of historical floods. A comparison with local urban hydrological (flood) model will be made in order to investigate differences, pros and cons in each model setup. See section 2 for details on the HYPE model.

2. An integrated fully distributed local flood model with all relevant hydrological processes included. This model is a combined urban drainage and hydrological model. The hydrological model is a national model of the freshwater cycle in Denmark built in the MIKE SHE environment, also known as the DK-model (Henriksen et al., 2003). The hydraulic model is a local drainage model built in MIKE URBAN. The following processes are included in the integrated setup: overland flow, evapotranspiration, unsaturated flow, saturated flow, stream flow, and sewer flow. See Figure 10 for the model setup.

3. An integrated local flood model (as setup no. 2) with large scale HYPE model as boundary condition for river flow, ground water level, etc.

4. A simplified setup of setup no. 3 where pre-simulated flood scenarios is applied to run in real-time. This aims at developing a framework for running real-time models without compromising the complexity of the model. The idea is to pre-simulate multiple systems states building a multidimensional catalogue of possible model outputs. Based on sampling from this catalogue, real time models can be executed fast. It is crucial to identify the main model drivers and the system response to each

state of this driver and potential interaction between drivers. Furthermore, it is important of be able to estimate and propagate the uncertainty sampling from the pre-simulated catalogue in comparison to the full model.

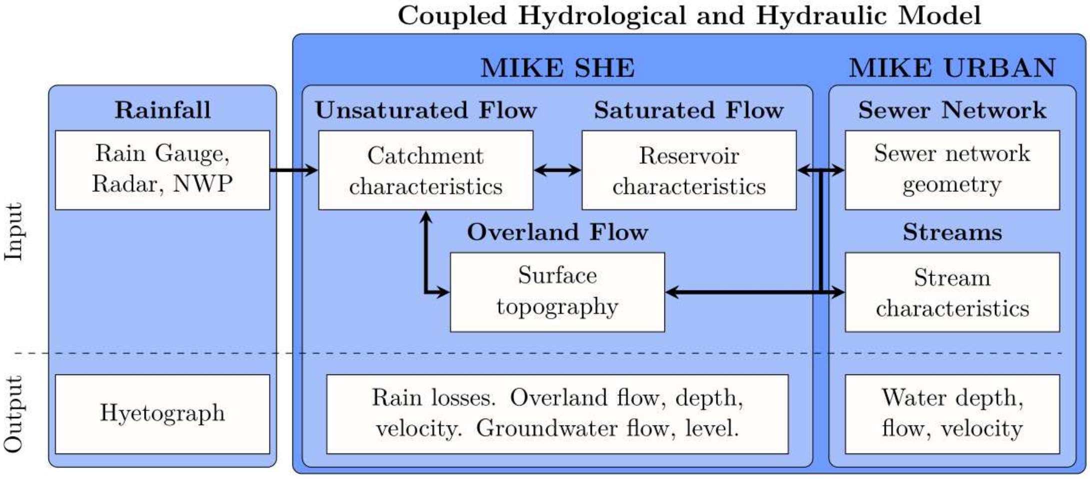


Figure 10 Overview of integrated flood model setup for urban areas

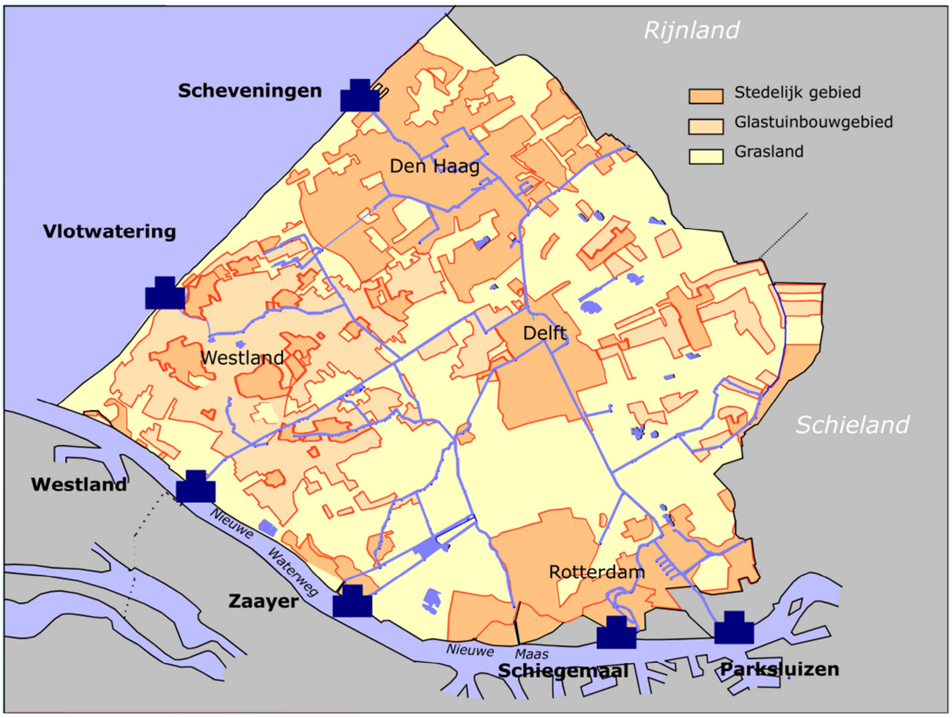
For each model setup the following procedures are conducted:

- Calibration of the setup against available data
- Mapping of rainfall-flood response based on historical time series and selection of flood producing events for a catalogue of historical events with estimation of return periods.
- Test with real-time operation and real-time data assimilation

The model setups will be evaluated and compared with regards to:

- Space/ resolutions of models and inputs
- Comparisons of return periods of rainfall and flood response
- Predictive skills of local flooding

3.2. Rotterdam



Rotterdam might not be the best place to investigate multiscale issues with HYPE. Surface waters are divided over many polders and transport channels, and water flows are heavily regulated by weirs and pumping stations. Given the resolution of the HYPE model (1h) and type of environment it has been developed for, it is unlikely that meaningful results for Rotterdam with this type of approach will be achieved in 2017. At best, HYPE could be used to model the regional surface water channel system in the bigger Delfland region (see map below).

The city of Rotterdam is mostly interested in higher situation awareness and better post-flood assessment driven by observational approaches such as high-resolution rainfall/flow data. They also have an interest in hydrological modeling and forecasting, but mostly on the level of the stormwater drainage system. To do anything meaningful at these scales, resolutions of at least 1km/5 min are necessary. Setting up HYPE for this would therefore require higher resolution than 1h. Also, it would mean importing the entire sewer pipe network of the city, which we are not ready to do at this stage of the project.

What was done in 2017 and will be continued in 2018 is to set up HYPE for modeling the surface waters in Delfland using the best-possible already available open data and run the model like that for the time being. If the multi-scale HYPE experiments conducted in Finland, Denmark and Sweden are promising; more time can be invested into this line of research.
Ultimately, 3Di should become available in the 2018 which will open more options. We could test the model using the high-resolution radar data or artificial rainfall scenarios generated by a stochastic rainfall simulator. The problem, however, is that 3Di is set up in such a way that the user does not have ownership: the model is hosted in the cloud and the user pays for a licence that allows a given number of calculation and a given amount of data storage. This

makes it not very flexible to play around with all kinds of scenarios (unless the business model should be changed in the future).

Based on this, the following experiments are proposed:

3.2.1. Experiments

- Compare rainfall forecasts at different spatial and temporal resolutions to learn more about trade-offs between resolution, lead-time and accuracy.
- Evaluate the accuracy of different rainfall products, for example C-band KNMI vs X-band TUD vs rain gauges vs numerical weather prediction model.
- Test the effect of spatial and temporal resolutions in rainfall inputs on hydrological predictability and identify the most relevant scales for explaining hydrological variability as a function of lead time by comparing the rainfall data and hydrological response over selected districts. Inputs can be radar nowcasts (upscaled or downscaled), HARMONIE forecasts or WRF outputs with/without assimilation of radar data (not ready yet).
- Explore new ways of displaying rainfall forecasts and flood risks in the form of (a) a map showing the remaining time until a critical threshold will be exceeded and (b) Maps of exceedance probabilities for location-specific thresholds depending on catchment size and imperviousness.
- Simulation experiments based on artificial rainfall fields generated using a stochastic rainfall simulator developed by M. Schleiss. The simulated rainfall fields can be used to conduct controlled experiments, varying rainfall structures, size and intensity to test the hydrological response and sensitivity of results to spatial and temporal scales (e.g., by aggregating the simulated data to lower resolutions). Results from these studies can also be compared with real-world analyses based on observed rainfall, water levels and flows.

3.2.2. Hydrological observations and studies

More data will become available over time. But for now, Martijn Mulder has compiled a database with water level observations at 20+ sensors for 38 rain events from 1 June to 31 December 2016. Each event has at least 5 mm of rainfall accumulation. There are also daily files of flows and sewer overflow volumes at several pumping stations across Rotterdam starting in 2010. These can be used to analyze hydrological response (in selected districts) with respect to the different rainfall events, datasets and resolutions. For example, in his MSc thesis, Christian Bouwens compiled a list of 8070 citizen flood reports for the city of Rotterdam between 2010 and 2016, correlating them with 5-min national C-band radar composites to analyze the relationship between rainfall and flooding in different districts of Rotterdam. From this database, the 40 days with the largest observed number of citizen reports and total sewer overflow volumes were extracted. Using changepoint analysis, critical rainfall thresholds after which flooding incidents started to increase significantly can be identified (see Figure 11).

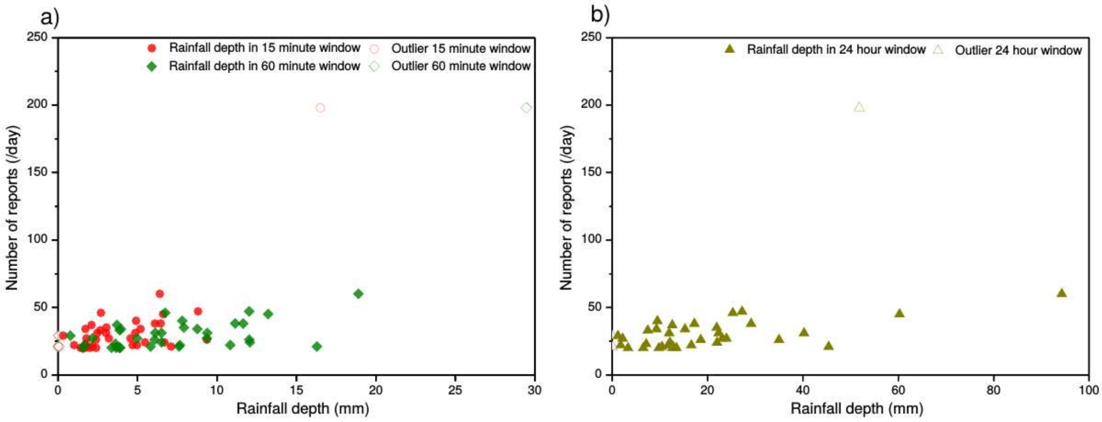


Figure 11 (a) Relationship between maximum rainfall 15-min and 60-min rainfall depth and daily citizen flood reports and (b) relationship between daily rainfall depth and citizen reports.

In addition, a 1x1m DEM of Rotterdam was used to delineate 58 urban catchments or watersheds using a threshold value of 300 m2 for minimum size of the watersheds. While deriving the watersheds, also a stream map is created, showing the preferential flow paths defined by the highest accumulation of surface runoff (see Figure 12). The outflow point of an urban watershed is defined by the downstream end of the stream. As for now, only 33 of the 58 delineated watersheds contain reports. These 33 watersheds were investigated to see whether elevation differences can be related to urban pluvial flooding.

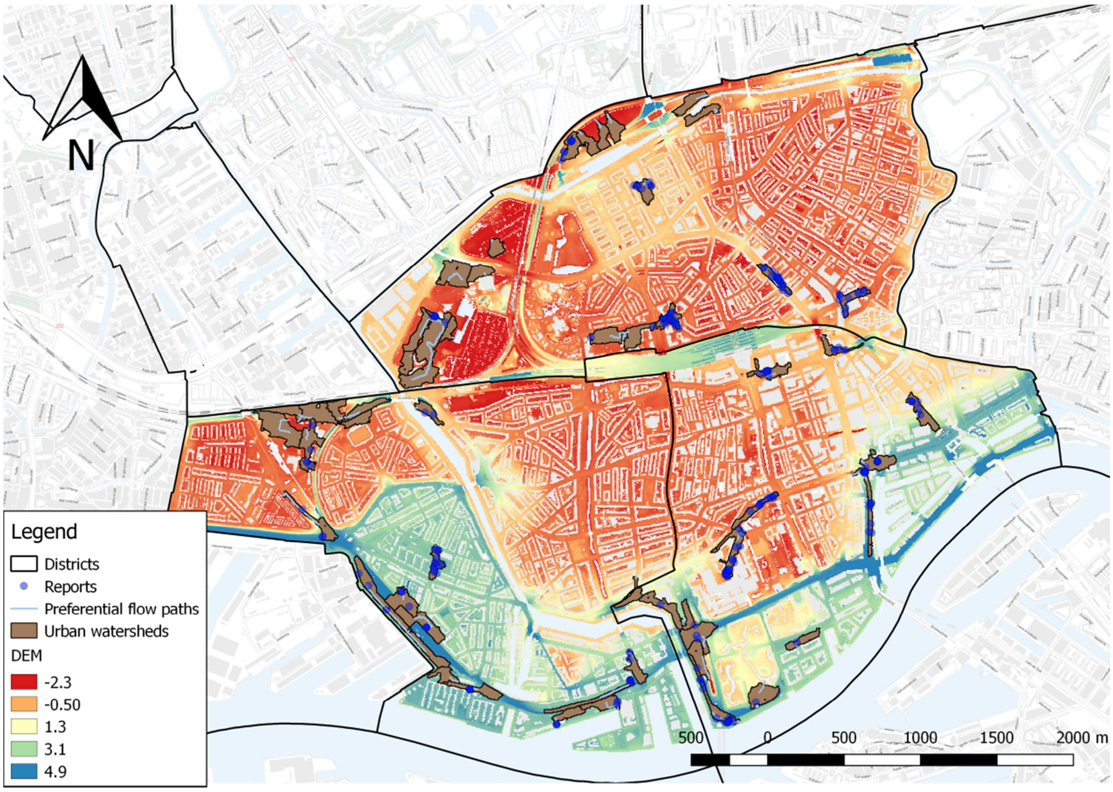


Figure 12 DEM and urban watersheds in the centre of Rotterdam.

3.2.3. Rainfall sources

There are many different rainfall products available over the Netherlands and the city of Rotterdam. This includes:

- KNMI national C-band 1 km gauge-adjusted radar composite (using 325 gauges) at 24h resolution (from 08:00-08:00 UTC) from 2008-03 to present.
- KNMI national C-band 1 km gauge-adjusted radar composites (32 gauges) at 3 h resolution from 2010-01 to present.
- KNMI operational C-band 1 km 5 min uncorrected radar composites for selected days and events in 2017.
- Rotterdam X-band radar. The radar has been installed in August 2017 and 1-min data are being transmitted in near real-time to TUD servers. The radar provides data but most of the algorithms for quantitative precipitation estimation still need to be developed and improved. The biggest problems for now are calibration and attenuation correction.
- TUD Micro-rain radar (MRR). A vertically pointing K-band MRR has been purchased in 2017 and installed on the roof of the CiTG building at TUD in August 2017. It collects vertical profiles of rain rates reflectivity, liquid water content and particle size distributions at 10 s and 35 m resolution. Data are available in NetCDF format upon request to TUD. The radar is expected to be moved to Rotterdam in the summer of 2018.

Rainfall forecasts:

- Operational KNMI national C-band radar nowcasts at 1 km 5 min based on optical flow for lead times of up to 2 h (in steps of 5min), from 2017 to present
- HARMONIE model outputs and model forecasts at 1h and 2.5 km resolution for lead times up to 48h, back to 2010 (upon request to KNMI)

WRF high-resolution rainfall forecasts:

The state-of-the art Weather Research and Forecasting software (WRF 3.9) has been set up over Rotterdam and can be used to perform high-resolution numerical weather modelling and forecasting for selected rainfall events. The model has a parent domain of 5 km grid spacing covering the BeNeLux region, a second domain of 1 km grid spacing over the Netherlands and a third innermost domain over Rotterdam at 200 m grid spacing and 135 vertical levels. Both single- and double-moment microphysics schemes have been implemented and results compared against a network of radar and rain gauge observations. To assist with the execution of the WRF model simulations, we applied for a NWO grant under the “Access to the National Computer Facilities Pilot projects” funding scheme. The application was successful and in August 2017 we were allocated 500,000 computing hours on the Cartesius HPC system.

3.3. Helsinki

The Finnish case study aims to improve nowcasting of extreme precipitation and the associated urban flooding in the capital area of Finland. In addition, the impact of urban densification on the susceptibility to flooding will be explored, as well as the possibilities to alleviate the adverse effects of urban development with low impact development (LID) tools.

3.3.1. Catchment descriptions

In the Helsinki case, two nested catchments are studied. The smaller (~1 km^2) catchment, Länsi-Pakila, is a low-density residential area in northern Helsinki. It is characterized mostly with single-family houses (Figure 13). The area is known to be prone to stormwater flooding, which has caused e.g. water entering basements and yards of individual houses in the past. The area is subject to urban development and densification in near future, which puts it at a risk of more severe problems caused by urban flooding unless due attention is given to sensible stormwater management.

Figure 13 Länsi-Pakila catchment in Helsinki, Finland.

The Länsi-Pakila catchment is a sub-catchment of the larger (~11 km^2) Haaganpuro catchment (Figure 14). The landuse in Haaganpuro is more varied than in Länsi-Pakila, comprising e.g. a large green area intersecting the catchment, the low-density residential Länsi-Pakila area in northern parts, and a higher-density residential area in south-western parts of the catchment.

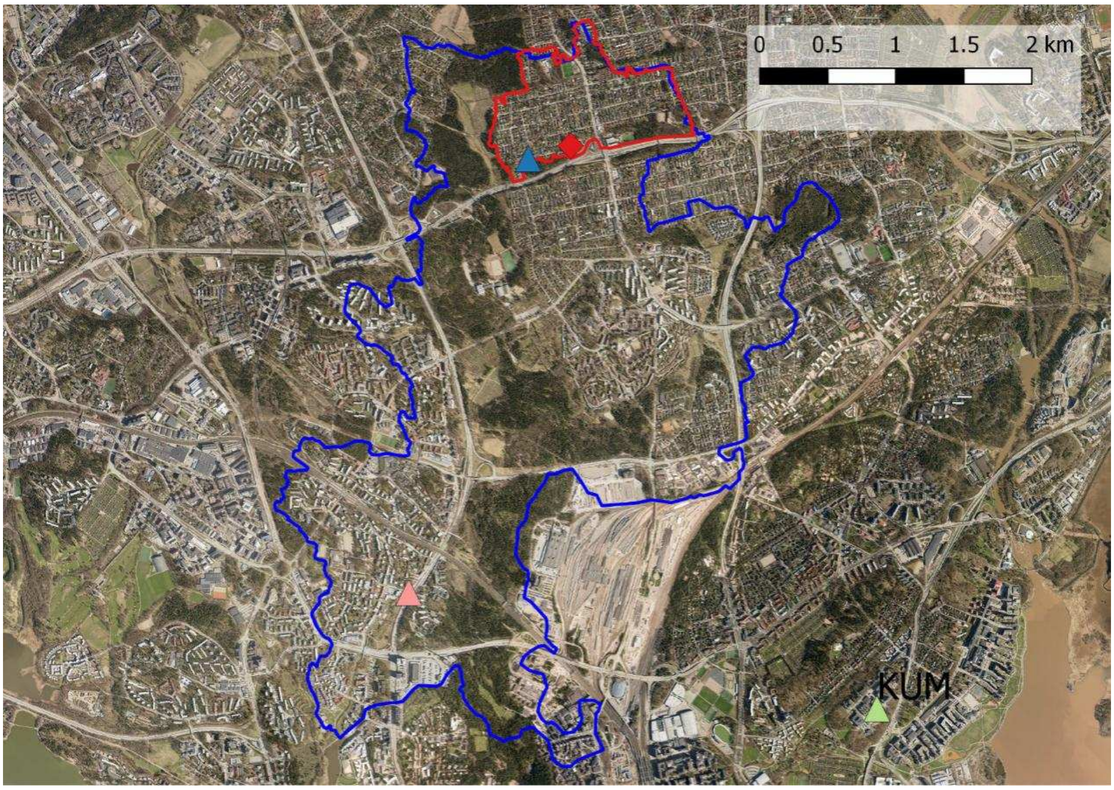


Figure 14. Haaganpuro catchment (blue border, ~11 km^2) and the flood prone Länsi-Pakila subcatchment (red border, ~1 km^2) in Helsinki, Finland. Location of the University of Helsinki Kumpula weather radar (KUM) and the FMI weather station is depicted with the green triangle. The blue and pink triangles depict the runoff observation stations. The red diamond depicts the location of on-site rain gauges at Länsi-Pakila catchment.

3.3.2. Hydro-meteorological data

Three co-located high-resolution fully automatic tipping-bucket rain gauges (Decagon ECRN-100 High Resolution Rain Gauge) (Figure 15) have been installed at the Länsi-Pakila catchment to provide on-site rainfall measurements for the snow-free periods of 2017 and 2018 at 1 min temporal resolution. In addition, the Finnish Meteorological Institute (FMI) provides openly continuous weather station observations in 10 min temporal resolution, with four weather stations within a distance of 10 km from the catchments.

Figure 15. Three co-located on-site high-resolution tipping bucket rain gauges in Länsi-Pakila.

In addition to the weather station observations, the FMI provides real-time weather radar observations openly for end users in a 500x500 m^2 Cartesian grid with a 5 min temporal resolution. The FMI weather radar network comprises 10 dual-polarization C-band radars, with the nearest radar (Vantaa) located approximately 5 km from the catchments.

The radar meteorology group of the University of Helsinki has constructed a composite quantitative precipitation estimate (QPE) product for the capital area utilizing three dual-polarized C-band radars, namely the FMI operated Vantaa radar (VAN), the University of Helsinki operated Kumpula radar (KUM), and the Vaisala Oyj operated Kerava radar (KER) (Figure 16). Use of a multi-radar setup mitigates the common problems in urban radar measurements by providing extra observations for filling gaps in individual radar measurements and by extending the range of low elevation observations. A high quality QPE with a Cartesian grid resolution of 250x250 m^2 is achieved by using several quality control methods on calibrated polarimetric radar data and by quality based compositing. Furthermore, the accuracy of rainfall estimate in a given location is increased by using advection interpolation on the composited QPE field to achieve a temporal resolution of 1 min. This product has recently been upgraded to take advantage of the dual-polarization measurements and it is available for the Helsinki case study in the MUFFIN project.

Aalto University is amongst the many users of the widely applied precipitation nowcasting model STEPS. In MUFFIN-project, STEPS is used to provide short-term radar-based ensemble predictions of precipitation for Helsinki region. The three-radar composite QPE by the University of Helsinki and the FMI operational radar data will serve as high-resolution input data for the STEPS model.

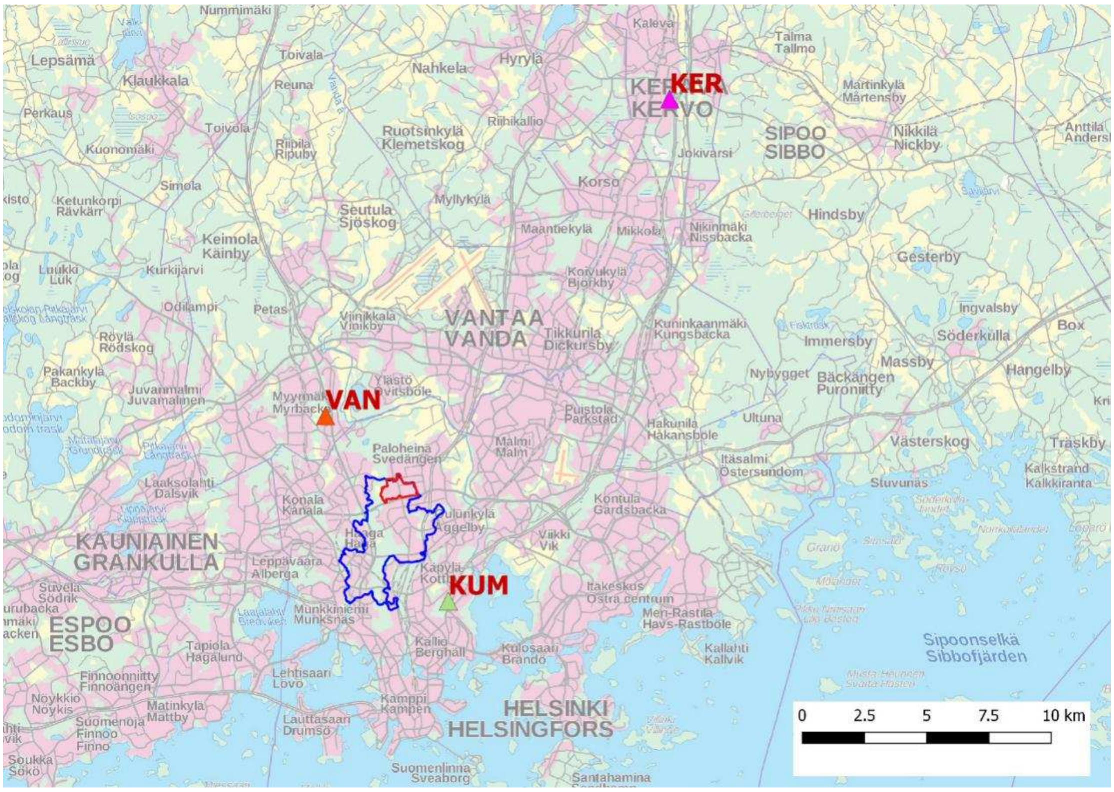


Figure 16 Weather radars at in the Helsinki metropolitan region. FMI operated Vantaa radar (VAN, orange triangle), University of Helsinki operated Kumpula radar (KUM, green triangle), and Vaisala Oyj operated Kerava radar (KER, purple triangle).

On-site runoff observations were collected in a measurement campaign between May and November 2017 to provide calibration and validation data for runoff simulations. High-resolution Starflow Ultrasonic Doppler Instruments were installed at both Länsi-Pakila and Haaganpuro catchments to provide water level and flow velocity measurements at 1 min interval (Figure 14).

3.3.3. Model development

A high-resolution Storm Water Management Model (SWMM) description for the Länsi-Pakila catchment has been built (Figure 17) utilizing a novel GisToSWMM5 tool which automates parts of the model building process (Warsta et al., 2017). Mostly openly available data was utilized, including the 1x1 m^2 digital elevation model from the City of Helsinki, and the land cover description data from the Helsinki Region Environmental Services Authority HSY. The model includes description of surface runoff, infiltration, evaporation, and flow routing in the stormwater network. Due to the very high resolution of the available input and forcing data, it has been possible to construct the model using a subcatchment spatial resolution of 1 m^2 and to use a simulation time step of 1 min.

In MUFFIN-project, the GisToSWMM5 tool has been improved to allow for automatically constructing computationally less expensive SWMM model descriptions while retaining the high-resolution details of the source data. The on-site rain gauge measurements and the meteorological data from the Kumpula weather station have been used to force the model, and the on-site runoff observations from Länsi-Pakila are used to calibrate the model.

Figure 17. Länsi-Pakila landuse description in SWMM model.

A HYPE model has been constructed for the larger Haaganpuro catchment. See section 2.

The nested experimental setup of two catchments will be used for exploring whether there is any predictive skill in conducting simulations with the large-scale HYPE model in the larger Haaganpuro catchment in estimating the storm water related problems in the flood prone Länsi-Pakila catchment. Especially, it is interesting to study how well the HYPE output with 1 h resolution works as a trigger for indicating urban runoff induced problems in flood prone areas. In addition, utilizing STEPS model will allow nowcasting of storm water runoff using nowcasted precipitation fields as an input to SWMM, which is then used to provide runoff nowcasts at the Länsi-Pakila catchment. Finally, SWMM model allows to assess the efficiency of alternative storm water management scenarios in the flood-prone Länsi-Pakila catchment.

The Helsinki case study of the MUFFIN project is expected to produce:

- Assessment about the usability of the large-scale HYPE model as a trigger for more detailed in-depth studies in high-resolution settings.
- Assessment about the accuracy of precipitation and runoff nowcasts in the Helsinki metropolitan region utilizing the composite radar rainfall product.
- Assessment about the possibilities of green infrastructure and other stormwater management solutions for the densifying, flood-prone Länsi-Pakila region.

4. References

Ahm, M., Rasmussen, M.R., 2017. Rainfall measurement based on in-situ storm drainage flow sensors. Urban Water Journal 14, 23–33. doi:10.1080/1573062X.2015.1057176

Henriksen, H.J., Troldborg, L., Nyegaard, P., Sonnenborg, T.O., Refsgaard, J.C., Madsen, B., 2003. Methodology for construction, calibration and validation of a national hydrological model for Denmark. Journal of Hydrology 280, 52–71. doi:10.1016/S0022-1694(03)00186-0

Madsen, H., Arnbjerg-Nielsen, K., Mikkelsen, P.S., 2009. Update of regional intensity-duration-frequency curves in Denmark: Tendency towards increased storm intensities. Atmospheric Research 92, 343–349. doi:10.1016/j.atmosres.2009.01.013

Nielsen, J.E., S, T., Ahm, M., Rasmussen, M.R., 2017. Combining high resolution X-band and long range C-band measurements for radar nowcasting, in: Proceedings of the International Symposium on Weather Radar and Hydrology , April 2017. Seoul, South Korea.

Nielsen, R., Thorndahl, S., 2017. Low-cost remotely sensed environmental monitoring stations, in: Conference Proceedings of the 14th IWA/IAHR International Conference on Urban Drainage, September 10-15, 2017. Prague, Czech Republic.

Warsta, L., Niemi, T.J., Taka, M., Krebs, G., Haahti, K., Koivusalo, H., Kokkonen, T., 2017. Development and application of an automated subcatchment generator for SWMM using open data. Urban Water Journal 14, 954–963. doi:10.1080/1573062X.2017.1325496