SSD

SCIENCE FOR A SUSTAINABLE DEVELOPMENT

FORECASTING AND MANAGEMENT OF EXTREME RAINFALL INDUCED RISKS IN THE URBAN ENVIRONMENT

"PLURISK"

WILLEMS P., DE CRUZ L., DELOBBE L., REYNIERS M., VAN OOTEGEM L., MAHY G., LI X., MUÑOZ LOPEZ C., MURLA TUYLS D., WANG L-P., NTEGEKA V., WOLFS V., FORESTI L., LEBEAU J., MARECHAL J., BOGAERT J., VAN HERCK K., CRETEN T., VAN BALEN K.

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FORECASTING AND MANAGEMENT OF EXTREME RAINFALL INDUCED RISKS IN THE URBAN ENVIRONMENT

"PLURISK"

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PLURISK: forecasting and management of extreme rainfall induced risks in the urban environment

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ACRONYMS, ABBREVIATIONS AND UNITS

2D	Two-dimensional
BOM	Bureau of Meteorology (Australian)
DTM	Digital Terrain Model
ESs	ecosystem services
GSF	green structure framework
GXABT	Gembloux Agro-Bio Tech
HIVA	KU Leuven Research Institute for Work and Society
HYDR	KU Leuven Hydraulics Section
INCA-BE	Integrated Nowcasting through Comprehensive Analysis for Belgium
LAWR	Local Area Weather Radar
MFB	mean field bias
NWP	Numerical Weather Prediction
RDA	range dependent adjustment
RLICC	KU Leuven - R. Lemaire International Center for Conservation
RMI	Royal Meteorological institute of Belgium
SPW	Service Public de Wallonie
STEPS	Short-Term Ensemble Prediction System
STEPS-BE	STEPS implementation in Belgium
ULg	University of Liège
VMM	Vlaamse Milieumaatschappij

SUMMARY

A. Context

Extreme local rain storms may induce severe floods and related socio-economic impacts on the urban environment (Belgian cities). While floods along rivers have been studied already extensively, quantification, forecasting, control and management of inundations along sewer systems and urban rivers have to face particular difficulties. They need fine-scale (local, short duration) rainfall estimation and nowcasting (= short-term forecasting in real time). They also require involvement of local authorities, which typically have low capacity in setting up risk quantification, forecasting, control and management systems.

B. Objectives

This PLURISK project supported the local authorities in the quantification, forecasting, warning, control and management of pluvial floods. Methodologies and software tools are being developed for:

(1) Nowcasting of fine-scale extreme rainfall, using advanced techniques for storm cell tracking and integrating national (C-band) and local (X-band) radar technology, numerical weather prediction (NWP); quantification of the uncertainty in this nowcasting.

(2) Two-dimensional fine-scale modelling, mapping and nowcasting of inundations in urban areas, and quantification of uncertainties on these inundation quantifications.

(3) Socio-economic risk quantification, incl. material and immaterial (social, ecological) damage assessment, quantification of risk perception (awareness), coping capacity and recovery capacity, impacts on built heritage, and uncertainty estimation on these impacts.

(4) Risk communication and flood risk warning based on the nowcasting results; also extreme rainfall and lightning warnings will be addressed.

(5) Risk reduction by both prevention/management, with particular focus on new management strategies, i.e. better interfacing between spatial planning, eco-management and urban water management (e.g. green – blue water; role of landscape architecture; restoration of biodiversity in urban areas incl. ecotechnologies on buildings and very dense urbanized areas, and considering the services of biodiversity for human population)

While the nowcasting system for extreme weather conditions developed in (1) has been developed nation-wide (covering the whole Belgian territory), the methodologies and software tools developed in (2) - (5) have been tested and demonstrated for selected Belgian cities as case-studies. More specifically, the cities of Leuven and Gent (area of Oostakker and Sint-Amandsberg) were considered as case studies. For the Leuven case, the PLURISK project was linked to the RainGain Interreg IVB NEW project, which completed in 2015. The methodologies and tools developed within PLURISK are, however, applicable to any city or urban area in Belgium.

C. Conclusions

The main conclusions on the research activities and results are:

For WP1 - Nowcasting of fine-scale extreme rainfall:

A detailed international literature review was conducted on methods and experiences in radar based fine scale rainfall estimation. Methods were selected, advanced and applied to integrate the X-band with the C-band radar observations and with rain gauge data, in order to generate hybrid spatial rainfall composites with high resolution. The results show that for both the X-band and C-band radar data, the radar estimates could be greatly improved by all the adjustment procedures. The gauge-radar residuals however remain quite large, even after the adjustments. We moreover concluded that the adjusted X-band radar measurements are not always better estimates than the corresponding C-band measurements. Further investigation showed that the rain gauges and radars could simulate the spatially more uniform winter storms with almost the same accuracy. The results are different for summer events, where the added value of the radar data becomes more evident.

Moreover, important progress was achieved with the implementation of the Short-Term Ensemble Prediction System (STEPS). The STEPS framework has shown flexibility to meet the scientific objectives of WP1 such as the non-conservative extrapolation of rain fields, uncertainty quantification of both radar observations and nowcasts, etc. STEPS-BE was set up for ensemble quantitative precipitation estimation and forecasting as well as the deterministic, probabilistic and ensemble verification of STEPS nowcasts. Additionally, the STEPS-BE software suite is able to run both in an operational environment on real-time data, as well as on archived data for case studies. Nowcasts were produced for selected storms and applied for testing the integration with the urban flood modelling in WP2 in the PLURISK case studies.

The STEPS-BE software suite was installed on the operational high-performance computing infrastructure of the RMI, which allowed for an increase of the ensemble size from 20 to 48 members. The resulting products are being tested in real time by external users, among whom the City of Ghent, the Flemish water management company Farys and the Meteo Wing of the Belgian army.

The real-time mode of STEPS-BE is being used side-by-side with INCA-BE, the current operational deterministic nowcasting system at the RMI. A new lightning module was added to this deterministic system, and the performance of this module is continuously monitored in a real-time verification utility.

To extend the skilful lead time of the STEPS-BE nowcasts, a scale- and skill-dependent blending of the radar extrapolation with numerical weather prediction (NWP) output was implemented. The blending was performed with output of ALARO, the operational, convection-permitting NWP model of the RMI that runs at a resolution of 1.3km. ALARO was adapted to produce output at the same temporal frequency as the radar to enable this blending. The blended product, STEPS-ALARO, has a 6-hour lead time and will prove useful in future early warning systems.

Weather radar data were also prepared and delivered to WP3 in order to extend the multivariate depth-damage models with rainfall-damage models. They consist of monthly maximum hourly rainfall accumulations derived from the quantitative precipitation estimation product of the Wideumont radar.

For WP2 - Two-dimensional urban flood modelling, mapping and nowcasting:

For the Leuven case, a detailed sewer system model, implemented in InfoWorks-CS, was calibrated and validated based on in-sewer measurements of water levels and flow velocities. After that, the model was applied to simulate more than 50 rainfall events, including 10 extreme rain storms. For the Gent case, the sewer model is up and running as well, and 10 extreme rain storms were simulated. The rainfall inputs were based on the different radar adjustment and fine-scale rainfall estimation methods developed in WP1, to study the effect on the sewer flow and water level results.

Based on these simulation results and applying the dual drainage approach, sewer surface inundations were modelled in a 2D way. Detailed and simplified full 2D versus 1D approaches were implemented and tested for that task. For the full 2D approach, different mesh resolutions were tested and the optimal resolution selected. To enhance the application of such 2D surface inundation modelling and mapping, simplified approaches – but identified and calibrated to the detailed approaches – were tested and implemented. This sewer inundation model has also been applied for simulation of the STEPS nowcasts provided by WP1 for selected storms, to obtain urban flood hazard maps to be combined with the urban damage functions obtained by WP3 to obtain urban flood risk maps.

For WP3 - Socio-economic risk quantification:

Based on a theoretical and analytical literature on flood damages and risks (functions), a specifically targeted questionnaire was distributed among flood victims. We managed to get the permission from the Belgian Privacy Commission to allow us to use the data from the Belgian Disaster Fund so that we could execute a large-scale written questionnaire. This created possibilities for innovative statistical analysis, which were completed. Two distinct types of multivariate flood damage models, "depth-damage" models and "rainfall-damage" models, were developed. Moreover, an intangible damage analysis was conducted with interesting findings. Also the potential damage to historic buildings and sites was explored. The "depth-damage" model was implemented for integration with the 2D sewer inundation depth results of WP2. The same was done for the "rainfall-damage" model, in view of WP4.

For WP4 - Risk communication and flood risk warning:

All PLURISK components (rainfall nowcasts, radar – rain gauge merged products, urban inundation model, socio-economic impact assessment approach) were brought together for the Gent case study to come up with a prototype integrated and multi-disciplinary urban inundation risk nowcasting system. By running the different STEPS-BE ensemble members, the rainfall nowcast uncertainty is propagated to the inundation hazard and risk results. The other uncertainties on the inundation modelling and socio-economic impact assessment are being added and propagated in that modelling chain. Different visualization approaches of the uncertainties were tested, which formed the basis for the urban inundation risk warning.

For WP5 - Risk reduction by eco-solutions:

A state of the art of concepts for eco-solutions and evaluation of such solutions was reviewed, which identified three main "gaps" in the literature. These include gaps reg. the definition of green spaces, the typology of green spaces, as well as the role of different types of green spaces in water regulation. The analysis of infiltration and runoff data collected from the literature highlighted a lack of consensus, showing the difficulty to evaluate the (function of) ecosystem services.

Assuming that ecological processes / ecosystem services depend on the spatial structure of green spaces, this structure was analysed by calculating different indices of the landscape. Five cities in the same region were studied to identify possible similarities between spatial patterns. The total amount of green spaces for the five cities was found comparable to other European cities. The size of green spaces was found increasing along an urban-rural gradient. At the same time, their density decreases. We also find that the connectivity of green spaces increases and that the shape becomes more complex along the urban-rural gradient.

Four categories of green infrastructures were identified as being useful in rainwater management, actively preventing flooding by reducing runoff. They are green roofs, bio-swales, infiltration trenches and rain gardens. Each one was developed in a specific technical leaflet. In parallel, study cases were analysed in Gent. The studied neighbourhood regularly flooded under heavy rains. A holistic analysis has been made from a spatial planning perspective to integrate the most appropriate green infrastructures in order to prevent flooding and to enhance the urban biodiversity.

D. Contribution of the project in a context of scientific support to a sustainable development policy

The PLURISK project focused on:

- "Natural risks" related to the "extreme meteorological phenomena": extreme rain storms, urban floods;
- "Areas at risk", being the Belgian society in the urban environment, and the "material cultural heritage";

and considered the following chain to describe the risks:

- Hazards: probability that fine-scale extreme high rainfall (that might induce urban flooding) will occur (variability) at a certain intensity, time and given place; and highlighting precursory signs (based on NWP), conditions that will induce urban floods (sewer hydraulics), as well as the potential aggravation of risks caused by a combination of other hazards and site effects (high downstream water levels). Uncertainties as regards to the fine-scale extreme rainfall hazards were reduced through different types of rainfall-based data sources, and explicitly quantified.
- Vulnerability: identification and evaluation of the impacts on and potential damage to, as well as potential resilience of, at-risk areas. The research in particular took into account the multiple socio-economic and environmental factors which determine or influence such vulnerability.
- Scientific support for managing risk: this involved i) evaluating risk based on the integration of scientific knowledge of the risk and the vulnerability in question; ii) analysing measurements of risk management while looking for a balance between measures to ensure early detection, prevention, impact limitation and restoration to support reduction or adaptation of the risk; and iii) analysing perception of the risk, concerns and values of society in order to suggest how to manage risk in a way that is acceptable to society and how to communicate this in a suitable manner.

The proposed research thus was multidisciplinary and systemic, and covered all three elements of the considered risk chain.

The PLURISK project more concretely aimed to support the local authorities in the quantification, forecasting, warning, control and management of pluvial floods. This aim was reached through the development and testing of methodologies and software tools for:

1. Nowcasting of fine-scale extreme rainfall, using advanced techniques for storm cell tracking and integrating national (C-band) and local (X-band) radar technology, and numerical weather prediction; quantification of the uncertainty in this nowcasting (WP1);
2. Two-dimensional fine-scale modelling, mapping and nowcasting of inundations in urban areas, and quantification of uncertainties on these inundation quantifications (WP2);

3. Socio-economic risk quantification, incl. material and immaterial (social, ecological) damage assessment, quantification of risk perception (awareness), coping capacity and recovery capacity, impacts on built heritage, and uncertainty estimation on these impacts (WP3);
4. Risk communication and flood risk warning based on the extreme rainfall and urban flood nowcasting results (WP4);
5. Risk reduction by both prevention/management and real-time control actions. New management strategies were developed by better interfacing between spatial planning, eco-management and urban water management (e.g. green – blue water; role of landscape architecture; restoration of biodiversity in urban areas incl. ecotechnologies on buildings and very dense urbanized areas, and considering the services of biodiversity for human population) (WP5).

E. Keywords

Urban, floods, cities, risks, pluvial flooding, forecasting, nowcasting, rainfall, precipitation, extremes, damage, socio-economic consequences, blue-green solutions, eco-solutions, management

1. INTRODUCTION

Cities thus are becoming increasingly vulnerable to flooding because of rapid urbanization, installation of complex infrastructure, and changes in the precipitation patterns caused by anthropogenic climate change. We still remember the recent severe sewer inundations in Belgium. They were the result of extreme local rain storms and caused high socio-economic damage. The risks of such floods induced by local, fine-scale rainfall extremes above urban areas, called 'pluvial floods', need to be assessed in a perspective of sustainable development.

This PLURISK project supported the local authorities in the quantification, forecasting, warning, control and management of pluvial floods. Methodologies and software tools were being developed for:

(1) Nowcasting of fine-scale extreme rainfall, using advanced techniques for storm cell tracking and integrating national (C-band) and local (X-band) radar technology, and numerical weather prediction (NWP); quantification of the uncertainty in this nowcasting.

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(3) Socio-economic risk quantification, incl. material and immaterial (social, ecological) damage assessment, quantification of risk perception (awareness), coping capacity and recovery capacity, impacts on built heritage, and uncertainty estimation on these impacts.

(4) Risk communication and flood risk warning based on the nowcasting results; also extreme rainfall warnings were addressed.

(5) Risk reduction by prevention and management. New management strategies were developed by better interfacing between spatial planning, eco-management and urban water management (e.g. green – blue water; role of landscape architecture; restoration of biodiversity in urban areas incl. ecotechnologies on buildings and very dense urbanized areas, and considering the services of biodiversity for human population).

These were the 5 main objectives of the project, which matched with the 5 Work Packages (WPs) of the project.

2. METHODOLOGY AND RESULTS

The different research tasks were applied to selected Belgian cities as case-studies. Two case-studies were selected at the start of the project (during the 1st Follow-up Committee meeting) after consultation of the members of the Follow-up Committee (given that these are the end users of the results). These are the cities of Leuven (given the availability of the X-band radar, the availability of a sewer system model and the support by Aquafin through the link with the RainGain project) and Gent (given the availability of a sewer system model and high interest of the city and the water company Farys that operates the urban drainage system). A third case study was discussed during the Follow-up Committee meeting. The proposed case was part of the Brussels Capital region, more specifically the Woluwe area (given its high flood hazard). One of the key problems for that case was that no sewer system model could be made available. Because this would have strong practical implications for the project, and considering the advice formulated by the international expert panel after the mid-term project evaluation, the project was limited to the two case studies, where the Gent case is selected as pilot case for bringing all components (rainfall nowcasting system, radar – rain gauge merging tools, urban inundation model, socio-economic impact assessment approach, eco-system solutions) together to come up with an integrated and multi-disciplinary urban inundation risk modelling, nowcasting and management system. The aim is that the tools developed and tested for the selected case studies are applicable to any city or urban area in the country.

The methodology and results are hereafter summarized for each of the WPs.

WP1: NOWCASTING OF FINE-SCALE EXTREME RAINFALL

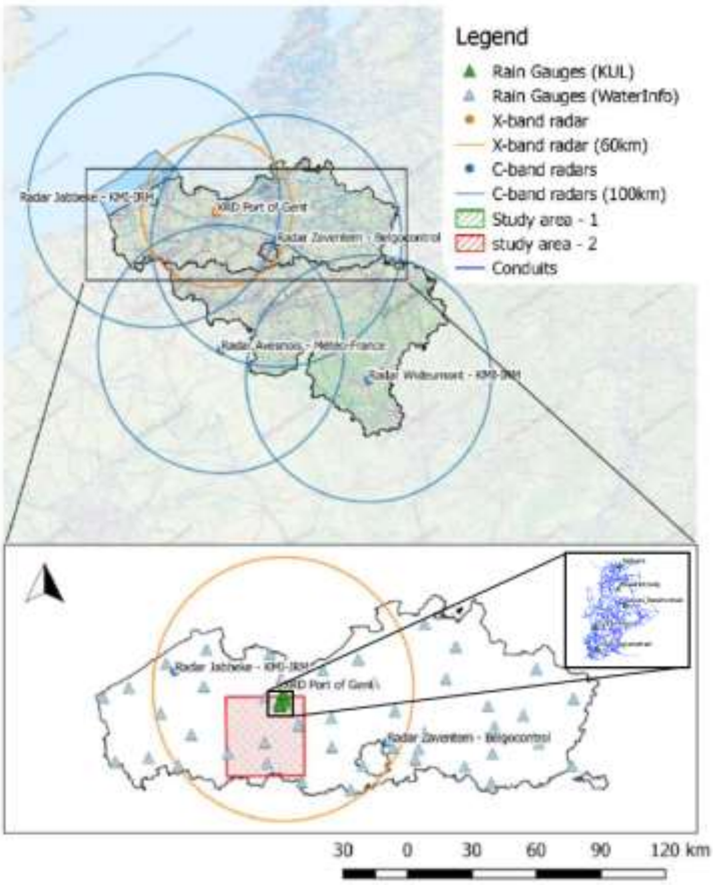
A real-time system was developed for fine-scale rainfall nowcasting (short-term forecasting). The system is based on the development of a spatial rainfall extrapolation scheme after integration of results from numerical weather prediction (NWP) with the coarse-scale C-band radar data, fine-scale X-band radar data and rain gauge data.

WP1 - Task 1.1: Calibration and evaluation of the performance of X-band radar data

The Leuven high resolution X-band radar was calibrated and evaluated for its performance and full scale acquisition of X-band radar data and merging of the X-band radar data with rain gauge data. This was done after a detailed international literature review on fine-scale radar adjustment and performance evaluation methods. A 90-pages review report has been prepared on methods and experiences in radar based fine scale rainfall estimation (Decloedt et al., 2013).

After that review, different adjustment methods were implemented and tested. More specifically, the methods "mean field bias correction (MBF)", "range dependent adjustment (RDA)", "Brandes correction", "Kriging with radar-based error correction (KRE)" and "Kriging with external drift (KED)" were applied to both the C-band and the raw X-band radar data. The results show that the raw radar estimates could be greatly improved by all the adjustment procedures. However, based on the experience of the application of these methods and some identified shortcomings, new adjustment methods were developed and tested. A first method accounts for more influential variables such as the duration of the rainfall event, the size of the rainfall field, the cloud movement speed and direction, temperature, and the convective or stratiform nature. A convective - stratiform separation algorithm (based on Steiner et al. 1995) was implemented and adapted for this local scale application. The new procedure significantly improved the X-band fine-scale rainfall estimated, as shown after comparison with the rain gauge data. This was first done for the rainfall data provided by Aquafin since 2008, by 9 tipping-bucket and 3 non-recording rain gauges in and surrounding the Leuven case study area. The same was afterwards done for the 2 X-band radars that were installed for the PLURISK project - in kind by the Japanese company FURUNO - in the Gent case study area. For the Leuven area, 5 additional rain gauges were installed by Aquafin in summer 2012. For the Gent case, 5 additional rain gauges were installed in spring 2015. All these new rain gauges were calibrated within the scope of this project, using a dynamic calibration approach. The outcome of that calibration were calibration curves, that support the correction of the rainfall intensities as a function of the intensity (higher underestimation for higher intensities because of the tipping-bucket measuring principle, and the loss of rain water during the tipping movements of the buckets). After these corrections, two other adjustment procedures were developed and tested: based on quantile mapping, and a Bayesian adjustment method extended with an innovative local singularity sensitive method to improve the merging under the presence of local rain cells (convective storms). These new procedures for radar adjustment were applied to improve the available C-band and X-band radar data based on all available rain gauge data. One of the problems detected during this application was the existence of clutter. Some grid cells in the radar images were found influenced by permanent clutter. Therefore, the rainfall data for these grid cells were filled by spatially interpolating the rainfall intensities at the neighbouring cells. Next to the spatial interpolation, also temporal interpolation was studied; given that one of the findings of our impact analysis (WP1 & WP2) was that the temporal resolution of the rainfall input for urban flood modelling applications is more important than the spatial resolution.

Three international journal papers were written on the data merging and evaluation (Wang et al., 2015a,b; Ochoa-Rodriguez et al., 2015), and the techniques and analysis were presented at several international conferences and workshops.



The Ghent study area together with the different rainfall data sources

X-band Radars in Gent – FURUNO WR2100 Smallest dual-pol X-band radar

2 scans each for elevation at 0 degree, 2 degree, and 4 degree.

Spatial resolution: 100m in range, approx 0.75 degree in azimuth

Temporal resolution: 1 min

Products in:

- rr (Rainfall intensity);
- **Zhh (Horizontal reflectivity);**
- V (Doppler speed);
- Zdr (Reflection factor difference);
- Kdp (Propagation Phase Difference rate of change);
- Φdp (Differential phase shift);
- Phv (Correlation coefficient before horizontal and vertical);
- W (Doppler speed width).

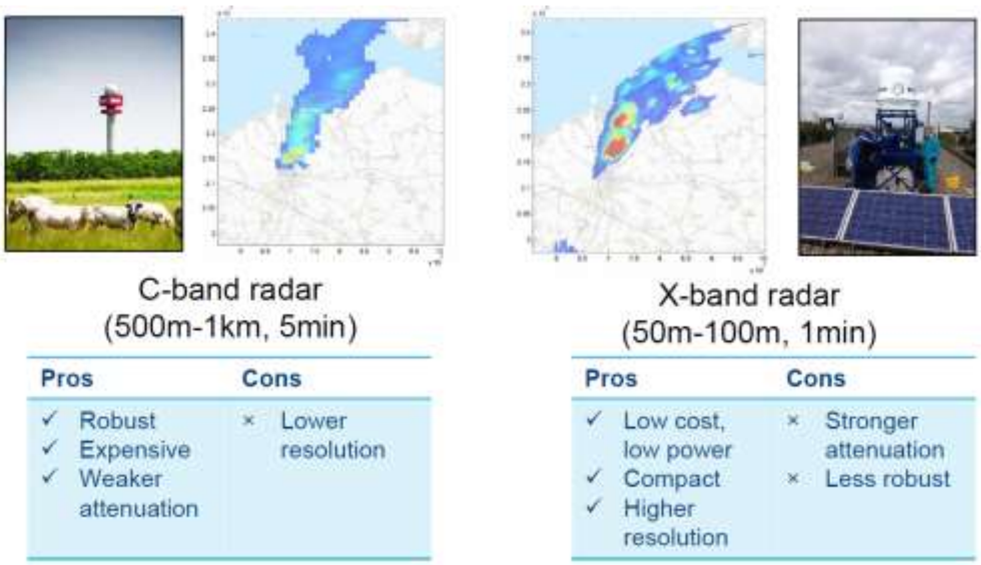
The properties of the two FURUNO WR2100 installed in Ghent within the scope of the PLURISK project

WP1 - Task 1.2: Integration of C-band and X-band radar data with rain gauge data to generate hybrid spatial rainfall composites

A detailed international literature review has been made on methods for merging/integrating different rainfall sources, which are in this case: rain gauges, X-band radar data for the Leuven case and radar data by the C-band radars of the Royal Meteorological Institute of Belgium (RMI). Based on that review, recommended methods were selected and applied to integrate the X-band with the C-band radar observations and with rain gauge data, in order to generate hybrid spatial rainfall composites with high resolution. The results of Task 1.1 are considered for the X-band radar data. First, comparison was made of the results of Task 1.1. with similar results obtained after merging of the C-band radar data with rain gauge data. This was done for 10 extreme historical rain storms. They were selected based on the full time series of available rainfall data and information collected on the dates of recent historical floods in the study areas.

Overview of the different C-band and X-band radars considered in this project

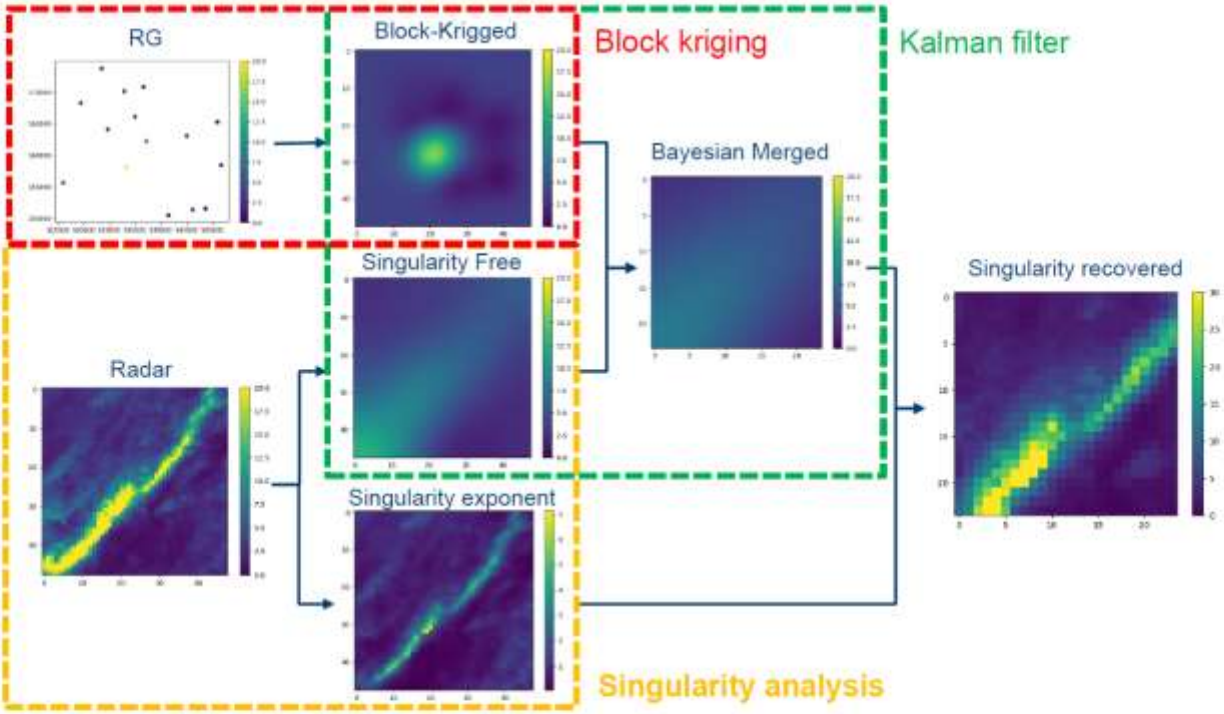
More specifically, the basic methods MBF, RDA, Brandes correction, KRE, KED, and Bayesian adjustment were applied as well as the new singularity-sensitive Bayesian method developed in Task 1.1. They were applied to the raw data of the C-band radar at Wideumont and compared with the results of Task 1.1 for the X-band radar data at Leuven. The rain gauge data provided by Aquafin for the Leuven case and those of the new rain gauges installed for the Gent case were used as supplementary information. The results show that also for the C-band raw radar data, the radar estimates could be greatly improved by all the adjustment procedures. The gauge-radar residuals however remain quite large, even after the adjustments. We moreover concluded that the adjusted X-band radar measurements are not always better estimates than the corresponding C-band measurements, although the newer generation X-band radars (FURUNO WR-2100 city radars; as installed at Gent) clearly outperforms the older generation X-band radar (as installed at Leuven). This was tested based on different statistical indicators for the summer and winter periods after the adjustments on the X- and C-band radar based estimates. Results moreover showed that the rain gauges and radars could estimate the spatially more uniform winter storm intensities with almost the same accuracy. The results are different for the extreme summer events, where the added value of the radar data becomes more evident. The analysis has been presented at several international conferences and workshops, and an international journal paper on this topic is in preparation.



Overview of the main pros and cons of the C-band and X-band radars tested in the PLURISK project

Category	Methods	Description
Simple error computing-based	Mean Field Bias (MFB)	global mean field applied across the domain
Geostatistical-based	Block Kriging (BK) Kriging with External Drift(KED)	local mean field inferred from rain gauge/radar data
Bayesian-based	Bayesian Merging(BM, Todini, 2001); Singularity-Bayesian Merging(SINM, Wang et al., 2015)	co-variance of estimation errors from radar and rain gauges

The different methods evaluated in the PLURISK project for merging of the different rainfall data sources (C-band radar data, X-band radar data and rain gauge data)



The new singularity sensitive Bayesian merging method, for enhanced estimation of convective rain cells

WP1 - Task 1.3: Implementation and testing of real-time fine-scale rainfall forecasting

Activities on the development of a fine-scale rainfall forecasting system were already initiated at the RMI prior to the PLURISK project. A comprehensive literature review on quantitative precipitation forecasts was carried out in 2008 (Reyniers, 2008). In recent years, the RMI gradually implemented a nowcasting system for precipitation, which is largely based on the INCA system (Haiden et al., 2011) developed at ZAMG, Austria. In its current form, the software suite produces every ten minutes a deterministic precipitation forecast for four hours ahead, with a time step of 10 minutes and a spatial resolution of 1 km. The current implementation combines C-band radar observations with real-time gauge data, and merges this information with NWP output. An area correlation method supplemented with NWP information is used to determine the displacement of the precipitation field.

The performance of the Belgian implementation INCA-BE is overall satisfying. Current users include the forecasters of the RMI, OMS (Oceanografisch Meteorologisch Station) and Meteolux, the regional hydrological authorities VMM (Vlaamse Milieumaatschappij) and SPW (Service Public de Wallonie), and the Belgian aviation agency Belgocontrol. Recent additions to the system include the integration of lightning data to the precipitation module of INCA-BE. A "lightning activity field" has been defined for this purpose, and is advected along with the precipitation. This advected field has to be interpreted as a "risk zone" where lightning can potentially occur. The lightning forecast has been verified on some recent cases. A new INCA-BE module was developed for this purpose, allowing an online verification of the produced lightning activity forecast.
The existing system was taken as a benchmark for the development of the new real-time ensemble rainfall forecasting system STEPS (Bowler et al., 2006), a state-of-the-art probabilistic nowcasting system developed at Bureau of Meteorology (BOM) in collaboration with the UK MetOffice. STEPS is one of the few nowcasting systems that can provide both a forecast and an estimation of its associated uncertainty using the ensemble framework. The additional nowcast products that were derived from the STEPS ensemble are the ensemble mean forecast, which accounts for the predictability limits of rainfall fields, and probabilistic forecasts of exceeding various precipitation thresholds.

A Belgian version of STEPS has been developed in the project, denoted as STEPS-BE. It provides a non-conservative extrapolation of rainfall fields (growth and decay) and uncertainty quantification of both rainfall estimations and forecasts. Several efforts were done in order to ingest the Belgian radar data, calibrate the system and derive a number of forecast products. STEPS-BE was implemented in archive and real-time modes to provide ensemble nowcasts up to 2 hours lead time at 5-minute temporal and 1 km^2 spatial resolution. The archive mode served to generate a set of nowcasts for the PLURISK case studies. Forecast products were delivered over the case study regions of Leuven and Ghent separately, which reduces the data storage requirements. Testing and calibration of the ensemble QPE results were done. Some technical advances were also realized to improve STEPS, in particular to speed up its computations and to obtain reliable forecasts also for cases with isolated convection. Through collaboration with Alan Seed at the Australian BOM, regular exchanges were made of research advancements, source code and joint publications around STEPS. Two international journal papers were written: one on the STEPS implementation, calibration and verification for Belgium, and another one analyzing the scale-dependence of the rainfall predictability by STEPS (Foresti and Seed, 2014; Foresti et al., 2016).

STEPS-BE has been successfully running in real-time at RMI since February 2015. STEPS-BE provides 20 member ensemble precipitation nowcasts at 1 km and 5 min resolutions up to 2 hours lead time using a 4 C-band radar composite as input (Wideumont, Zaventem, Jabbeke, Avesnois). STEPS-BE exploits the visualization interface of INCA-BE, which allows taking full advantage of the multi-dimensional information content of probabilistic and ensemble forecasts. Training sessions were given to weather forecasters and to our end users at the city of Ghent, who provided feedback during the PLURISK Final Symposium. A couple of major code improvements were included in STEPS-BE, in particular to obtain smoother velocity fields and to condition the stochastic simulations within the advected radar domain. The forecasts of STEPS-BE were verified using recent precipitation events that caused flooding in Belgium including floods in Leuven and Ghent, including the 30^{th} May 2016 event and several other extreme rainfall events in the period May-June 2016, which caused severe pluvial flood consequences in many places in Belgium (total flood damage of around 300 10^6 EUR).

In 2015, the entire STEPS-BE software suite was migrated to the new high performance computing (HPC) infrastructure of the RMI. The aim of that migration was twofold: (1) running STEPS-BE in a monitored, operational environment, and (2) allowing for additions and improvements that require more computing power. On the new computing cluster, STEPS-BE runs faster and has more computing resources, which allows an increase of the ensemble size from 20 to 48 members and to extend the forecast lead time from 2 to 6 hours.

However, in order the extend the lead time up to 6 hours, and to avoid a lack of skill for longer lead times, blending with NWP precipitation forecast is required. This blending was implemented in 2017. The NWP forecast field is treated with the same procedure as the radar field (decomposition in a multiplicative cascade), and the blending is done at cascade level. The weights of this blending are dynamically determined, and regressed towards values that represent the climatological skill of the components.. This involves (1) determining the respective climatological cascade-level-dependent skill of the radar nowcast and NWP and (2) implementing a real-time skill estimation, per cascade level, to determine the real-time weights of the radar nowcast and NWP. More specifically:

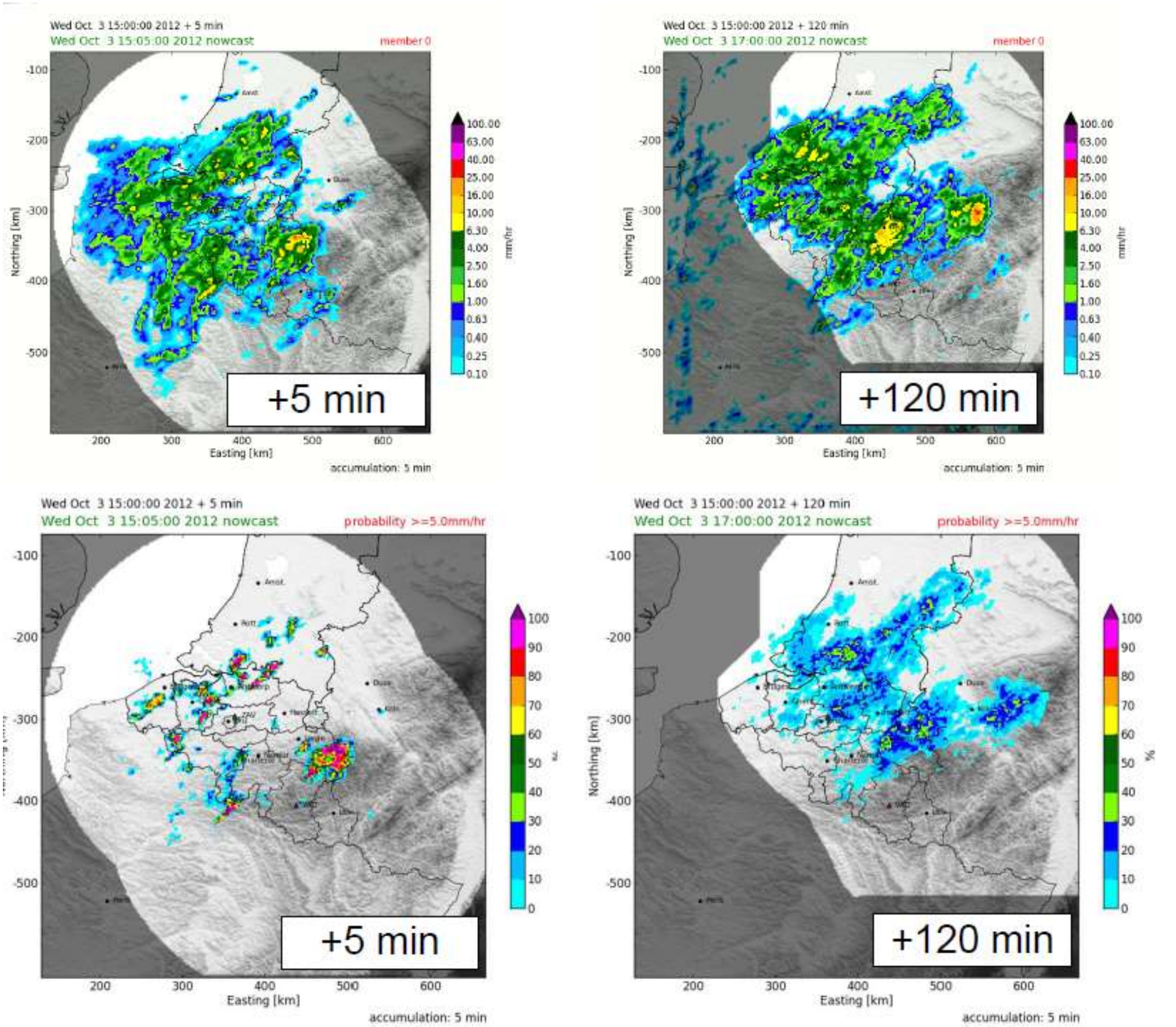
- The skill of each cascade level of the radar extrapolation is determined by the Lagrangian autocorrelation. The hierarchy of AR-1 processes evolve the expected skill of each cascade level with increasing lead time.
- The correlation of the respective cascade levels of the radar rainfall analysis and the corresponding NWP forecast determines its skill at zero lead time. As the lead time increases, the NWP skill is regressed towards a climatological skill for each cascade level.
- The weight of the stochastic noise contribution for each cascade level is chosen so that the quadratic sum of the three weights is equal to one.

To account for seasonal variations, a rolling window of 1 month is used to compute climatological skill of the NWP forecasts.

In order to realise this advanced radar-NWP blending in STEPS-BE, the precipitation output frequency of ALARO, the operational NWP model of the RMI (usually 1h) has been decreased to be closer to the time step of STEPS-BE. The precipitation is stored per time step (45s) and re-aggregated into 5-minute accumulations, which corresponds to the temporal frequency of the radar images. This important prerequisite for a smooth blending was only possible by fully exploiting the capabilities of the new HPC infrastructure of the RMI.

The validation and operational set-up of this combined product, STEPS-ALARO, is ongoing follow-up work. The STEPS-ALARO combined nowcast will prove useful as the short-term component of a seamless early warning system. For a seamless, probabilistic early warning system, one can even perform the blending in STEPS-ALARO with RMI-EPS, the high-resolution 22-member ensemble prediction system of the RMI. In practice, this would involve blending a number of STEPS-members per NWP-member to create a mega-ensemble with (1) a better short-term skill thanks to the radar extrapolation component, (2) a better representation of uncertainty and variability at all time and spatial scales due to the STEPS formalism, (3) the long-term skill of NWP and (4) a better-represented uncertainty at longer lead times, provided by the NWP EPS.

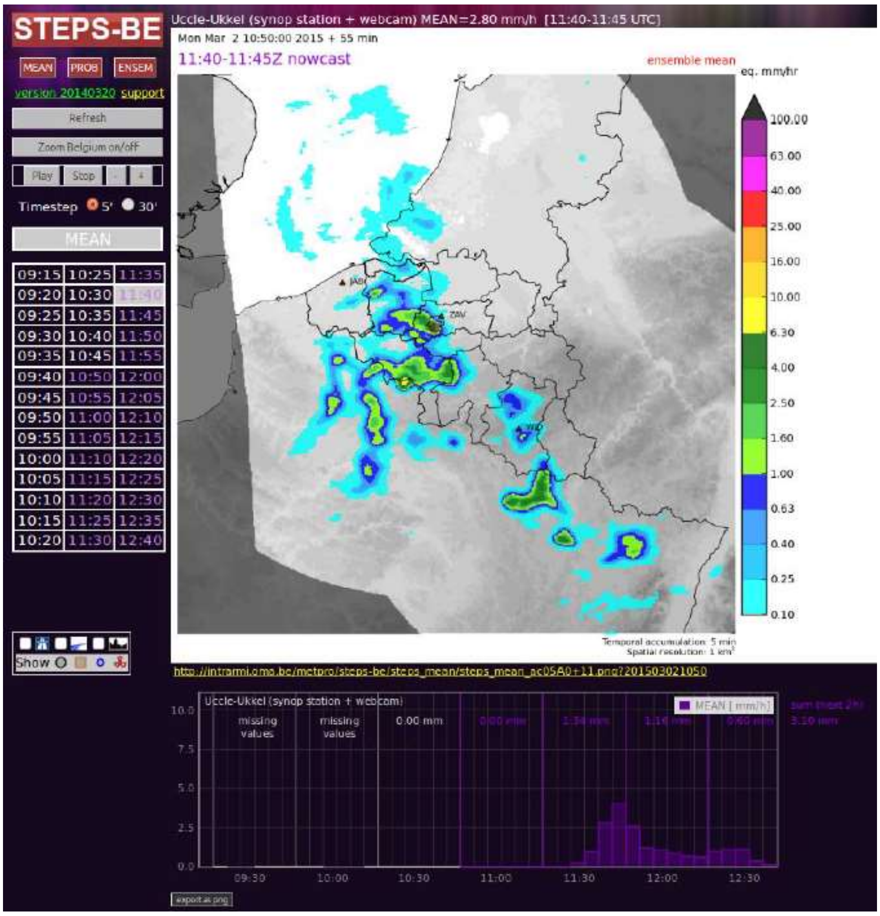
One can even envision the integration of STEPS-ALARO with INDRA, the probabilistic INtegrateD RMI Alert system that is based on EPS output for various time horizons, from days (RMI-EPS, GLAMEPS) to weeks (ECMWF's ENS) ahead. This integration would result in a fully seamless, probabilistic early warning system that could provide alerts from hours up to weeks ahead.



Example of STEPS-BE probabilistic rainfall nowcasts. Upper panel: results for one of the ensemble members; Bottom panel: probabilities of rainfall intensities exceeding 5 mm/h, for different lead times

The real-time mode of STEPS-BE is currently being used side-by-side with the existing operational nowcasting system INCA-BE by weather forecasters of RMI to issue warnings of high-impact weather (WP4). External test users of the STEPS-BE products, include the City of Ghent, the Flemish water management company Farys and the Meteo Wing of the Belgian army. They have access to the interactive STEPS-BE viewer.

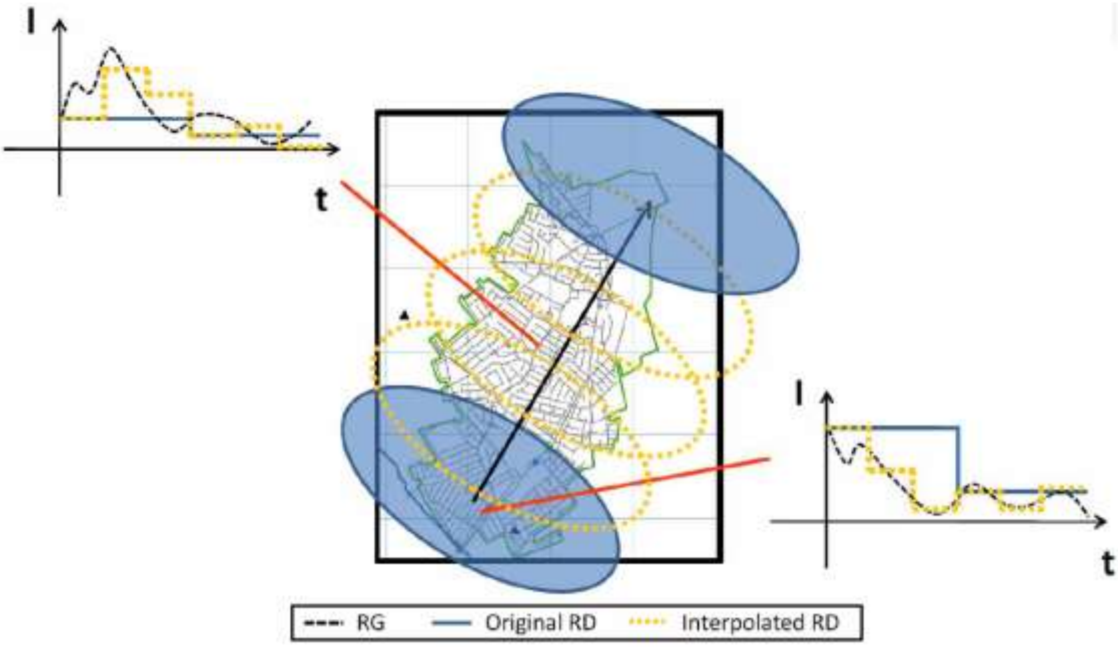
STEPS-BE is being developed side by side with INCA-BE, which still provides more capabilities than STEPS, e.g. convective analysis fields and a new lightning nowcasting module.



The STEPS-BE viewer, ready for use by end users such as city authorities

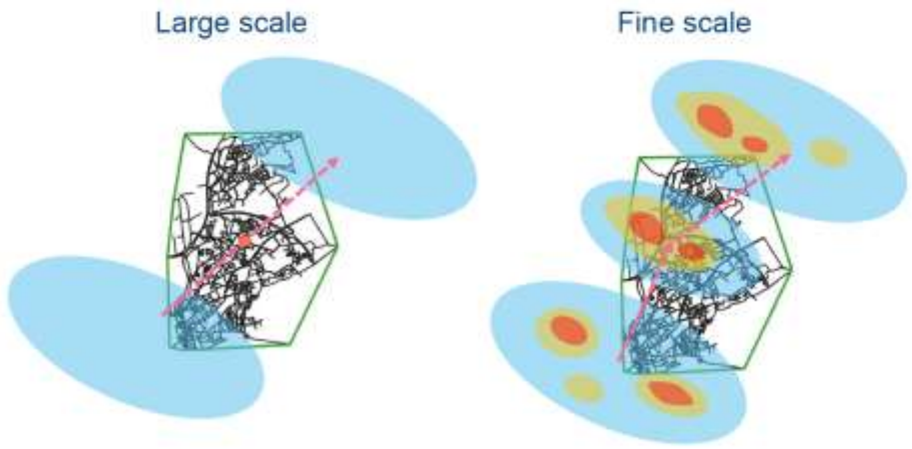
WP1 - Task 1.4: Downscaling of C-band radar data

Because it was learned from Task 2.1 that temporal resolution is more important than spatial resolution for the impact results on the urban inundations – because of the very quick response time of urban drainage systems – a new method for temporal interpolation of the 5-min C-band data to 1-min temporal resolution was developed and tested. The proposed methodology entails two main steps: (1) Temporal interpolation of radar images from the originally-available temporal resolution (i.e. 5 min) to the finer resolution at which the local rain gauge data are available (i.e. 1 min). This is done using a novel interpolation technique, based upon the multi-scale variational optical flow technique, and which can well capture the small-scale rainfall structures relevant at urban scales. (2) Local and dynamic gauge-based adjustment of the higher temporal resolution radar rainfall estimates is performed afterwards, by means of the Bayesian data merging method. The proposed methodology was tested using a total of 8 storm events observed in the Leuven case study. The results indicated that the proposed methodology for temporal downscaling can provide significantly improved radar rainfall estimates and thereby generate more accurate runoff simulations at urban scales, over and above the benefits derived from the mere application of Bayesian merging at the original temporal resolution at which radar estimates are available. The benefits of the proposed temporal interpolation + merging methodology are particularly evident in storm events with strong and fast-changing (convective-like) rain cells. The method was published in Journal of Hydrology (Wang et al., 2015b).

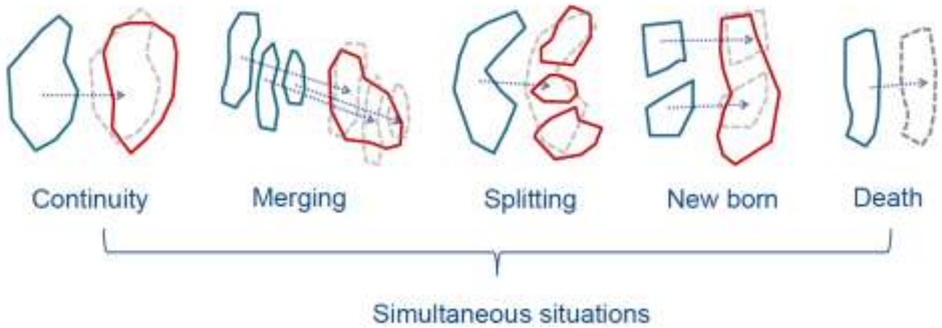


The optical flow temporal downscaling method developed in the PLURISK project (Wang et al., 2015b)

Because it is expected that further advancements can be made on this method, conducting the temporal interpolation based on an enhanced rain storm and cells tracking algorithm, research was initiated on such tracking. A new object-based storm tracking algorithm, based upon TITAN (Thunderstorm Identification, Tracking, Analysis and Nowcasting), was proposed. TITAN is a widely-used convective storm tracking algorithm but has limitations in handling small-scale yet high-intensity storm entities due to its single-threshold identification approach. It also has difficulties to effectively track fast-moving storms because of the employed matching approach that largely relies on the overlapping areas between successive storm entities. To address these deficiencies, a number of modifications were proposed and tested in this paper. These include a two-stage multi-threshold storm identification, a new formulation for characterizing storm's physical features, and an enhanced matching technique in synergy with an optical-flow storm field tracker, as well as, according to these modifications, a more complex merging and splitting scheme. The C-band radar (5-min and 529-m) radar reflectivity data for 18 storm events over Belgium were used to calibrate and evaluate the algorithm. The performance of the proposed algorithm was compared with that of the original TITAN. The results indicated that the proposed algorithm can better isolate and match convective rainfall entities, as well as to provide more reliable and detailed motion estimates. Furthermore, the improvement is found to be more significant for higher rainfall intensities. The new algorithm has the potential to serve as a basis for further applications, such as storm nowcasting and long-term stochastic spatial and temporal rainfall generation. The new tracking method and algorithm was published in Atmospheric Research (Muñoz et al., 2018).



Object-based storm tracking method for fine-scale rainfall nowcasting, developed by the PLURISK project



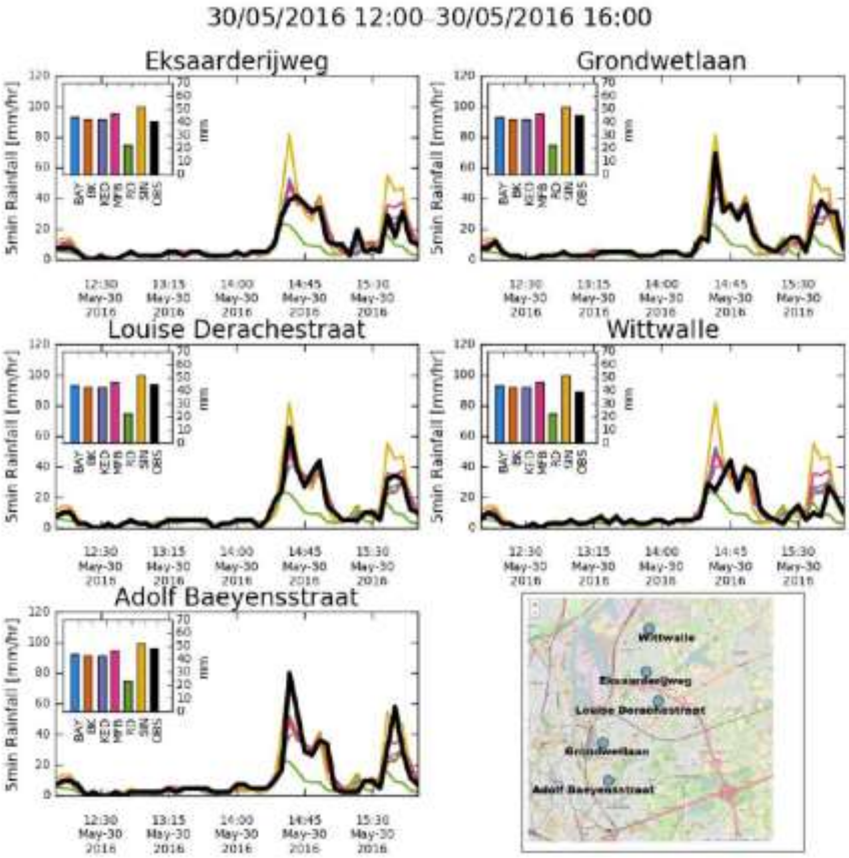
Different types of situations for rain cell splitting/matching considered in the new object-based storm tracking method

Also the calibration of a conceptual rain storm model has been tested as part of that process, albeit the conceptual rain storm model would also be very useful for other rainfall modelling tasks (spatial interpolation, stochastic rainfall generator). Both the temporal downscaling and the storm and cell tracking algorithms were extensively tested based on the C-band radar data. The outcomes have been presented at several international conferences and workshops.

For the spatial downscaling, the random cascade based method was tested in cooperation with Auguste Gires of ParisTech in France. It makes use of a random cascade approach, and scaling properties of rainfall both in space and in time. It allowed information to be obtained on the uncertainty in the downscaled rainfall intensities. A joint journal publication on the method has been delivered (Gires et al., 2017).

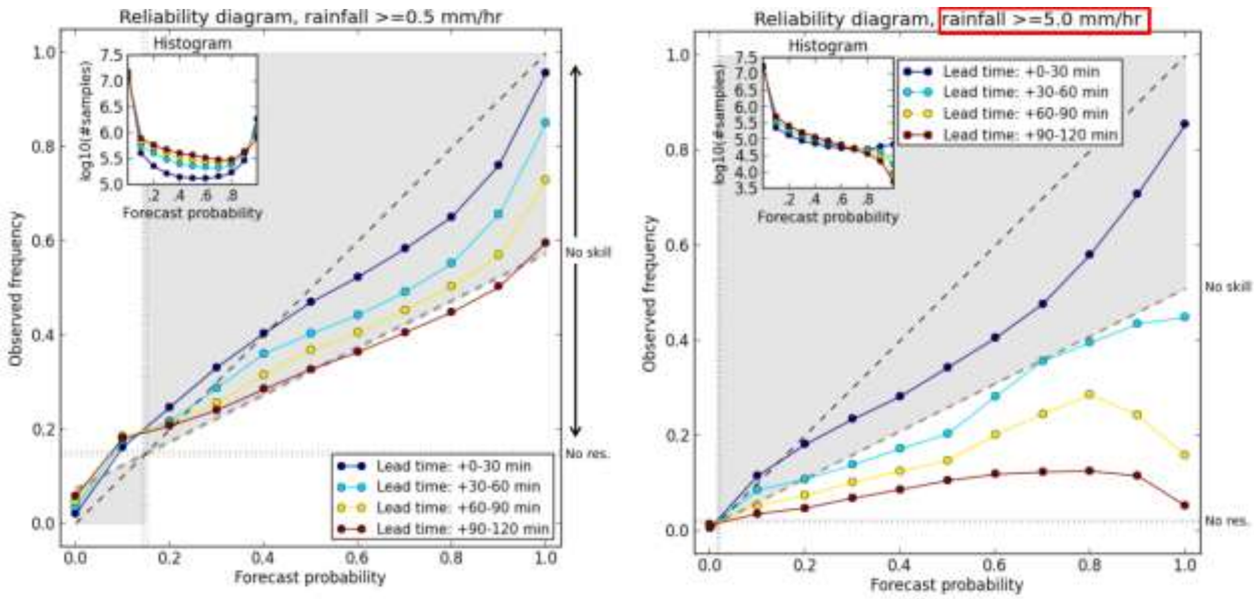
WP1 - Task 1.5: Uncertainty estimation on fine-scale rainfall estimation and forecasting

A detailed review was made of the international literature on available methods for uncertainty estimation of fine-scale rainfall estimates. These can be classified broadly in approximate analytical methods, techniques based on statistical analysis of model errors, approximate numerical methods or sensitivity analyses, and non-probabilistic methods (based on random set theory, evidence theory, fuzzy set theory or possibility theory). Based on that review, a non-parametric data-based approach was developed and implemented. The method is based on the estimation of the empirical frequency distribution of rainfall residuals (in relation to the rainfall intensity and the lead time) from historical rainfall forecasts. It allows the rainfall estimates to be accompanied with confidence intervals.



Evaluation of the different rainfall merging methods for the extreme 30th May 2016 event, based on the 5 rain gauges installed for the Ghent case within the scope of the PLURISK project

An extensive deterministic, probabilistic and ensemble verification of STEPS-BE nowcasts was performed for the entire domain of Belgium using precipitation events that caused sewer system floods in the cities of Leuven and Ghent (Foresti et al., 2016). The results demonstrated that probabilistic nowcasts are quite reliable, but also reveal the need for improving the quality of the radar observations that are used as inputs. The predictability of large areas of rain is lost after roughly 2 hours, while the one of small convective showers already after half an hour. This result is consistent with previous findings in the literature. According to the ensemble spread, the forecast uncertainty is slightly underestimated, i.e. the STEPS-BE ensembles are slightly underdispersive. For the case studies considered, the multiplicative forecast biases over the cities of Leuven and Ghent are small and comprised between -0.5 and +0.5 dB.



Reliability (= agreement between forecast probability and observed frequency) of the STEPS-BE probabilistic rainfall forecasts, for rainfall thresholds of 0.5 and 5 mm/h and different lead time ranges:

The STEPS framework can also be used to generate ensembles that represent the radar measurement uncertainty, which is considered as the residual errors with respect to rain gauges. Some tests and comparisons of radar ensembles with rain gauges were done in summer 2014 and presented at the ERAD conference (Foresti et al., 2014). However, more developments are needed to produce radar ensembles with the correct spatio-temporal correlations and spread of the errors.

An uncertainty estimate was added to the precipitation module of the operational nowcasting system INCA-BE by post-processing the deterministic output. This feature was added to the smartphone app of the RMI, and will contribute to a familiarisation of the broad public to probabilistic forecasts.

WP1 - Task 1.6 Organization of an international workshop on fine-scale rainfall estimation and nowcasting

On 31 March 2014, an international workshop on fine-scale rainfall estimation and nowcasting was held at Antwerp. This was done in cooperation with the RainGain project. 42 international and national experts in radar technology, rainfall statistical analysis, NWP and rainfall forecasting participated. The PLURISK WP1 results were presented at the workshop by Maarten Reyniers (RMI), Loris Foresti (RMI), Lipen Wang (HYDR) and Patrick Willems (HYDR), but also 7 international participants presented their recent (research) activities on rainfall nowcasting. Another workshop supported by the World Meteorological Organization Nowcasting Group, was organized in Munich on 30-31 August 2014 by Loris Foresti, Alan Seed and Isztar Zawadzki. This WMO workshop helped understanding which are the feasible research directions given the available computational and human resources. The representation of radar measurement uncertainty by means of radar ensembles, the forecast verification and real-time prediction of the expected forecast accuracy were identified as examples of interesting and achievable research topics. Another workshop, in the form of a symposium, was organized at the end of the PLURISK-project, on 4 October 2017 in Brussels, in order to disseminate the final outcomes of the project. The PLURISK WP1, WP2, WP3 and WP4 results were presented by the different project partners. Four members of the PLURISK Follow-up Committee and key end users of the PLURISK outcomes gave a presentation on their experiences. The city of Ghent gave feedback on their testing of the STEPS-BE system and the pluvial flood model results.

International workshop on fine-scale rainfall estimation and nowcasting, 31 May 2014 at Antwerp

WP1 - Main conclusions

A detailed international literature review was conducted on methods and experiences in radar based fine scale rainfall estimation. Based on that review, different adjustment methods were implemented and tested and a new, innovative adjustment method has been developed that accounts for more influential variables, rainfall quantile biases and local singularities. The new procedures significantly improved the fine-scale rainfall estimates, as shown after comparison with the rain gauge data. This was done for the rainfall data provided by Aquafin since 2008 for 8 rain gauges in and surrounding the Leuven case; and 4 rain gauges for the Gent case. For the Leuven case, 5 additional rain gauges were installed in summer 2012 and a dynamic calibration was conducted. Idem for 5 additional rain gauges installed for the Gent case in spring 2015.

Also methods were selected and applied to integrate the X-band with the C-band radar observations and with rain gauge data, in order to generate hybrid spatial rainfall composites with high resolution. First, the different adjustment methods were tested also for the C-band radar data. The results show that also for the C-band raw radar data, the radar estimates could be greatly improved by the adjustment. The gauge-radar residuals however remain quite large, even after the adjustments. We moreover concluded that the adjusted X-band radar measurements are not always better estimates than the corresponding C-band measurements. Further investigation showed that the rain gauges and radars could simulate the spatially more uniform winter storms with almost the same accuracy. The results are different for summer events, where the added value of the radar data becomes more evident.

As additional activity, a rain storm and cells tracking algorithm has been implemented and tested incl. calibration of a conceptual rain storm model. This activity was not planned, but considered important in support of conducting the temporal interpolation of the C-band data for the urban hydrological impact focus of this project. Another additional, not planned, activity was the installation of two new X-band radars for the case study of Gent, provided in kind by the Japanese company FURUNO.

The generation of STEPS ensemble precipitation estimates and nowcasts for the PLURISK case studies and the associated forecast verification are successful. It is shown that the predictability is limited to the first two hours for large areas of rain but only to half an hour for smaller convective showers. Ensemble rainfall nowcasts are produced as essential inputs for WP2. Additionally, the STEPS-BE software suite was migrated towards a fully operational, monitored and powerful (HPC) environment which will allow further development of the suite.

Two international workshops were supported: one on fine-scale rainfall estimation and nowcasting in collaboration with the EU-project RainGain (Antwerp, 31 March 2014), and another one with support by the WMO Nowcasting Group (Munich, 30-31 August 2014). A final PLURISK-symposium was organized on 4 October 2017 in Brussels for dissemination of the project outcomes to our end users.

WP2: TWO-DIMENSIONAL FINE-SCALE MODELLING, MAPPING AND NOWCASTING OF INUNDATIONS IN URBAN AREAS

The fine-scale rainfall estimates (after merging of the X-band and C-band based spatial rainfall data with the rain gauge data, or after downscaling) and the rainfall forecasts were simulated in the sewer network models of the case studies. Existing models were used for that purpose, such as the existing models implemented in the InfoWorks-CS software for the Leuven and Gent cases. The improvement in the hydraulic simulation results due to the use of fine-scale rainfall estimates (the outcome of WP1) was analyzed. This was done by comparing the simulation results obtained with the traditional rainfall input (based on rain gauge data only), with the use of the coarse-scale but calibrated C-band radar data, and with the use of the fine-scale rainfall estimates (after merging of X- and C-band radar data and rain gauge data, or after downscaling). Comparison is also made with discharge and water level measurements in the sewer systems. For the Leuven case, flow survey campaigns were made available by Aquafin. For the Gent case, this was done by Farys; idem for water level data at pumping stations.

After validation of the fine-scale rainfall estimates and model simulation results, the fine-scale rainfall forecasts of WP1 were simulated in the model to obtain forecasts in the hydraulic variables (discharges and water levels in the sewer system). The existing sewer system models are traditional in the sense that they do not consider hydraulic simulation of inundations. The software therefore was extended to allow 2D modelling and mapping of surface inundations.

WP2 - Task 2.1: Simulation of the historical X-band and C-band based fine-scale spatial rainfall estimates and forecasts in sewer system models

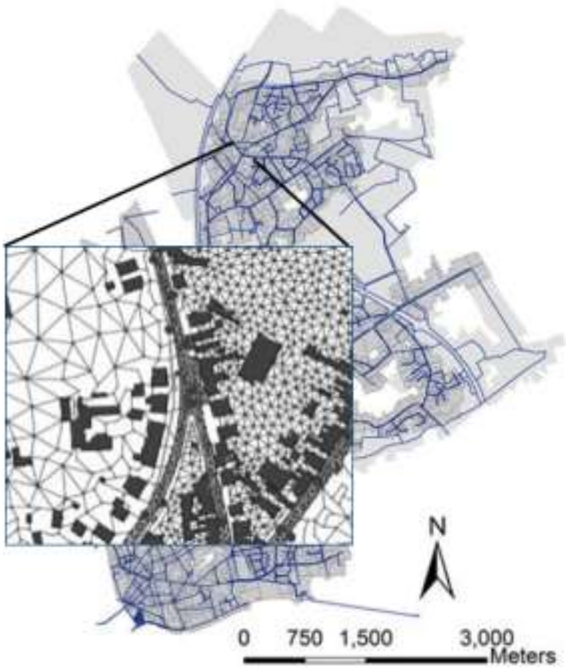
For the Leuven case, it was agreed with Aquafin to focus on the area of Wilsele-Herent-Wijgmaal. A sewer system model, implemented in InfoWorks-CS for that area, was made available by Aquafin. The different types of rainfall inputs, after application of the different adjustment methods tested and developed in WP1, were implemented in the sewer model. In-sewer measurements of water levels and flow velocities were available for 2 pipes in the system and water level measurements at 3 overflows. After a detailed calibration and validation of the sewer system model, the model was applied to simulate the historical rainfall events. The effect of the different types of rainfall input was investigated. It was found that the results strongly depend on the spatial density of the rain gauge data considered as well as on the radar adjustment method. Additional simulations were done to further explain the results and to explain the total model residuals, given that these residuals are due to three types of uncertainties: the uncertainties related to the rainfall input, the uncertainties related to the sewer system model and the sewer measurement errors.

For the Gent case, close cooperation was set with the company Farys (formerly Water-Link). It was agreed that for the city of Gent, the area of Oostakker - Sint-Amandsberg is studied, because it is a flood-prone area and because a good sewer model is already available for that area. Access was given to that sewer model as well as to the related data on the sewer system properties. Investigation was done on the rain gauge data available for that area. Only two rain gauges were found available close to the study area, and few other rain gauges at larger distance. For that reason, five additional rain gauges were installed by Farys, with the practical support of the Hydraulics Section of KU Leuven. A high-resolution Digital Terrain Model (DTM) for the Gent case was made available by the Agentschap AGIV. Also a database on the recent flood events in the Gent case was collected. After several meetings and exchanges with the Japanese company FURUNO, KU Leuven – Hydraulics Section, Farys, and the owners of buildings, two X-band radars (provided in kind, for research purposes) were installed around the Gent study area. The available rain gauge and C-band radar data, merged after application of the different adjustment methods tested and developed in WP1, were implemented as rainfall inputs to the sewer models. This was done for the different extreme historical rainfall events selected for WP1. Because at the start of the project, similar activities were ongoing within the EU RainGain-project for case studies in the UK, collaboration was setup with researchers from Imperial College London (prof. Christian Onof, prof. Cedo Maksimovic). Several international conference and journal papers were prepared together with this group; by testing whether conclusions are robust for different case studies in Belgium, UK, France and The Netherlands. A journal paper was published in Journal of Hydrology (Ochoa-Rodriguez et al., 2015).

WP2 - Task 2.2: Extension of the current models with a 2D surface flood calculation module

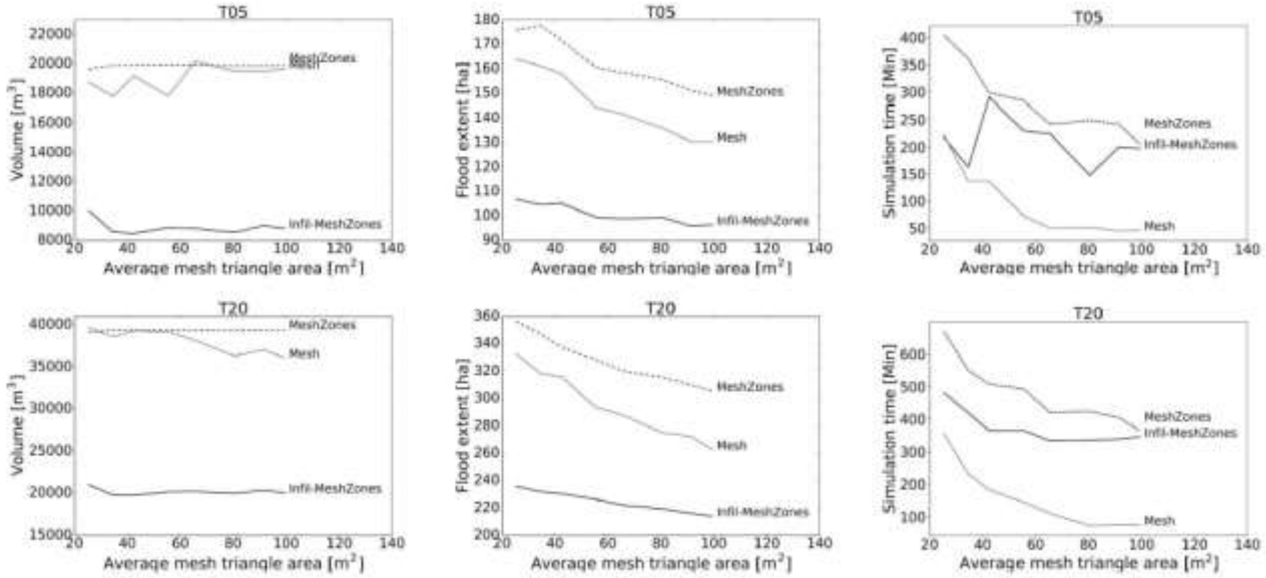
Based on the sewer system models for the Leuven and Gent cases (implemented in the InfoWorks CS software), different methods for 2D surface flood modeling and mapping were investigated. This was done incorporating the dual drainage concept into the modelling of the urban drainage systems. This concept distinguishes between the sewer system (modelled in 1D, following the sewer pipes) and the surface system (overland flowpaths, water courses and other surface features). Two types of surface systems were considered: 1-dimensional (1D) urban surface models (based on flood cones), coupled with the model of the sewer system and 2-dimensional (2D) models, where the surface is coupled to the sewer model but in a more accurate way. This led to two sewer-surface combinations: 1D/1D and 1D/2D.

In the 2D implementation of the sewer catchment surface, the sewer catchment was discretized as a continuous mesh of regular or irregular elements (triangles). The mesh generation was based on the digital terrain model (DTM) of the catchment. In addition, land use and soil type were specified as parameters of each grid element. For the Gent case, a new high resolution DTM (0.5 m) were obtained from AGIV. For the Leuven case, the older DTM with 5 m spatial resolution was applied. Green areas in the catchment were identified and used to define surface infiltration areas and parameters. In order to decrease the computational time, an adaptive grid based method was applied. Main streets as mesh zones together with buildings as void regions constitute one specific mesh resolution ($3.75m^2$ – $15m^2$) and they have been included since they channel most of the flood water from the manholes and they improve the accuracy of interactions within the 1D sewer network. Other areas that recorded flooding outside the main streets have been also included, but with a second mesh resolution for the accurate determination of flood maps ($12.5m^2$ – $50m^2$). Permeable areas have been identified and used as infiltration zones using the Horton infiltration model. A mesh sensitivity analysis has been performed for the low flood risk areas, where after a third mesh resolution of $75m^2$ – $300m^2$ was chosen. Comparing flood mapping outcomes produced by flood cones (1D) or 2D urban surfaces with or without infiltration for several synthetic and historical storm events shows that the 1D approach leads to systematic biases (overestimations) in flood depths and areas. By including the infiltration model, reduction of flood extents has been observed in the range 39%-68% while the flood volumes reduced on average 86%. It also was concluded that further advancements may lie in the use of a more accurate spatially distributed rainfall input.



1D-2D dual drainage model for the Ghent study area, applying a nested approach with different surface mesh resolutions

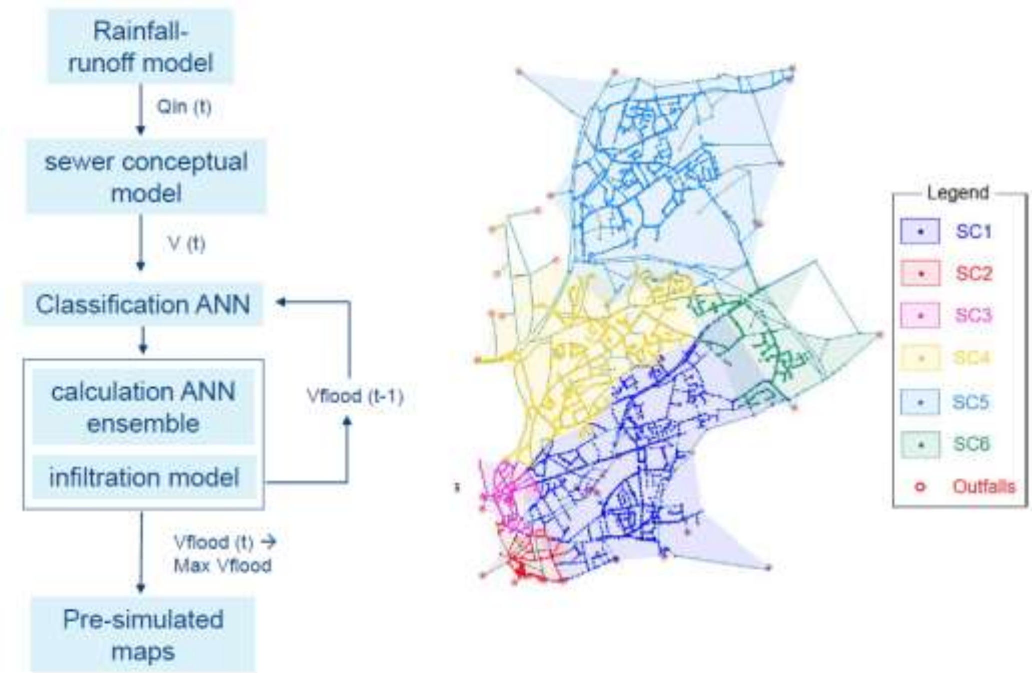
1D-2D dual drainage approach, with different mesh sizes tested an including Horton infiltration in green zones



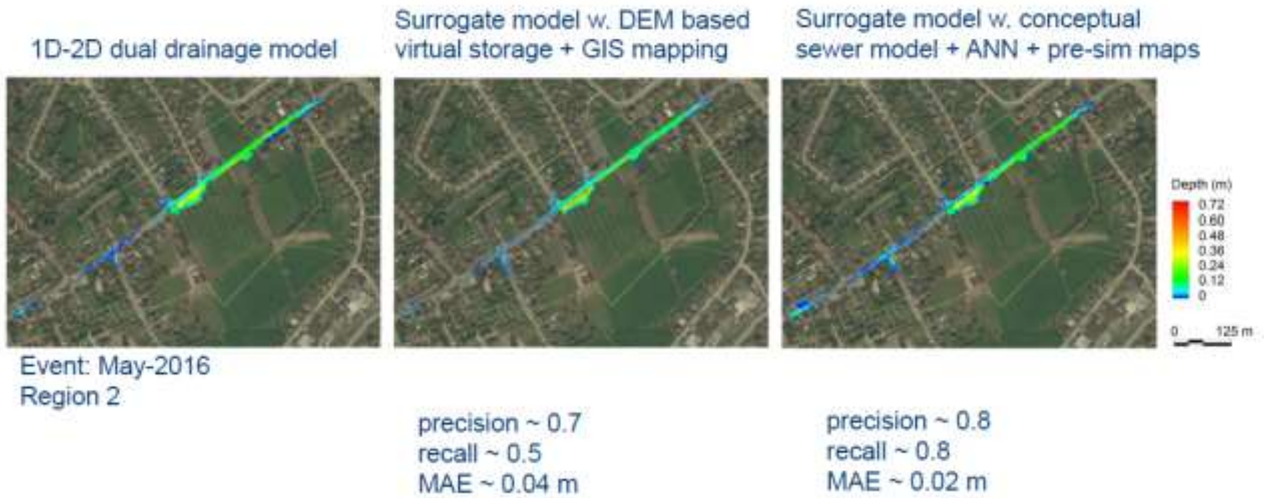
1D-2D dual drainage model for the Ghent study area: sensitivity of model results to meshing approach and average mesh size

After analyzing the obtained results of the 2D nested model with a proper mesh resolution and detail, for the synthetic storms and historical rain events, it is clear that the use of this type of approach offers to urban water managers a powerful and reasonable tool to study and better understand the water and inundation dynamics within and at the surface of the urban drainage system.

To enhance the application of the 2D surface inundation modelling and mapping, and reduce the computational time, such that it can be applied for real-time urban pluvial flood nowcasting, simplified conceptual approaches – but identified and calibrated to the detailed approaches – were tested and implemented. We proposed and tested two computationally efficient surrogate models. The first approach links a detailed 1D sewer model to a GIS-based overland flood network. For the second approach, we developed a conceptual sewer and flood model using data-driven and physically based structures, and coupled the model to pre-simulated flood maps. They were extensively tested for the Ghent case study. It was concluded that both surrogate models could provide comparable results to the original model in terms of peak surface flood volumes and maximum flood extent and depth maps, with a significant reduction in computing time (simulation time with a factor 10^5 smaller in comparison with the full hydrodynamic model). The results were presented at international conferences and workshops. Two international journal papers have been prepared and are currently in revision and review (Ntegeka et al., in revision; Bermúdez et al., in review).



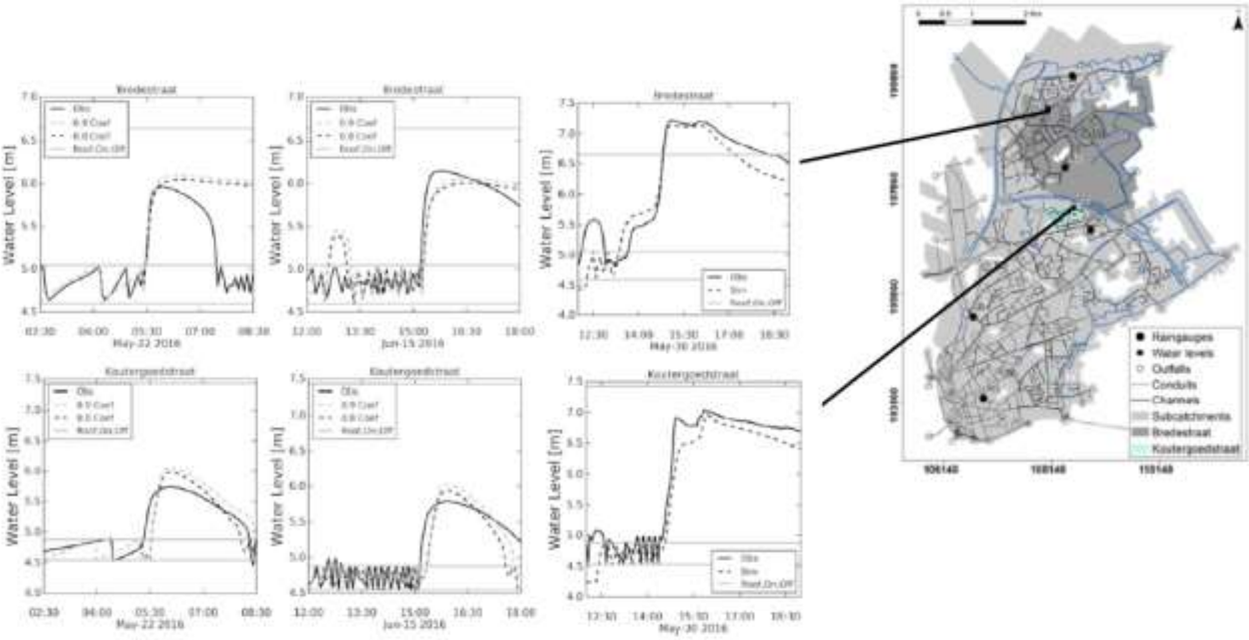
One of the computationally efficient, surrogate modelling approaches tested



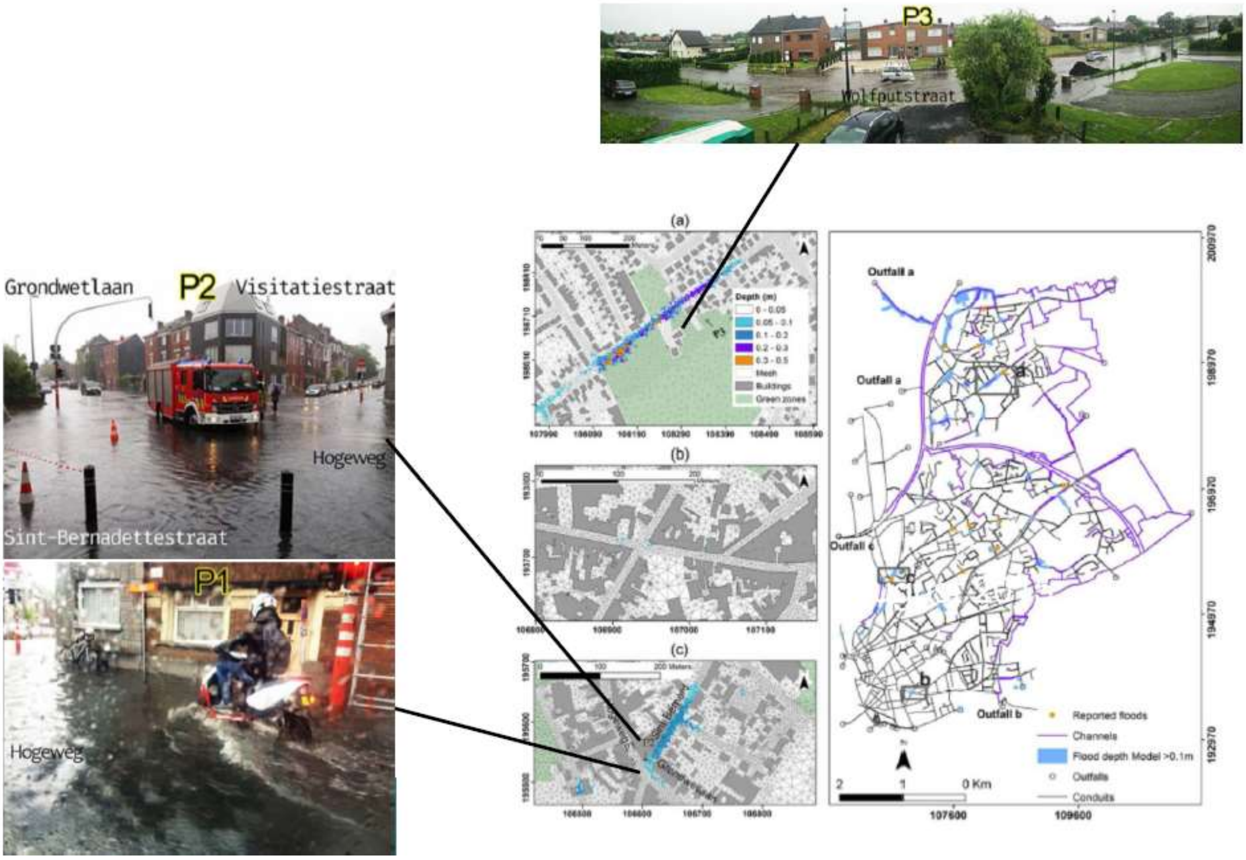
Comparison of inundation maps between the detailed 1D-2D dual drainage model and two types of computationally efficient, surrogate models

WP2 - Task 2.3: Evaluation of the sewer simulation results

Comparison was made for the simulated recent extreme rain storm events of the hydraulic model results (discharges, water levels, inundation information) through direct and mainly indirect observations (e.g. pumping station data, media items on historical floods), albeit very scattered. This provided an assessment of the additional uncertainty in the inundation results next to the rainfall input uncertainties. This evaluation also involved intercomparison of the different detailed and simplified 2D inundation modelling and mapping approaches developed in Task 2.2. Bias in sewer piezometric levels in the order of magnitude of 10 cm was found. Given that this bias is very limited, it was decided that there is no need to apply bias correction to the sewer hydraulic model results.

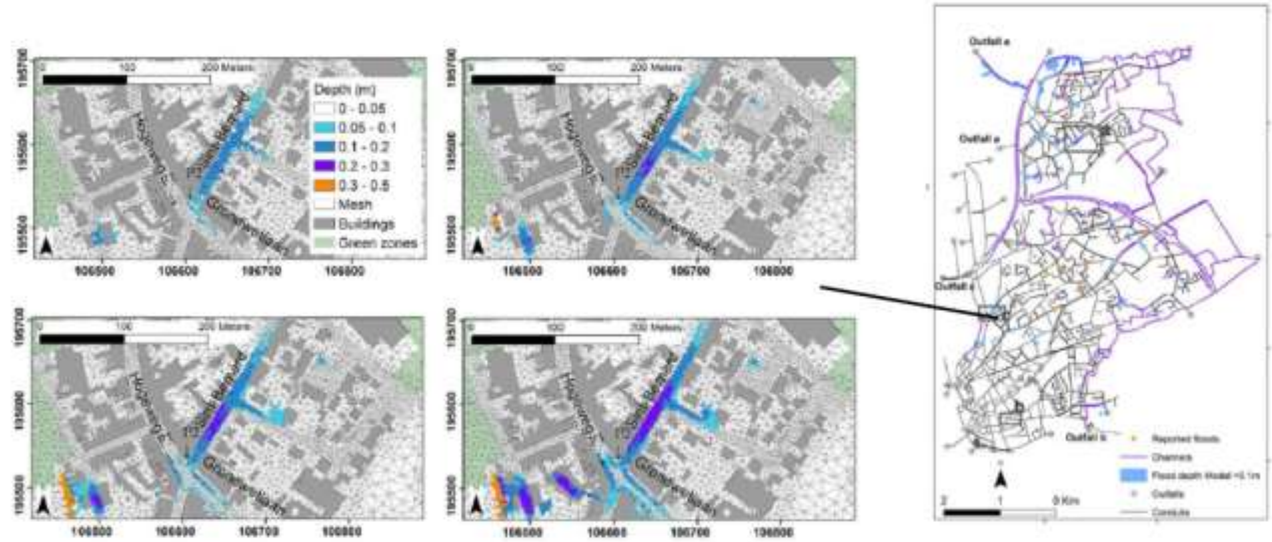


Validation of sewer simulation results based on water level data at pumping stations



Validation of sewer inundation results based on crowdsource data (newspapers, disaster journalists, social media)

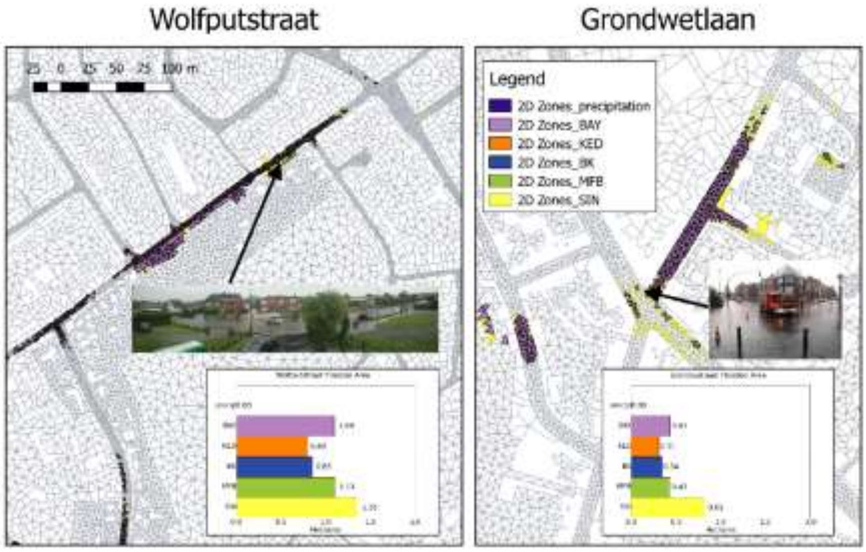
In order to further evaluate the sewer simulation results and their uncertainties, a sensitivity analysis was conducted on the soil infiltration rates. This was done for the same events and based on the same data. The soil infiltration rates were varied using two different soil types representing higher and lower infiltration rates than the assumed soil type. Results showed that infiltration has an important influence on the extent of the inundation. The magnitude of the reduction in flood extent hence largely depends on the soil type. Another influence of high importance, for locations close to sewer outfalls, are the backwater effects resulting from high river water levels. It therefore was concluded that the dynamic interaction between the river and sewer systems needs to be considered. This can be done by coupling a hydrodynamic model for the river with the sewer model.



Differences in inundation maps due to differences in river water levels as boundary conditions

WP2 - Task 2.4: Analysis of added value of the fine-scale rainfall data for urban flood simulation, prediction and warning

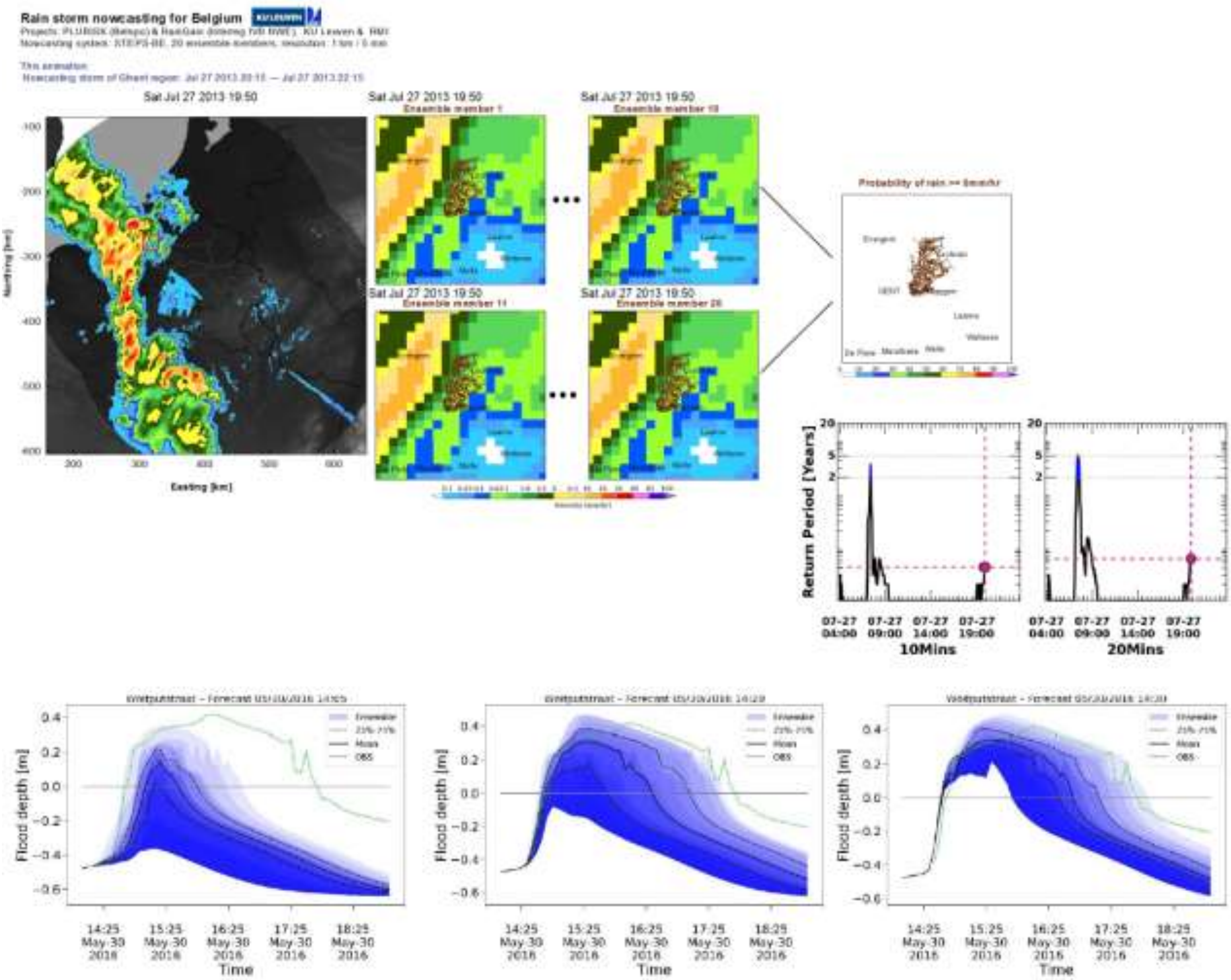
Based on the time series and statistical evaluations of Tasks 2.1 and 2.3, the added value of the fine-scale rainfall data for accurate (extreme) rainfall estimation and urban flood simulation, prediction and warning was analyzed. The uncertainty on these results was quantified. For the recent and severe 30th May flood event, rainfall estimates based on the different radar adjustment methods of WP1 were simulated in the model. The 2D surface flood simulation results were evaluated by comparison of the 2D inundation areas and depths with historical information on the real inundation areas and depths. This was done based on sewer flood data collected from various sources incl. crowd sourced data (social media, newspapers) and interventions by the fire brigade. Reported flood locations mostly matched the flooded streets (depth greater than 10 cm) in the model.



Evaluation of the maximum flood extent simulated by the 1D-2D nested urban flood model, for the 30th May 2016 event in the Ghent case (floods in the Wolfputstraat and Grondwetstraat) and after use of different rainfall merging methods

WP2 - Task 2.5: Development of a real-time urban flood forecasting system

For recent flood events incl. the recent extreme rain storm event of 30th May 2016, the STEPS-BE nowcasts were simulated in the model. The 2D surface flood simulation results were evaluated by comparison of the 2D inundation areas and depths with historical information on the real inundation areas and depths (see Task 2.4). Based on the simulations for that event, is was shown that the different algorithms and tools developed in WP1 and WP2 can smoothly be integrated to obtain real-time urban pluvial flood nowcasts together with the nowcast uncertainty. It was shown that the integration of these components successfully delivers probabilistic urban flood hazard maps. Further integration was done with the relationships between inundation depth and flood damage derived by WP3, in order to transfer the urban flood hazard maps into flood risk maps. The latter step was rather straightforward.



Examples of rainfall and urban pluvial flood nowcasting results for the Ghent study area

WP2 - Task 2.6: Organization of an international workshop on 2D fine-scale modelling, mapping and nowcasting of inundations in urban areas

Given the cooperation with Imperial College London and the RainGain project at the start of the PLURISK-project, an international workshop on the topic of pluvial flood modelling was organized at Exeter on 6 October 2014. The PLURISK results were presented and exchanged with the EU colleagues. The PLURISK WP2 results were presented at that workshop.

Given that this project focused on the local urban scale and aims to help local authorities in setting up a risk quantification, control and management system (which typically have too low capacity to do so), next to the international workshop, a final PLURISK-symposium was organized on 4 October 2017 in Brussels to disseminate the PLURISK-results to these local authorities. Next to the local authorities of the study cases, all Belgian community and city authorities responsible for local urban flood management in their area were invited. We had about 60 participants.

WP2 - Main conclusions

For the Leuven and Gent cases, detailed sewer system models implemented in InfoWorks-CS, were applied to simulate extreme rain storms (of which many were accompanied with sewer flooding) per case. The rainfall inputs to the sewer models were for these storms based on the radar adjustment and fine-scale rainfall estimation methods developed in WP1. For the Leuven case, the accuracy of the sewer flow and water level results could be evaluated after comparison with in-sewer measurements of water levels and flow velocities. These measurements were available for 2 pipes in the system and water level measurements at 3 overflows. Based on high-resolution DTMs, three different methods for 2D inundation modelling were tested and results inter-compared, showing advantages and disadvantages of the different methods. The best method was selected to simulate both the rainfall estimates as ensemble nowcasts of selected historical storms. This sewer inundation model was integrated with the STEPS_BE nowcasts provided by WP1, as well as with the urban damage functions obtained by WP3 (see next).

WP3: SOCIO-ECONOMIC RISK QUANTIFICATION FOR URBAN AREAS

Currently, water managers in Belgium only assess material flood risk. The damage functions, describing the vulnerability of a specific element-at-risk to flood water, have not been designed for assessing urban flood risks. The flood damage functions that are used also have never been calibrated to primary flood damage data for Belgium. Another fact is that most damage functions assume an overly simplistic relationship between exposure and damage (only using one explanatory variable: often flood depth). Improvement of the current methods is necessary in order to reduce uncertainty. Progress in this respect critically depends on data availability. The latter, however, remains a major bottleneck. Therefore, a survey was conducted among Belgian households that have already been affected by urban pluvial flooding. The objective was to collect primary urban flood data and information on (1) how people evaluate social pluvial flood impacts, (2) the pluvial flood risk reducing effects of risk awareness, warnings and private precautionary measures, (3) the relationship between urban pluvial flood characteristics and material damage and (4) damage to cultural heritage. This was targeted by executing successful questionnaires.

A methodology for assessing damage to historic buildings and sites was developed and applied to the study areas. Damage to historic buildings differs from "ordinary" buildings in the fact that they also possess heritage values and that they have no real replacement value. Risk for damage due to flooding of immovable heritage places in Belgian cities (monuments, sites, architectural units and archaeological sites) is looked into, disregarding movable heritage (paintings, sculptures, musical instruments and other art objects, manuscripts and archives) if they are not included in the aforementioned heritage places.

WP3 - Task 3.1 Development and execution of a questionnaire targeting Flemish households that have already been affected by urban flooding

At the start of the PLURISK project, the Belgian Disaster Fund and Assuralia were contacted to obtain access to their databases on flood damage claims such that these addresses could be used as the population for the questionnaire. We started a procedure which was necessary for the Belgian Privacy Commission to allow us to use the addresses from the Belgian Disaster Fund. For a long time it was not clear / certain if we would get access to these data. Therefore, also Flemish municipalities and fire departments were contacted in order to obtain additional information (respondents) for the questionnaire. Finally, we got permission from the Privacy Commission (April 4th 2013) to use the data from the Belgian Disaster Fund. At that moment, since we had addresses of several thousands of victims of floods, it became clear that an optimal use of the budget for subcontracting (for the questionnaire) would be to launch a large-scale written questionnaire. The original database of the Disaster Fund needed to be cleaned. We ended up using the addresses of (3963) Flemish households that have been affected by urban pluvial flooding.

The questionnaire was developed using the state-of-the-art knowledge with respect to socio-economic flood risks and the risk reducing effects of risk awareness, warnings and private precautionary measures. The members of the project consortium were consulted on the questionnaire and adaptations were made. The KU Leuven - R. Lemaire International Center for Conservation (RLICC) contributed by defining how the impact of urban flooding on heritage and related social factors could be holistically integrated in the questionnaire without waiving national and international conventions. Also, the questionnaire were pre-tested several times.

The objective was to collect primary data in order to be able to (1) evaluate and improve existing damage functions and/or develop new ones, (2) evaluate the effectiveness of private protection measures and warnings, (3) evaluate the importance of risk awareness, (4) derive information on how people value flood impacts and damage and are aware (or not) of their cultural heritage, (5) devote specific attention to the non-tangible effects of being a flood victim and (6) compare to some extent with non-flood victims. This was made possible since similar questions were asked to non-victims (for a sample representative of the Flemish population, developed in another context, at Gent University).

The response was done in a written form or using an online application. The response rate was 24.5 % (before cleaning for missing values and zeros). Ultimately, we could use information about 620 respondents for the (statistical) analysis.

WP3 - Task 3.2 Definition and (e)valuation of specific social flood impacts

To be able to evaluate the impact of floods, a series of flood-(impact-)variables were defined and constructed: the time of occurrence of the flood incident, the compensation received from the national disaster fund, the estimated monetary damage to buildings and to content, whether the flood was in the basement or on the ground floor. Also, explanatory variables for the econometric modelling were constructed: hazard indicators (e.g. depth), building characteristics (e.g. detached or terraced), behavioural predictors (e.g. risk awareness) and general socio-economic indicators.

For the statistical processing of the damage functions, first, we used the ordinary least squares estimation technique. Second, we used a more appropriate technique: Tobit-estimations that specifically take into account the treatment of reported zero damage (as an example, victims can have only damage to contents, and not to the building). This detailed information, combined with the specific Tobit-technique, is innovative in research on damage and impact evaluation. The method allowed uncertainties to be described and quantified in order to allow for a correct use of the results that can be obtained with the valuation function. Additional results were produced because of the attention for non-tangible effects of floods and because of the possibility to compare with non-victims. The intangible variables were on the one hand self-reported predictors of well-being (life satisfaction, capabilities, social relations, subjective health, etc.) and on the other hand self-reported achievements and personality traits.

	Observations	Zero damage observations	Mean Euro	Max damage Euro
Total damage	331	50	8146.3	91657.6
Damage to building	274	22	6246.6	77499.3
Damage to contents	306	122	3218.5	65576.3
Total damage recovered from the disaster fund or insurance company	170	0	2052.3	19307.8

Note that figures for mean and maximum damage are expressed in euros and corrected for inflation

Data on damage to buildings and contents, corrected for inflation

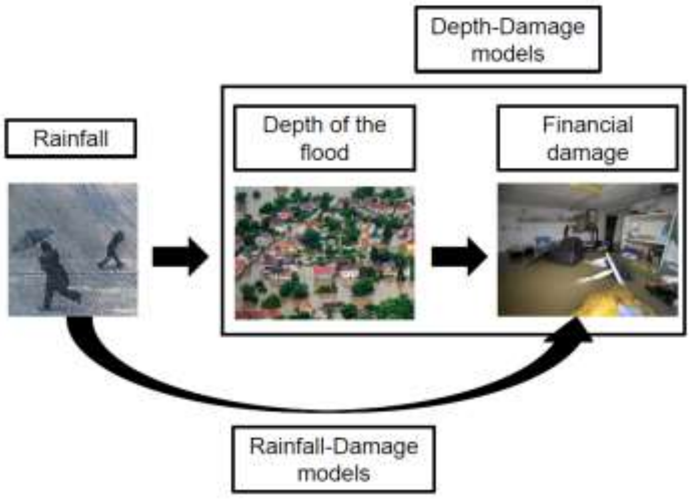
WP3 - Task 3.3 Assessment of the flood risk reducing effects of flood risk awareness, flood warnings and private precautionary measures

A specific challenge of WP3 (specifically Task 3.6) was to examine the effect of flood risk awareness, flood warnings, and private precautionary measures. That information is a necessary building block for the development of a communication strategy concerning early warnings and risk communication (topic of WP4). The state-of-the-art knowledge on the risk reducing effects of risk awareness, warnings and private precautionary measures were reviewed and that information was integrated in the questionnaire (Task 3.1).

In our empirical research, we used the following variables: recurrence (number of floods), risk awareness (risky location, risk consciousness just before the flooding) and different emergency measures (e.g. possession of a pump is a damage reducing variable). The act of moving contents to another floor is positively correlated with damage, indicating that this is more of an emergency measure (panic), and not a precautionary action. Specifically, the Tobit-estimations point to a negative effect (this is damage reducing) of recurrence on damage to content in the case of a basement flood. Also, being aware of the risk just before the flood took place significantly reduces the content damage in both cases (basement as well as ground floor flooding). Those results indicate that people learn how to deal with floods and are capable of taking damage reducing measures in case they are aware of being at risk at the time of the flood.

WP3 - Task 3.4 Evaluation and calibration of existing depth damage functions

We made an in-depth review of the literature of flood impacts. Most of the existing literature is making use of (1) uni-variate depth-damage functions, (2) for fluvial floods, and is making use of an (3) estimation methodology that does not take into account the effect of zero-reported damage figures (mostly ordinary least squares is used). Also, (4) the damage is mostly assessed in monetary terms. Each of these features of the existing literature is evaluated (and improved upon): we used (1) multivariate damage functions applied to (2) problems of pluvial flooding. Next to an OLS-framework; we used (3) Tobit regression techniques to take into account the effect of reported zero damages. Also, we calibrated (4) multivariate intangible damage models.



Two types of two distinct types of multivariate flood damage models were considered: "depth-damage" models and "rainfall-damage" models

More specifically, we explored the potential of two distinct types of multivariate flood damage models: "depth-damage" models and "rainfall-damage" models. In order to calibrate the rainfall-damage model, rainfall data were derived for all flood damage claims in the database (see Task 3.1) both from rain gauge data and from the radar data. The results show that in the "depth-damage" models, flood depth has a significant impact on the damage. In the "rainfall-damage" models, we find a significant impact of rainfall accumulation on the damage for the gauge rainfall data, but surprisingly not for the radar rainfall data. For both the "depth-damage" and the "rainfall-damage" models, we find that also non-hazard indicators are important for explaining pluvial flood damage. An international journal paper was published in Journal of Flood Risk Management about this joint PLURISK work (Van Ootegem et al., in press). A more specific international journal paper on the depth-damage estimation was published in Environmental Impact Assessment Review (Van Ootegem et al., 2015).

	Damage to building	Damage to content	Total damage
Basement	1.18%	0.97%	1.20%
Ground floor	2.35%	4.93%	3.11%

Impacts of an additional cm of the inundation depth in the basement or on the ground floor on financial damage to building / content / total damage

	Damage to building	Damage to content	Total damage
Rainfall KULeuven	1.21%	1.47%	1.20%
Rainfall RMI	2.73%	No sig. impact	No sig. impact

Impacts of an additional mm of rainfall on financial damage to building / content / total damage

For the intangible damage analysis, we used and compared two different concepts to examine the subjective well-being of flood disaster victims: life satisfaction and capabilities in life. We compared two samples: a general sample (Flemish respondents) and a specific sample of people that have been the victim of a pluvial flood. Well-being as life satisfaction is not related to past (or expected future) flooding. Well-being as capabilities in life is (negatively) related to past and future expected flooding. This might indicate that past floods have their influence through a fear for future flooding. For the flood victims, no relation was found with the monetary damage that caused by the flood. It are the flood hazard indicators (the flood depth and its duration) that have a direct negative relation with the capabilities deficiency. Also about this work, an international journal paper was published in Environmental Impact Assessment Review (Van Ootegem & Verhofstadt, 2016).

Flood place	Satisfaction	Capabilities
Ground floor	-,020	-,120**
Garage	-,040	-,097**
Basement	-,033	-,128**

Correlation of life satisfaction and capabilities in life with the probability (0 to 100%) of future flooding (5 years)

WP3 - Task 3.5 Damage to historic buildings and sites

A methodology has been developed for assessing pluvial flood damages and risks to historic buildings and sites. It is based on the overall PLURISK conceptual framework. Moreover, this framework has been complemented with the methodology on risk management already implemented by the RLICC in UNESCO World Heritage properties based on Waller's (2003) approach adopted by the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM) together with the Canadian Institute (CCI), Institute for Cultural Heritage of the Netherlands (ICN) to heritage collections and the Risk Management Australia/New Zealand Standard. Moreover, the aspects and dimensions of authenticity and their vulnerability to flooding were based on the Nara Grid methodology, values assessment tool developed by Van Balen (2008).

The starting point was (geo)datasets to perform the simple queries based on geographical attributes. This acquired database includes: (1) listed heritage, 'inventories', and its related ESRI shapefiles administered by Onroerend Erfgoed, including protected historic buildings, monuments, relicts, landscapes, UNESCO properties and ankerplaats, as well as their statutory protection; (2) the Central Reference Address Database (CRAB) managed by AGI; and (3) the PLURISK WP3 questionnaires. Furthermore, a review of the legal framework and protection was carried out in order to find the legal protection and benefits when flooding of the listed dwellings and proposed a GIS Warning System for analysis and as a visualisation tool.

The information was compared with the Flemish heritage inventory to (1) show which dwellings are in reality on the heritage inventory and statutory protected; (2) show which ones are close to a monuments, relicts, landscape, or ankerplaats, or are within a UNESCO World Heritage property; (3) determine the awareness of the owners/respondents about the status and level protection of their property, or the area where it is located; (4) determine the legal status of the listed buildings and its relation with the compensations received in order to implement any conservation or risk management activities.

There is not that much awareness of the respondents about heritage protection. However, a large number of the listed properties have received some kind of compensation for the damages caused by the flooding, especially by the disaster fund. No information is available about flooding or any compensations in cultural heritage through the "Onroerend Erfgoed" nor "Monumentenwacht" making it unfeasible to validate the data (answers) given by the correspondents.

WP3 - Task 3.6 Extension of flood nowcasting developed in WP2 to a flood risk nowcasting system

The "depth-damage" model derived in Task 3.4 was implemented for integration with the 2D sewer inundation depth results in WP2. The same was done for the "rainfall-damage" model, in order to initiate WP4. Correspondingly, the flood nowcasting system developed in WP2 was extended to a flood risk nowcasting system, where the forecasting and mapping of hydraulic variables (WP2) are transferred to socio-economic risks based on the results from the previous WP3 tasks.

WP3 - Main conclusions

Theoretical and analytical literature on flood damages and risks (functions) was collected and summarized. This literature was used (together with other information) for the construction and fine-tuning of a specifically targeted questionnaire that was sent to flood victims. Permission was obtained from the Belgian Privacy Commission to use the data from the Belgian Disaster Fund. The response rate was 24.5 % (before cleaning for missing values and zero's). Ultimately, the information could be used for about 620 respondents. This database created possibilities for innovative statistical analysis of the flood damage in function of hazard information as well as non-hazard variables as building characteristics (e.g. detached or terraced), behavioural predictors (e.g. risk awareness) and general socio-economic indicators. The latter kind of information is rather exceptional in the flood damage literature.

Most of the existing literature is making use of (1) univariate depth-damage functions, (2) for fluvial floods, and is making use of an (3) estimation methodology that does not take into account the effect of zero-reported damage figures (mostly ordinary least squares is used). Also, (4) the damage is mostly assessed in monetary terms. Each of these features of the existing literature is evaluated (and improved upon). We used (1) multivariate damage functions applied to (2) problems of pluvial flooding. Next to an OLS-framework, we used (3) Tobit regression techniques to take into account the effect of reported zero damages. The Tobit-estimations point to a negative effect of recurrence on damage to content in the case of a basement flood. Also, risk awareness significantly reduces the content damage in both cases (basement as well as ground floor flooding).

In summary, as it is the case in fluvial damage research, the depth of the flood was found to be the most important explanatory variable. However, when rain gauge rainfall data was used instead of flood depth, also this was found to be a good explanatory variable. The latter is very interesting, given that flood depths are only available in areas where the sewer inundations have been modelled (as we did for the case study areas in WP2). Expressive depth-damage and rainfall-damage functions were derived, but the multivariate analysis showed that also non-hazard indicators are important for explaining pluvial flood damage. Also the potential damage to historic buildings and sites was explored.

For the intangible damage analysis, the individual well-being of flood disaster victims was studied based on information on the life satisfaction and the capabilities in life. For the flood victims, no relation was found with the monetary damage that was caused by the flood. It are the flood hazard indicators (the flood depth and its duration) that have a direct negative relation with the capabilities deficiency.

WP4: RISK COMMUNICATION AND WARNINGS FOR FLOOD RISKS AND EXTREME RAINFALL

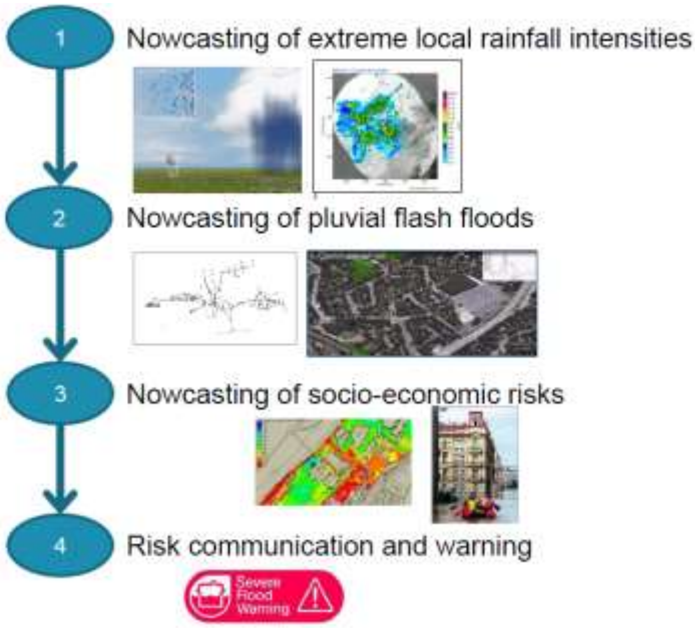
Through the methodologies and tools developed in previous WPs, forecasting of pluvial flooding could be conducted. This enables triggering structural and non-structural actions on time in order to minimize the negative effects that pluvial flooding can have on people and critical infrastructure. In this way, the resistance and resilience of cities to pluvial flooding can be enhanced. A first type of action is the setup of a warning system for extreme rainfall and urban pluvial floods based on fine-scale flood and flood risk predictions. Such system required an initial study of the current practices with and the potential of warning systems for those types of hazards. We culminated in the design of a real-time flood risk warning system's communication rules and procedures for the urban environment.

WP4 - Task 4.1 State-of-the-art knowledge/practices wrt. flood risk warnings to the public

A review was made of the existing approaches for flood risk warning and communication, including the consideration of uncertainties. This involved a literature review on the state-of-the-art knowledge/practices/systems with respect to delivering flood risk warnings to both the general public and managers of vulnerable infrastructures/activities. Critical side conditions for ensuring maximum effectiveness of warnings in an urban context (like e.g. the importance of a general awareness among the population, knowledge on what to do before and during a flood, required confidence level of the forecasts before launching a flood warning, communication media, etc.) were inventoried. A review report on the state-of-the-art knowledge/practices/systems with respect to delivering flood risk warnings to both the general public and managers of vulnerable infrastructures/activities was delivered (Van Herck et al., 2017).

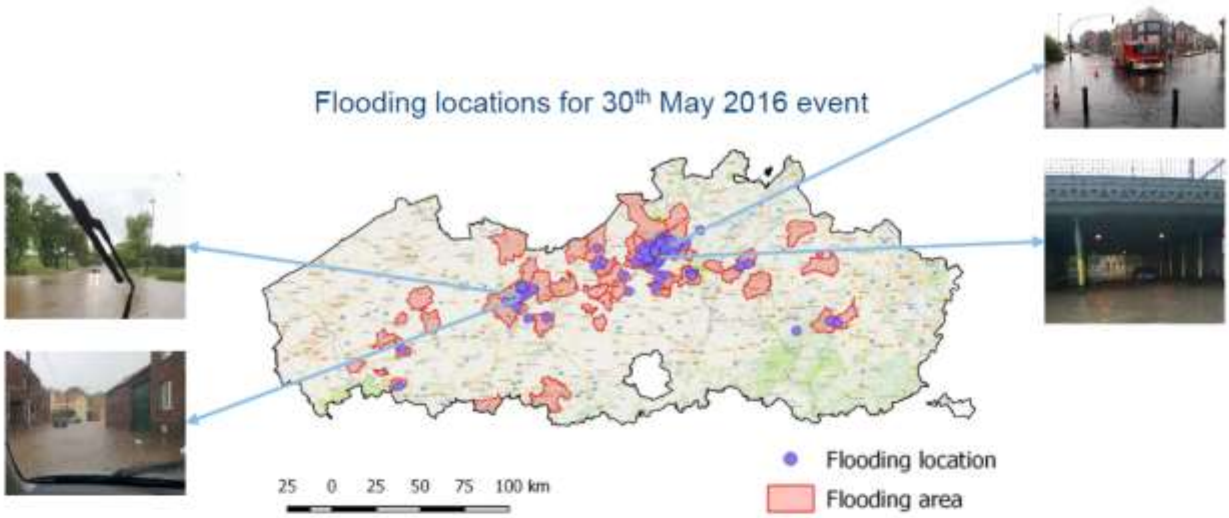
WP4 – Task 4.2 Design of a real-time flood risk warning system's communication rules and procedures for the urban context

For the Gent case as pilot case all components (rainfall nowcasts, radar – rain gauge merged products, urban inundation model, socio-economic impact assessment approach) were brought together to come up with a prototype integrated and multi-disciplinary urban inundation risk nowcasting system. By running the different STEPS-BE ensemble members, the rainfall nowcast uncertainty were propagated to the inundation hazard and risk results. The other uncertainties on the inundation modelling and socio-economic impact assessment were being added and propagated in that modelling chain. Different visualization approaches of the uncertainties were tried. Idem for the uncertainty quantification and visualization based on the rainfall nowcasts only. After integration of all components of the urban pluvial flood risk forecasting system, the system was completed by integrating a real-time flood risk warning system's communication strategy based on rules and procedures for the urban environment. The system and results were presented at several international conferences and workshops (Ntegeka et al., 2015; Ntegeka et al., 2016; Willems et al., 2016).

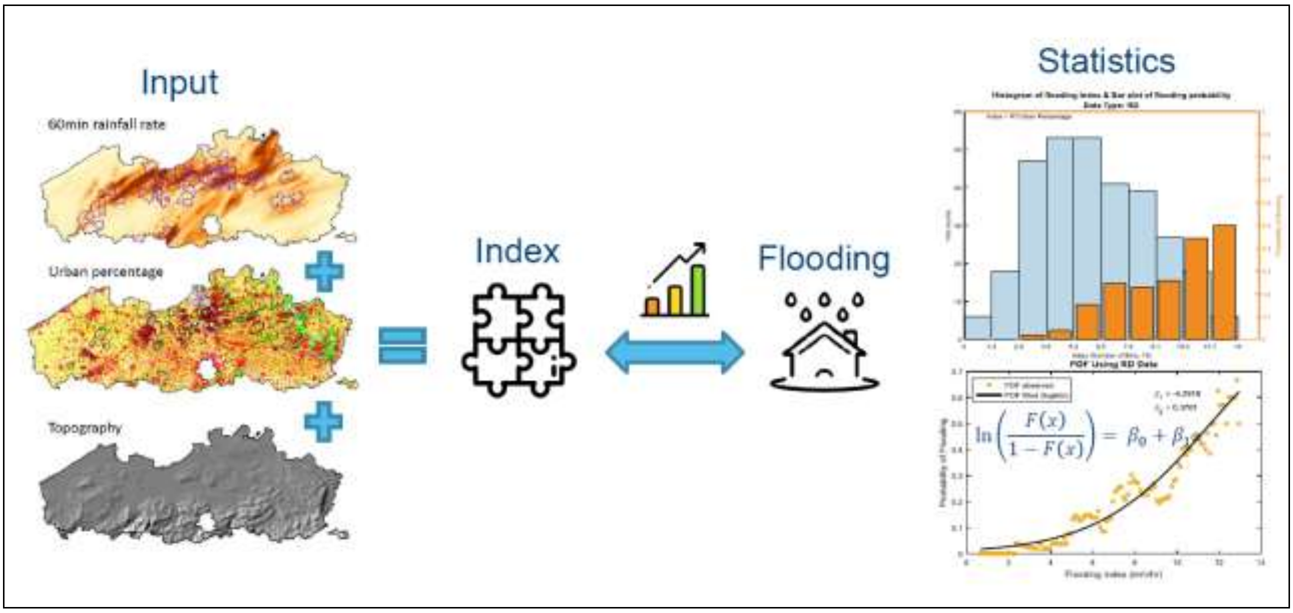


Components of the PLURISK urban pluvial flood risk nowcasting system

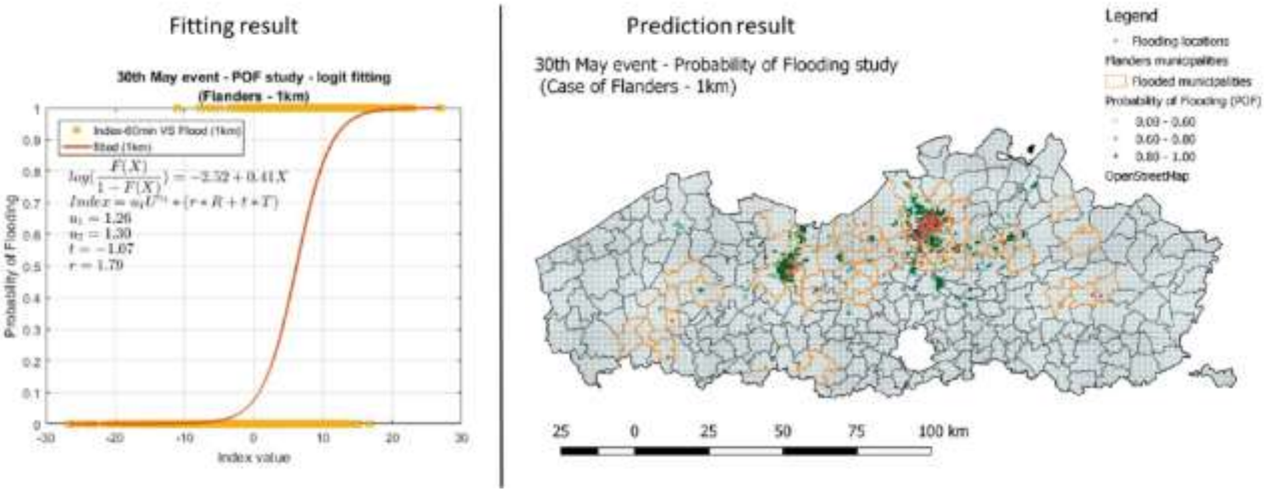
Two types of urban flood nowcasting and warning systems were considered: one covering a larger area (tested for the Flanders and Brussels area) based on a data-based approach, and one based on the detailed 2D urban flood modelling for specific cities (tested for Ghent). The data-based approach makes use of the STEPS-BE rainfall nowcasts and combines these with spatial data on topographical heights, land use incl. paved areas. An index has been obtained after evaluation based recent flood events in Belgium including the floods during the 30th May 2016 event. The index allows to compute the "probability of (urban) pluvial flooding".

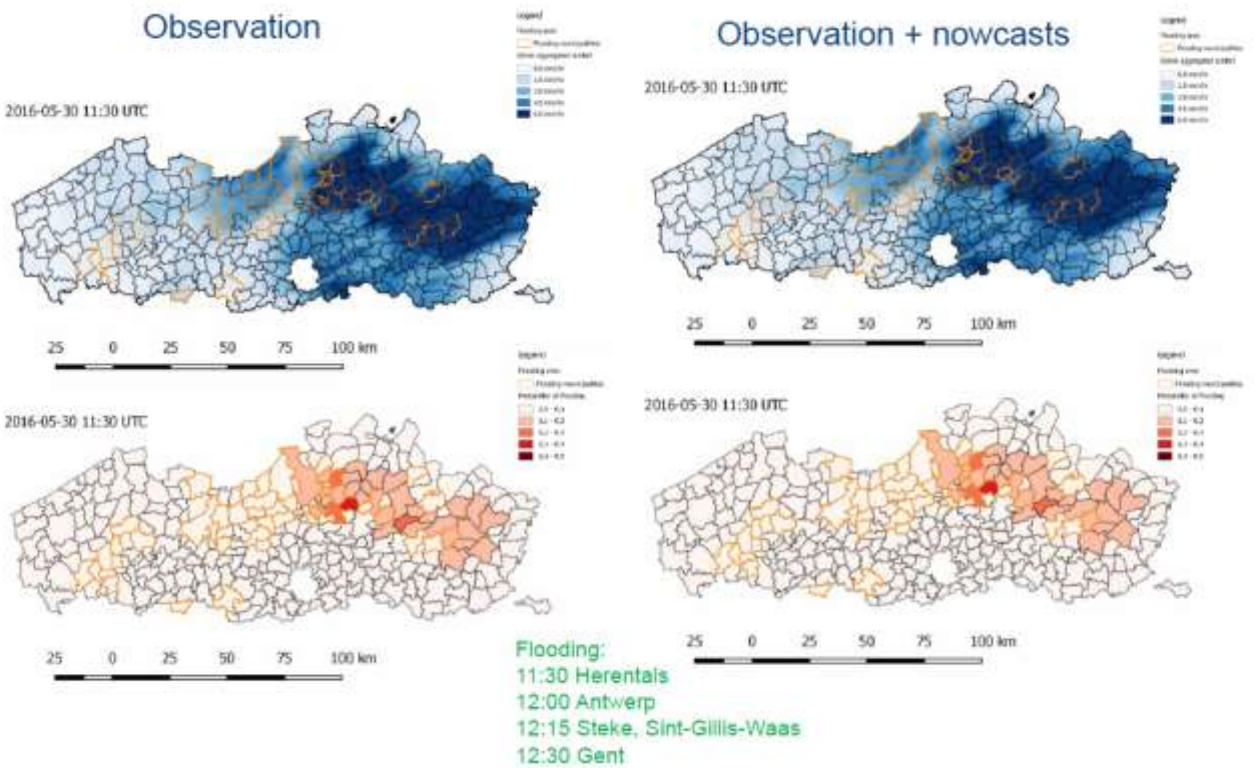


Overview of the different flooding locations for the 30th May 2016 event.



Data-based approach for large scale nowcasting and warning system for urban floods





Example of probabilistic urban pluvial flood nowcasting results for the 30th May 2016 event

WP4 - Main conclusions

All PLURISK components (rainfall nowcasts, radar – rain gauge merged products, urban inundation model, socio-economic impact assessment approach) were brought together to come up with a prototype integrated and multi-disciplinary urban inundation risk nowcasting system. By running the different STEPS-BE ensemble members, the rainfall nowcast uncertainty was propagated to the inundation hazard and risk results. The other uncertainties on the inundation modelling and socio-economic impact assessment were added and propagated in that modelling chain. Different visualization approaches of the uncertainties were tried, and form the basis for the urban inundation risk warning.

WP5: RISK REDUCTION BY BOTH PREVENTION/MANAGEMENT (BLUE-GREEN URBAN WATER INFRASTRUCTURES)

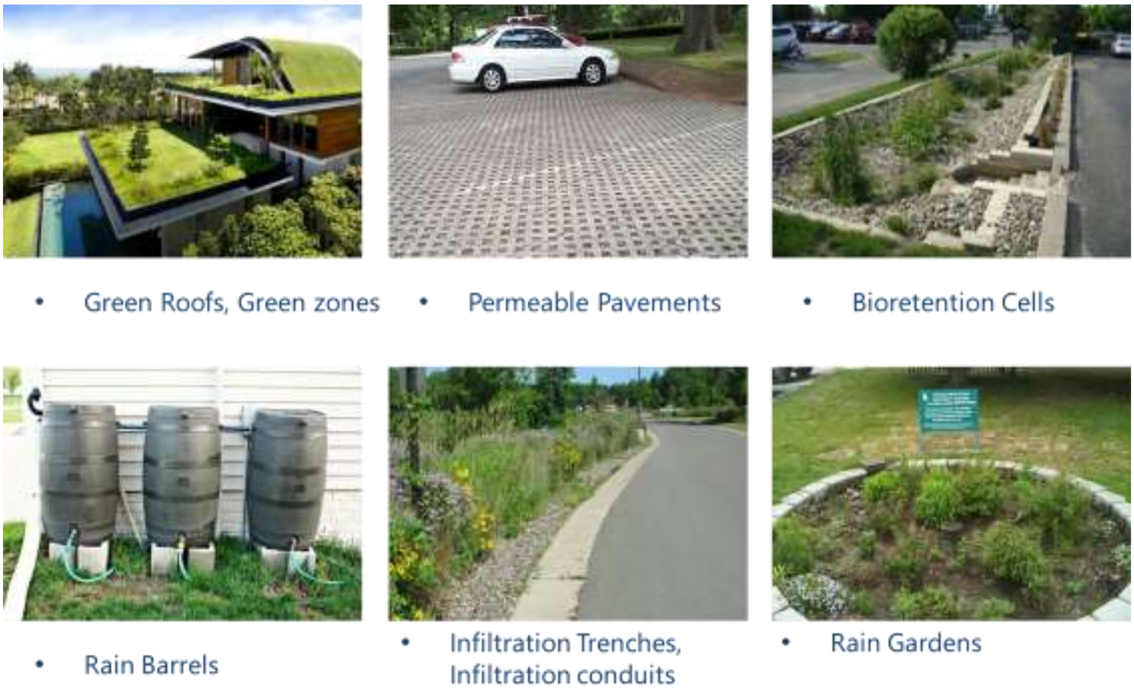
Actions were studied to reduce the vulnerability of cities to extreme rainfall by means of solutions for better storm water control and flood prevention. This became possible through the availability of detailed rainfall data, while in the current situation water managers rely on rainfall data from a single or a few rain gauges that are unable to capture rainfall variations within a city area. New, detailed information on peak rainfall and local flood risk provided new insight into the functioning of water systems at the pilot locations in reaction to heavy rainfall. This enables water managers to identify weak spots that need improvement and to develop and test adequate solutions.

Sustainable management strategies were being developed to limit/reduce urban flood risks by improved use of blue/green infrastructures after better interfacing eco-management, spatial planning and urban water management. This involved a study on the capacity of the green city structure to support ecosystem services linked to regulation of water flow at the landscape scale in the urban environment considering explicitly spatial dimensions. We provided a framework linking the most accessible data set (land use and ecosystem mapping) to the capacity of landscape to support well identified components of water flow control. This was done in order to provide tools for land management of green infrastructure in the context of urban flooding dynamics. The methodology involved: (i) The definition of a structured framework linking land use and ecosystem services related to water flow control. Because of the numerous uncertainties in ecosystem services measurements, qualitative evaluation (literature and expert judgment) are used. (ii) The identification of the drivers of change in landscape provisioning in ecosystem services linked to water flow control. This step mobilized the pattern-process concept of landscape ecology through temporal examination of landscape structure modifications in the case studies selected for the project. (iii) Development of a functional framework for spatial planning/management of green structure in relation to water flow control on the basis of generalization issued from the examination of the case studies.

WP5 - Task 5.1 Land use – ESs framework

Detailed literature review was conducted to identify the original green structures that have been reported to play a role in flooding control for the urban environment. These included green ecotechnologies specifically designed for water runoff control and the green network of habitat implemented in the first place for other ecological functions such as biodiversity development (ecological networks) and/or social/cultural functions (for example green ways, parks, private gardens). For the green network of habitats the different classes of land use were considered as different green structures to assess their potential ecosystem services (ESs). We focused on studies in temperate developed regions for the framework to be directly applicable to the case studies selected in the project. For each ecotechnology/green structure, the potential of the components of water regulation ecosystem service (interception, evapotranspiration, infiltration, runoff) was evaluated.

The literature has shown that the relationship between the components of the regulation of water and green structures is not well represented. Analysis of infiltration and runoff data in the literature highlighted a lack of consensus between the authors. It was found that there is no apparent link between ecosystem types and the proportion of (function of) ecosystem service provided. Similarly, the differences between (functions of) ecosystem services provided by the same type of ecosystem is not constant across studies. This mismatch could be explained by the variation of parameters inherent to the studies. The current data do not allow to generalize differences of (functions of) ecosystem services provided by the different types of ecosystems. It is therefore very difficult, based on existing literature to predict values of (functions of) ecosystem services that are provided by the different ecosystems. This means that objective quantification (not with expert judgment) of the components of water regulation ecosystem services for different ecosystems is not possible in the present state of knowledge and literature.



Blue-green solutions

WP5 - Task 5.2 Spatial analysis of ESs

Assuming that ecological processes / ecosystem services will depend on the spatial structure of green spaces, it was interesting to know and characterize this structure by calculating different indices of the landscape. Five cities in the same region (Antwerpen, Brugge, Gent, Leuven and Mechelen) were studied to identify possible similarities between spatial patterns of green spaces. We used an existing mapping of green spaces provided by AGIV (Agentschap voor Geografische Informatie Vlaanderen). Different indices of the landscape were calculated for the five cities: area (hectares), shape, density, distance to the nearest neighbor (meters). Those indices were calculated along an urban-rural gradient, in order to understand the evolution of the characteristics of green spaces according to their position in the city.

We found that the total amount of green spaces for the five cities is comparable to other European cities. The size of green spaces is increasing along an urban-rural gradient; at the same time, their density decreases. We also found that the connectivity of green spaces increases and that the shape becomes more complex along the urban-rural gradient. Those results helped to understand the pattern of green spaces in order to help the management related to ecosystem services improvement. Moreover, a sensitivity analysis was considered on the landscape ecology assumptions. Questions were answered such as: What is the added value of different hypothesis? Is there a link with the type of urban development? Also the link between the connectivity of green spaces and their role in flood management was additionally considered, such as: proximity of a river, position in the watershed, impervious surfaces, etc. Green spaces were classified according to the shape, their environment, etc. and it was identified what each class brings to the water regulation. Street view or lidar data could be used for the purpose.

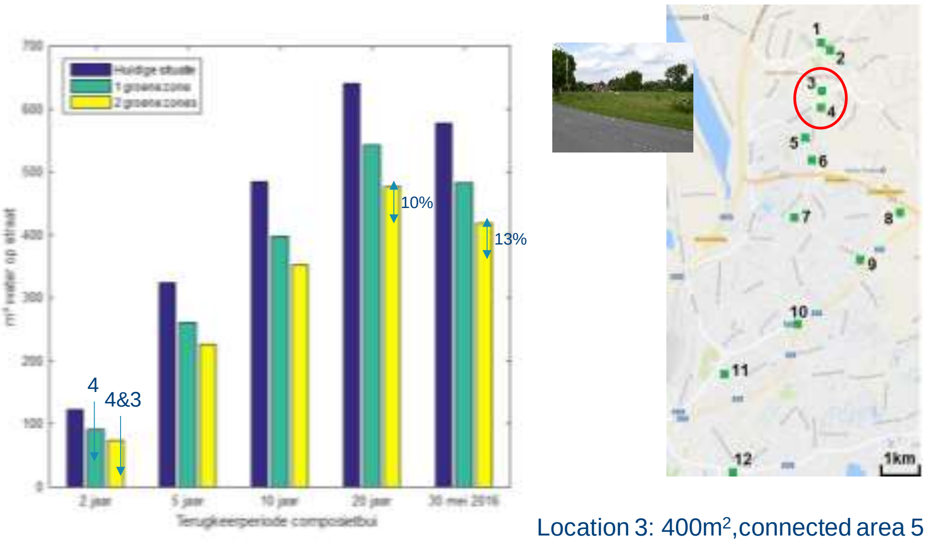
WP5 - Task 5.3 Management framework

The conclusions of WP5 have shown that it is difficult to predict the values of (functions of) ecosystem services provided by green spaces in terms of water regulation. As a result, the goal of this Task 5.3 was (1) to focus on local case studies, (2) to summarize existing techniques by evaluating them on different criteria. The local case studies aimed to make some landscape design in order to increase the water regulation service in risk areas. A database was being built on the basis of different sources and synthesized the existing techniques and their strengths, weaknesses, opportunities and threats. Three study cases located in Gent were selected, in the neighbourhood identified after the WP2 work on upstream drainage areas, and in concertation with the city of Gent. An analysis was made of the current situation and the rainwater related problems. This led them to propose appropriate green infrastructures to limit flooding. Five technical leaflets were realized: (a) a general document, explaining what is urban flooding, how it happens, what are the roles of green infrastructures in water regulation and what are the existing devices for stormwater management in urban areas; (b) four additional documents presenting technical data on each green infrastructure used to regulate water flow, explaining how and why it works, with examples and proposals for Belgian cities.

To further evaluate the contribution of existing green infrastructure to management of current and future flooding events, the efficiency of their spatial localization was assessed in regard to the flooding models developed in WP2. At the same time, it was evaluated how the increase in flood risk may negatively impact existing green infrastructure. The utility of the developed framework was illustrated by applying target components of the framework to the case studies to propose landscape design scenarios that increase ESs capacity for water flow control. These scenarios included land use change (spatial planning) and specific management/action in existing green infrastructures. Conflict with other ESs or reinforcement of other ESs issued from the landscape planning scenario were assessed. Our aim was not to provide a detailed cost-benefit analysis; rather, WP5 laid the basis for enable policy makers to consider cost and benefits in a later phase. Based on the experience gained with the three case studies, potential applications of the framework were generalized for planning, design and management of an the urban green structure for ESs linked to water flow control in temperate developed cities.

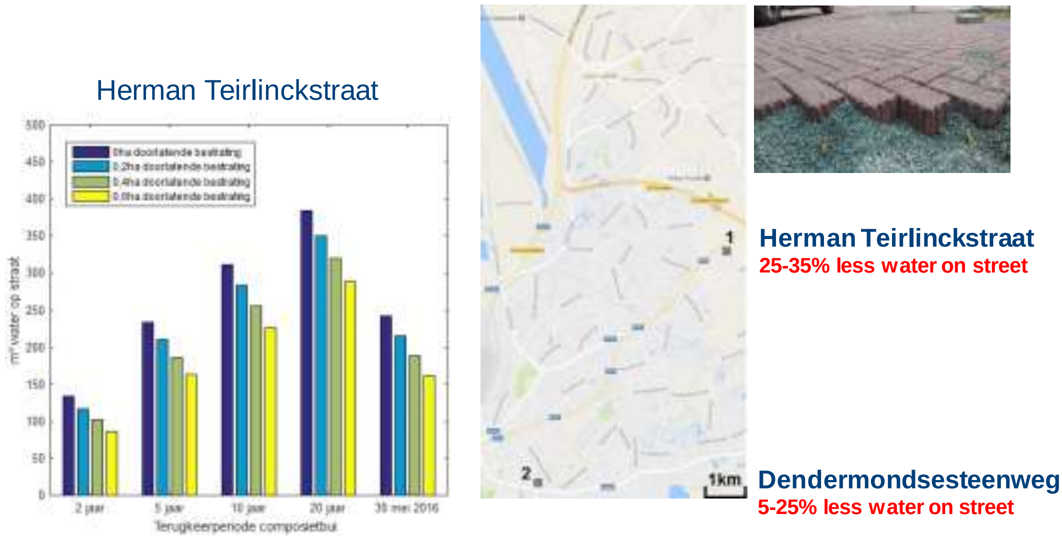
Impact simulations in the WP2 urban flood model indicated that the effect of storage and infiltration in green zones is most effective. See some examples of the results below. A report on these impact results has been prepared (Ntegeka et al., 2017).

Three types of sustainable urban drainage measures implemented in the urban flood model, together with their locations

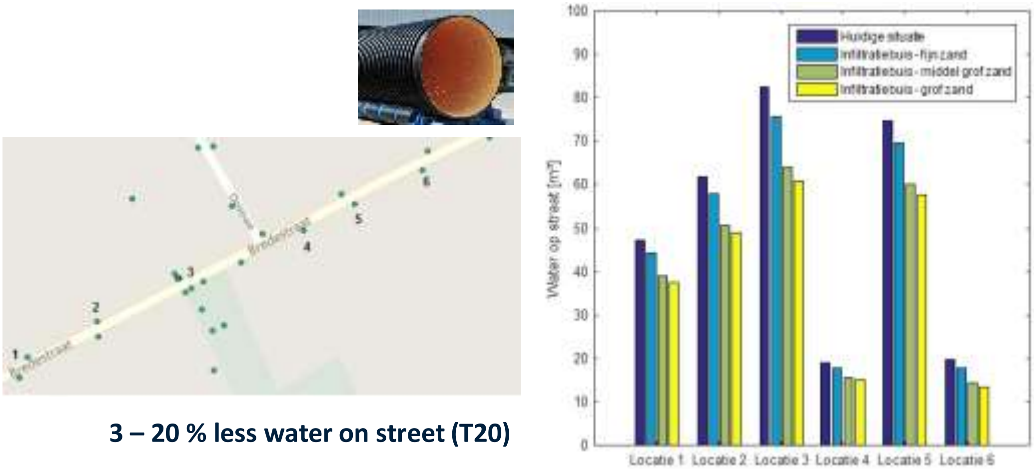


Location 3: 400m², connected area 5.36 ha
Location 4: 500m², connected area 1.20 ha

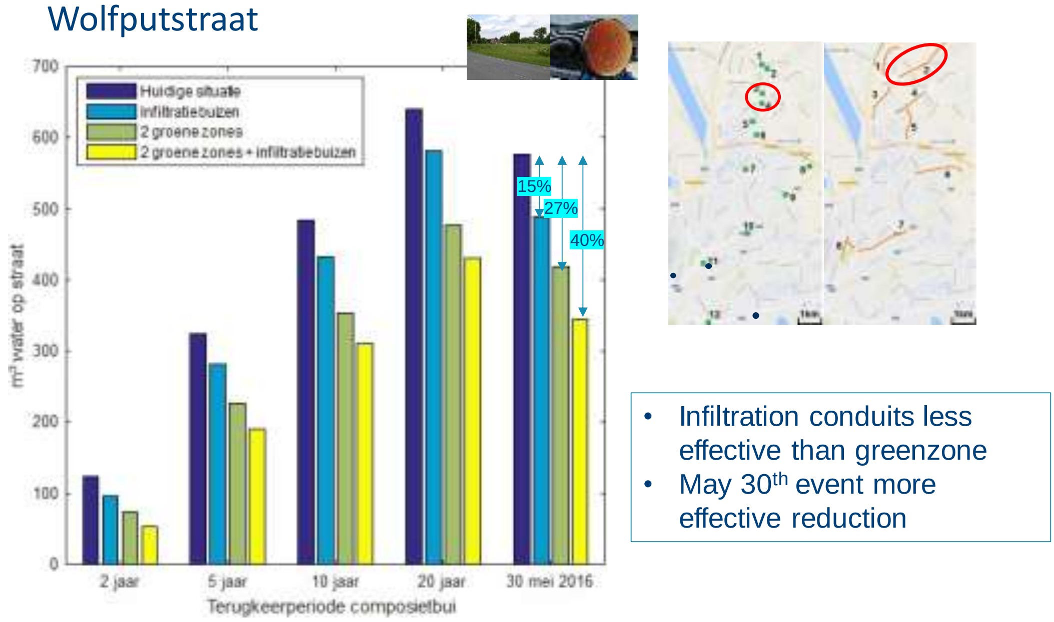
Example of impact results for the « green zones » solution



Example of impact results for the « permeable pavements » solution



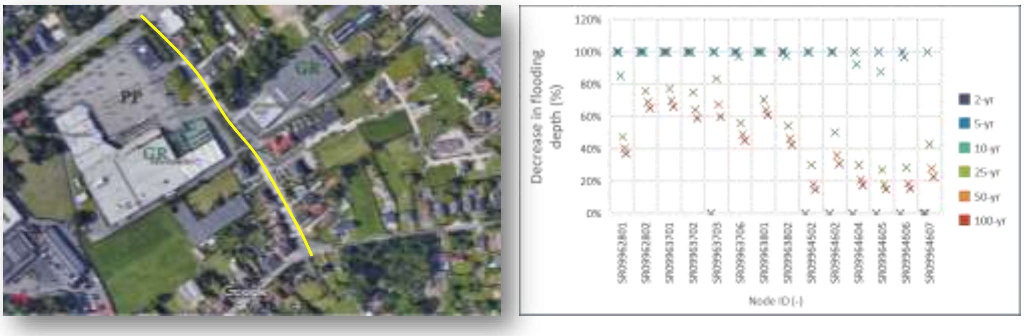
Example of impact results for the « infiltration conduits » solution



Example of impact results of combined sustainable urban drainage measures

Herman Teirlinckstraat

Subcatchment ID	SUDS ID	Area (m2)	Units (#)	Area (%)
SR09963701_1	GR	11050	1	23.273
	PP	5240	1	11.036
	PP	6170	1	12.995
SR09963706_1	GR	4760	1	29.862



Another example of impact results of combined sustainable urban drainage measures

Technical leaflets were worked out focusing on the different green infrastructures for urban storm water management. These technical documents provided information on definitions, ideal conditions of use, examples, proposal for Belgian cities, strengths and weaknesses and a conclusion.

Example pages from the leaflets

WP5 - Main conclusions

The literature review has highlighted three "gaps" in the literature. First, there is no consensus definition of green space. Second, there is no consensus typology of green spaces. Indeed, the green areas typologies classification approaches vary depending on the study. The choice of a typology depends on the purpose of the study. Third, it is not possible to synthesize the literature in order to quantify the role of different green spaces in water regulation. The analysis of infiltration and runoff data collected from the literature allowed to highlight a lack of consensus among the authors. It was concluded that current data do not allow us to predict different values of (function of) ecosystem services provided by the different types of ecosystems.

The analysis of the spatial structure of green spaces showed that the total amount of green spaces for the five cities is comparable to other European cities. The size of green spaces is increasing along an urban-rural gradient; at the same time, their density decreases. We also found that the connectivity of green spaces increases and that the shape becomes more complex along the urban-rural gradient.

More detailed analysis for the study areas highlighted that four vegetated devices play a role in urban stormwater management: green roofs, bio-swales, infiltration trenches and rain gardens. They all help with water regulation, but need to be addressed separately because of their shape, their components, or the way they work. For a city to develop vegetated devices for stormwater management, a case by case study must be realized to analyse specific conditions such as the available space, the local climate (temperature, light/shadow,...), and the budget. These devices and the methodology were described in technical leaflets.

3. POLICY SUPPORT

The PLURISK project has delivered important contributions to the policy support. It helped local authorities in setting up a risk quantification, control and management systems. This is important because these local authorities typically have too low capacity to do so. Next to the local authorities of the study cases, all Belgian community and city authorities responsible for local urban flood management can make use of the insights obtained on recommended approaches and of the methodologies and tools developed by the project. This is the case for the following outcomes of the project, hereafter classified per work package:

For WP1:

- Calibration and performance evaluation of local X-band radar, and tools for merging of the X-band radar with rain gauge data;
- Tools and evaluation on the integration of the different sources of rainfall data and the generation of hybrid composites;
- Development of the STEPS-BE software suite for the real-time and short-term forecasting of precipitation for Belgium, based on radar data and NWP
- The STEPS-BE system is operationally running at RMI and a viewer developed to make the short-term rainfall forecasting results available to end users;
- Testing of this nowcasting software suite for Belgium, for recent rain storms;
- Uncertainty analysis on the fine-scale rainfall estimation and forecasting results;
- International collaboration on the topic and exchange during international conferences and workshops, and by review reports and publications;
- Dissemination of the results during an, the final PLURISK-symposium and specific end user meetings.

For WP2:

- Sewer system simulation results for the various types of rainfall inputs (WP1) and evaluation / insights on the added value of these various rainfall data sources and merging methods;
- Sewer model extension with a module for 2D surface flood modelling and mapping;
- Recommended method for the approach and optimal mesh resolutions for the 2D surface flood modelling and mapping;
- Fast and efficient conceptual modelling approach developed for real-time applications;
- Validation of the flood simulation and forecast results for recent historical flood events;
- Evaluation of the added-value of the fine-scale rainfall estimates for flood simulation and of the fine-scale rainfall forecasts for flood prediction and warning;
- Computation of confidence limits on the flood simulation and prediction results;
- International collaboration on the topic and exchange during international conferences and workshops, and by review reports and publications;
- Dissemination of the results during an, the final PLURISK-symposium and specific end user meetings.

For WP3:

- Results of questionnaires among Flemish households that have been affected by urban flooding;
- Results on the statistical processing of the questionnaires and interpretation of the results;
- Development of basic valuation functions useful for urban flood impact analysis;
- Assessment of the (tangible and intangible) flood risk reducing effects of flood risk awareness, flood warnings and private precautionary measures;
- Evaluation and calibration of existing depth damage functions for houses and household goods;
- Evaluation and assessment of damage to immovable heritage places;
- Approach for real-time urban flood risk forecasting system recommended and successfully tested;
- International collaboration on the topic and exchange during international conferences and workshops, and by publications;
- Dissemination of the results during an, the final PLURISK-symposium and specific end user meetings.

For WP4:

- State-of-the-art overview of knowledge/practices/systems with respect to delivering flood risk and lightning stroke warnings to both the general public and managers of vulnerable infrastructures/activities;
- Design of communication rules and procedures for a real-time urban flood risk warning system for the urban context.

For WP5:

- Structured review of green ecotechnologies and green structures implicated in water flow management in the urban environment;
- Set up of a theoretical framework linking land use to green structures to the ecosystem service 'water flow control';
- Development of a generalized methodology to assess the capacity of urban landscapes' green structures to support ecosystem services 'water flow control', based on the examination for the case study areas; the method is expected to be pertinent for use in medium-size cities in temperate developed countries;
- Identification of historical trend for landscape's capacity to support water flow control in medium size cities in Belgium based on the examination of three case studies, and the key drivers of the temporal changes;
- Application of the land use – ESs framework for deriving land use recommendation for the case studies and development of a final framework including land use management strategies;
- Development and evaluation of the studied risk reduction strategies.

4. DISSEMINATION AND VALORISATION

The PLURISK project and results were presented / disseminated during the following policy related meetings:

- Regional symposium for regional city authorities on flood disasters and management: Willems P. (2012), 'Wateroverlast en verdroging in Vlaanderen: heden en toekomst', Studienamiddag BELEID EN OVERLEG (voor alle Vlaamse schepenen van openbare werken), Vlaams Parlement, 9 februari 2012
- National Observer Group (NOG) meetings of the RainGain Interreg IVB NWE project, Leuven, 18 April 2012 & Aartselaar, 15 May 2013: 29 persons from a very broad range of authorities attended the two meetings. Most of them were key experts of these authorities. Two river authorities proposed to give a short presentation on their radar/ flood forecasting activities, to look for synergy/cooperation between PLURISK and RainGain (urban applications) and other river management related activities.
- RainGain project workshops, London, 16-18 April 2013; Paris, 21-23 October 2013; Antwerp, 31 March-2 April 2014: about 30 persons attended these meetings, both from the academic world and water managers.
- AMICE Final Conference "Bridging Gaps!", 13-15 March 2013, Sedan, France: about 100 persons attended that meeting, many from the water authorities and other regional authorities of Flanders, Wallonia, Germany, France and The Netherlands
- Symposium on 'hydrological modelling of the Meuse basin', 13 September 2013, Liège: attended by about 50 persons, both from the academic world and water managers.
- Boussinesq Lecture 2013, Boussinesq Center for Hydrology, 24 October 2013, Royal Netherlands Academy of Arts and Sciences (KNAW) Amsterdam [invited lecture P.Willems]: attended by about 70 persons, both from the academic world and water managers.
- 66ste Vakantiecursus Drinkwater en Afvalwater: K3 (kosten, kwaliteit, kwetsbaarheid) in de watertechnologie, 10 January 2014, TU Delft, The Netherlands [invited lecture P.Willems]: attended by about 400 persons, mainly from the water sector in the Netherlands
- 8th Annual Meeting of Danish Research and Innovation Platform (DWRIP), KU Science, Frederiksberg, Denmark, 30 January 2014 [invited lecture P.Willems]: attended by about 200 persons, mainly from the water sector in Denmark
- VLARIO dag, Antwerpen Expo, 1 April 2014 [invited lecture P.Willems]: attended by 700 people from the urban drainage sector in Belgium
- VLARIO Studienamiddag Hemelwater, Brugge, 10 juni 2014 & Leuven, 12 juni 2014 [invited presentation P.Willems 'Klimaatverandering? En hoe er nu al mee omgaan in het rioleringsbeheer?']: 2 x 150 people
- Infoavond duurzame wijk De Vloei, Stadhuis Ieper, 17 september 2014 [invited lecture P.Willems 'Klimaatverandering en duurzaam waterbeheer'): 50 people
- Scheldecongres "De Schelde in 2050 - Beleids- en beheersopportuniteiten voor een welvarende toekomst", Antwerpen, 8 mei 2014 [invited presentation P.Willems, P., 'De impact van de klimaatwijziging op de waterhuishouding in het Scheldebekken: wat staat ons te wachten? / L'impact du changement climatique sur les ressources en eau de l'Escaut: ce qui nous attend?']: about 150 people attending

- Third RainGain Belgian National Observation Group (NOG), Leuven, 18 June 2014: about 20 people
- Stakeholdersmeeting 5de Assessmentrapport van het IPCC – deel 2: Impact, Adaptatie en Kwetsbaarheid - Conclusies en adaptatiemaatregelen in België / 5ème rapport d'évaluation du GIEC – partie 2: Changements climatiques : impacts, adaptation et vulnérabilité - Conclusions et actions d'adaptation en Belgique, Brussels, 6 May 2014 [invited presentation P.Willems 'Adaptatie aan meer hydrologische extremen in België / Adaptation aux extrêmes hydrologiques en Belgique']: attended by about 200 regional policy makers and experts from different climate related sectors
- RainGain Belgian NOG workshop, Wilrijk, 10 September 2015: Final results RainGain project [presentations by P.Willems, J. Van Assel, S. Kroll]: around 40 people attending
- Symposium Waterproef – Naar een klimaatbestendig Antwerpen, beweging.net Antwerpen, 5 October 2015 [presentation P.Willems]: around 60 people attending
- Energy and Climate Day for local authorities (Energie- en klimaatdag voor lokale besturen), Vlaamse Vereniging voor Steden en Gemeenten (VVSG), Leuven, 7 mei 2015 [presentation P.Willems]: around 500 people attending
- General stakeholders meeting of the water company "De Watergroep", Brussels, 5 June 2015 [presentation P.Willems]: around 300 people, mainly municipalities, attending
- Congres Publieke Ruimte 2015, Steunpunt Straten, Mechelen, 3 March 2015 [presentation P.Willems]: around 200 people attending
- RainGain Conference "Researchers & water managers preparing cities for a changing climate in the framework of the COP21 preparation", Marne-la-Vallée, France, 8-9 June 2015 [presentations: L-P. Wang, D.Murla, C.Muñoz, P.Willems]: about 100 people attending
- Conference "Environmental challenges & Climate change opportunities", Antwerp, 24-25 March 2015 [presentation P.Willems]: about 50 people attending
- STAR-FLOOD workshop "Overstromingen beheren in Vlaanderen en Wallonië: resultaten van vergelijkend onderzoek door STAR-FLOOD", Huis van het Nederlands, Brussel, 26 maart 2015 [presentation KU Leuven]: about 50 people attending
- Symposium by the l'Alliance Emploi-Environnement - Axe Eau, Gouvernement de la Région de Bruxelles-Capitale / de as Water van de Alliantie Werkgelegenheid-Leefmilieu, MundoB, Brussels, 3 April 2015 [presentation D.Murla]: about 40 people attending
- Training for Taiwanese officials on Climate change issues, College of Europe, Brugge, 17 July 2015 [invited guest lecture P.Willems]
- Voorstelling Klimaatrapport 2015, VMM, Aalst, 17 September 2015 [invited presentation P.Willems]: about 50 people attending
- Waterproef – Naar een klimaatbestendig Antwerpen, beweging.net Antwerpen, 5 October 2015 [invited presentation P.Willems]: about 50 people attending
- Symposium Meerlaagse Waterveiligheid (MLWV), CIW, 16 November 2015 [invited presentation P.Willems]: about 250 people attending
- Themamiddag "Help, de overstort verzuipt! Regenwater stopt niet bij het riool", Waterschap Aa & Maas & Kragten, 24 november 2015 [invited presentation P.Willems]: about 50 people attending
- Infonamiddag 'ontwerpen volgens nieuwe Code Van Goede Praktijk', INFRAX, Brussel, 8

December 2015 [invited presentation P.Willems]: about 40 people attending

- Klankbordgroep "Klimaatadaptatie Provincie Antwerpen", Antwerpen, 23 February 2016 [presentation P.Willems]: about 20 people attending
- Verkennende Benelux-workshop "Klimaatverandering en Rampenrisicovermindering in de Benelux", Brussel, 12 November 2015 [invited presentation P.Willems]: about 30 policy makers attending
- 11th EWA Brussels conference on "Water Challenges in Europe", European Water Association, Brussels, 16 November 2015 [invited presentation P.Willems]: about 50 people attending
- 20 jaar Maasafvoerverdrag, Riemst, 23 November 2015 [invited presentation P.Willems]: about 80 people attending
- Workshop on "Heavy Rainfalls in the Cities and Flood Risk Management", European Water Association - ETSC (European Technical and Scientific Committee), Hennef, Germany, 3 December 2015 [invited presentation KU Leuven]: about 20 people attending
- Workshop "Klimaatadaptatie in Transport en Mobiliteit in de Benelux en omgeving", Secretariaat-Generaal Benelux, Brussel, 29 April 2016 [invited presentation P.Willems]: about 30 policy makers attending
- INCA-BE end-user meeting, RMI, 22 October 2013: attended by ~20 end-users of INCA-BE. The goal of this meeting was to discuss and exchange the experiences with INCA-BE between the end-users, which are potential future end-users of STEPS nowcasts as well
- RMI seminar 'European lightning characteristics - local vs. long-range lightning location systems' by D. Poelman, 12 March 2014: attended by ~30 people from RMI including scientists, weather forecasters and operational IT people
- RMI seminar 'Probabilistic precipitation nowcasting with the Short Term Ensemble Prediction System (STEPS) in Belgium' by L. Foresti, 16 April 2014: attended by ~30 people from RMI including scientists, weather forecasters and operational IT people
- Information day for the regional hydrological services of Belgium, RMI, 27 April 2015: presentation of all RMI products relevant for hydrological applications including STEPS-BE and INCA-BE; attended by ~20 representatives of all regional hydrological authorities in Belgium (VMM, HIC, DGO2, IBGE/BIM)
- STEPS-BE training for the forecasters of the RMI, 13 August 2015, by L. Foresti
- INCA-BE training for the forecasters of the RMI (10, 11 and 17 December 2012), the forecasters of the Oceanografisch Meteorologisch Station (OMS) in Oostende (26 May 2014), and the forecasters of MeteoLux in Luxembourg (19 and 20 October 2015), by M. Reyniers
- Les Midis du Maillage Bleu + Quand la science se mêle de la gestion des eaux pluviales: Présentation de deux recherches du projet PLURISK / De Middagen van het Blauwe Netwerk + Wanneer wetenschap samengaat met regenwaterbeheer: Presentatie van twee onderzoeken uit het PLURISK-project, GroupOne pour l'Alliance Emploi-Environnement - Axe Eau, Gouvernement de la Région de Bruxelles-Capitale / de as Water van de Alliantie Werkgelegenheid-Leefmilieu, MundoB, Brussels, 3 April 2015: attended by ~30 people
- SURE (Society for Urban Ecology) World Conference 2013, 25-27 July 2013, Berlin (Germany): Maréchal Justine, oral communication, 'Assessment of ecosystem services related to urban green spaces in flood management: a review and development of a methodology'
- Symposium Paul Duvigneaud : Vers une nouvelle synthèse écologique, 5-6 November 2013, Bruxelles: Maréchal Justine, poster presentation, 'De l'évaluation des services écosystémiques

liés aux espaces verts urbains dans la gestion des inondations : revue bibliographie et développement d'une méthodologie'

- CIVA (Centre International pour la Ville, l'Architecture et le Paysage), 17 March 2014, Bruxelles: Maréchal Justine, oral communication, 'Espaces verts et services écosystémiques : le cas de la gestion des inondations en milieu urbain'
- BEES Christmas Market, 17 December 2014, Gembloux: J. Maréchal, poster presentation, 'Green structures as ecosystem services providers in urban adapatation strategies to flooding'
- ALTER-Net Conference Nature & Urban Wellbeing: Nature-Based Solutions to Societal Challenges, 19-20 May 2015, Ghent: J. Maréchal, poster presentation, 'About generalization of the spatial pattern of green spaces among different cities'
- EWA Brussels Conference, 13th EWA Brussels Conference: Recent Developments in EU Water Policy, 6-8 November 2017, Brussels; P.Willems, presentation on 'Climate change & water resources: call for smart climate adaptation strategies & innovations': attended by about 50 policy makers
- BRIGAID Consortium Meeting, Venice, 9 November 2017: P.Willems, presentation on 'testing of innovations', attended by about 60 people
- Kansai University – EU Research Center International Symposium, 10 March 2017: P.Willems, presentation 'Research overview and collaboration opportunities for Civil incl. Water Engineering'
- Conferentie Belgisch Nationaal Committee voor Geofysica en Geodesie (BNCGG), RMI, Uccle, 6 October 2016: P.Willems, presentation 'Urban flood modelling and nowcasting'
- Belgian Hydraulics Day, Louvain-la-Neuve, 25 October 2016: P.Willems, presentation 'Overview Hydraulics research at KU Leuven'
- Waterbouwdag 2016, Rotterdam, 10 November 2016: P.Willems, presentation 'Overstromingsproblemen in België': about 200 people incl. many policy makers attending
- Civieltechnisch Symposium, Universiteit Twente, Enshede, Nederland, 15 February 2017: P.Willems, presentation 'Waterproblemen in België': about 200 people attending
- Symposium en Algemene Vergadering Natuurpunt Oost-Brabant, Leuven, 18 February 2017: P.Willems, presentation 'Uitdagingen van de klimaatverandering en klimaatbuffering voor waterbeheer en de toekomstige rol van onze valleien en het watersysteem': about 50 stakeholders attending
- Debatavond "Water, Weer & Wonen; Impact en Aanpak van de Klimaatverandering", werkgroep Ethiek Groep Wetenschap & Technologie KU Leuven, Leuven, 1 March 2017: P.Willems, presentation 'Water & klimaatverandering in Vlaanderen: impact en adaptatie'
- Course Integrated Water Management: Case River 21, University of Lille, France, 13 March 2017: P.Willems, presentation 'Climate change and impacts on hydrological extremes'
- Vlariodag, Antwerpen, 22 March 2017: P.Willems, presentation 'Oplossingen om schade door regenval te beperken – Iedereen heeft zijn verantwoordelijkheid: burger, overheid en landbouw': about 300 stakeholders and policy makers attending
- Academiesessie 'duurzaamheid: water', beweging.net Brussel-Halle-Vilvoorde, 21 March 2017, Dilbeek: P.Willems, presentation on 'Wateroverlast'
- Uitstraling Permanente Vorming, 25 April 2017, VUB, Brussel: P.Willems, presentation 'Water & klimaatverandering'

- CORDEX.be Stakeholders meeting, KMI Ukkel, 25 September 2017: P.Willems, presentation on hydrological impacts
- End user workshop EU-project PUCS about "rampenplanning in een veranderend klimaat", Antwerpen, 27 September 2017: P.Willems, presentatie m.b.t. urban flood risks and forecasting

Next to these networking and valorisation activities, several Follow-up Committee meetings were organized: on 12 October 2012, 12 December 2013 and 4 March 2015. The reports of these meetings are attached. On 4 October 2017, a final PLURISK workshop was organized in Brussels, where the final PLURISK findings and results were disseminated to a broad audience of end users and other stakeholders. Four end users expressed their views; the city of Ghent presented their findings on the evaluation they did on the STEPS-BE system and the flood modelling results.

In summary, the participating end users were very interested in the project and its results, and made several very useful suggestions that were taken into account in the project. During the project, close collaboration was set up with end users in the study areas of Leuven and Gent. The Brussels Capital region was identified as a good candidate for another case study. There was a strong interest by Bruxelles Environnement - IBGE / Leefmilieu Brussel – BIM, but the existing sewer model could not be made available by the sewer company Vivaqua, who is owning that model. The city of Liège was explored as another option, but during the first Follow-up Committee meeting it became clear that this city suffers more from river floods (from the river Meuse) than sewer floods. The city of Tournai was another candidate but plans did not become concrete. As per the discussions on these options during the Follow-up Committee meetings, and also during the mid-term evaluation meeting, rather than considering three case studies in parallel, we changed the planning considering two case studies for testing methodologies, where after these methodologies become applicable to any city in Belgium.

For the case study Leuven, a very interesting link could be made with the ongoing Interreg IVB NWE project RainGain. We intensively cooperated with the water company Aquafin for that case. For the Gent case, strong collaboration was set up with the water company Farys and the city of Gent. Also interesting contacts were set up with the Japanse company FURUNO, who provided two new X-band radars in kind.

5. PUBLICATIONS

Peer review

Foresti, L., Seed, A. (2014). The effect of flow and orography on the spatial distribution of the very short-term predictability of rainfall from composite radar images. Hydrology and Earth System Sciences, 18, 4671-4686

Wang, L-P., Ochoa-Rodriguez, S., Onof, C., Willems, P. (2015a). Singularity-sensitive gauge-based radar rainfall adjustment methods for urban hydrological applications. Hydrology and Earth System Sciences, 19, 4001–4021

Wang, L-P., Ochoa-Rodriguez, S., Van Assel, J., Pina, R.D., Kroll, S., Pessemier, M., Willems, P., Onof, C. (2015b). Enhancement of radar rainfall estimates for urban hydrology through optical flow temporal interpolation and Bayesian gauge-based adjustment. Journal of Hydrology, 531, 408-426

Ochoa-Rodriguez, S., Wang, L-P., Gires, A., Pina, L.R., Reinoso Rondinel, R., Bruni, G., Ichiba, A., Gaitan, S., Cristiano, E., van Assel, J., Kroll, S., Murla-Tuyls, D., Schertzer, D., Tchiguirinskaia, I., Onof, C., Willems, P., ten Veldhuis, J.A.E. M-C. (2015). Impact of spatial and temporal resolution of rainfall inputs on urban hydrodynamic modeling: a multi-catchment investigation. Journal of Hydrology, 531(2), 389-407

Van Ootegem, L., Verhofstadt, E., Van Herck, K., Creten, T. (2015). Multivariate pluvial flood damage models. Environmental Impact Assessment Review, 54, 91-100

Foresti, L., Reyniers, M., Seed, A., and Delobbe, L. (2016). Development and verification of a real-time stochastic precipitation nowcasting system for urban hydrology in Belgium. Hydrology and Earth System Sciences, 20, 505-527

Goudenhoofdt, E., Delobbe, L. (2016). Generation and Verification of Rainfall Estimates from 10-Yr Volumetric Weather Radar Measurements. Journal of Hydrometeorology, 17, 1223-1242

Van Ootegem L., Verhofstadt, E. (2016). Well-being, life satisfaction and capabilities of flood disaster victims. Environmental Impact Assessment Review, 57, 134-138

Gires, A., Tchiguirinskaia, I., Schertzer, D., Ochoa Rodriguez, S., Willems, P., Ichiba, A., Wang, L-P., Pina, R., Van Assel, J., Bruni, G., Murla-Tuyls, D., ten Veldhuis, M-C. (2017). Fractal analysis of urban catchments and their representation in semi-distributed models: imperviousness and sewer system. Hydrology and Earth System Sciences, 21, 2361-2375

Muñoz, C., Wang, L-P., Willems, P. (2018). Enhanced object-based tracking algorithm for convective rain storms and cells. Atmospheric Research, 201, 144-158

In press: Van Ootegem, L., Van Herck, K., Creten, T., Verhofstadt, E., Foresti, L., Goudenhoofdt, E., Reyniers, M., Delobbe, L., Murla Tuyls, D., Willems, P. (in press). Pluvial flood damage models: Exploring the potential of multivariate rainfall models. Journal of Flood Risk Management, doi:10.1111/jfr3.12284, In press.

In revision: Ntegeka, V., Murla, D., Willems, P. (in revision). Development and testing of a nested 1D/2D urban surface flood model.

In review: Bermúdez, M., Ntegeka, V., Wolfs, V., Willems, P. (in review). Development and comparison of two fast surrogate models for urban pluvial flood simulations.

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For the Gent case, strong collaboration was set up with the water company Farys and the city of Gent.

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ANNEX 1. COPY OF THE PUBLICATIONS

Copies of the publications listed in section 5 « Publications ».

ANNEX 2. MINUTES OF THE FOLLOW-UP COMMITTEE MEETINGS

- Minutes, 1st follow-up committee meeting, Brussels, 12 October 2012
- Minutes, 2nd follow-up committee meeting, Brussels, 12 December 2013
- Minutes, 3th follow-up committee meeting, Brussels, 4 March 2015

The annexes are available on our website:

http://www.belspo.be/belspo/SSD/science/pr_risk_en.stm