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REAL-TIME FLOOD FORECASTING SYSTEM IN FLANDERS

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As a highly urbanized and flood prone region, Flanders has experienced multiple floods causing significant damage in the past. In response to the floods of 1998 and 2002 the Flemish Environment Agency, responsible for managing 1 400 km of unnavigable rivers, started setting up a real time flood forecasting system in 2003. Currently the system covers almost 2 000 km of unnavigable rivers, for which flood forecasts are accessible online (www.waterinfo.be).
The forecasting system comprises more than 1 000 hydrologic and 50 hydrodynamic models which are supplied with radar rainfall, rainfall forecasts and on-site observations. Forecasts for the next 2 days are generated hourly, while 10 day forecasts are generated twice a day. Additionally, twice daily simulations based on percentile rainfall forecasts (from EPS predictions) result in uncertainty bands for the latter. Subsequent flood forecasts use the most recent rainfall predictions and observed parameters at any time while uncertainty on the longer-term is taken into account. The flood forecasting system produces high resolution dynamic flood maps and graphs at about 200 river gauges and more than 3 000 forecast points. A customized emergency response system generates phone calls and text messages to a team of hydrologists initiating a pro-active response to prevent upcoming flood damage.
The flood forecasting system of the Flemish Environment Agency is constantly evolving and has proven to be an indispensable tool in flood crisis management. This was clearly the case during the November 2010 floods, when the agency issued a press release 2 days in advance allowing water managers, emergency services and civilians to take measures.

INTRODUCTION

Flanders is the Dutch speaking northern part of Belgium and has a total area of 13 500 km² of which nearly 10% is prone to floods, potentially affecting more than 100 000 people. In order to reduce the flood damage, the Flemish Environment Agency has developed a flood forecasting system based on detailed, hydrodynamic models (Figure 1). These models cover almost 2 000 km of rivers and consist of more than 50 000 nodes representing the riverbed cross sections, hydraulic structures, banks, storage areas, etc.

The forecasting system has been divided in 9 subsystems, each of which comprises 3 to 13 hydrodynamic models and performs 43 simulations per day. One simulation is used for saving the states consisting of initial stages and discharges within the hydraulic models as well as soil moisture content within the hydrologic models. Each of the following 42 simulations starts from these states. The simulation schedule consists of hourly short-term deterministic forecasts using high resolution rainfall forecasts and twice daily ensembles of short- and long-term probabilistic forecasts based on lower resolution rainfall forecasts as described in the section on rainfall forecasts.

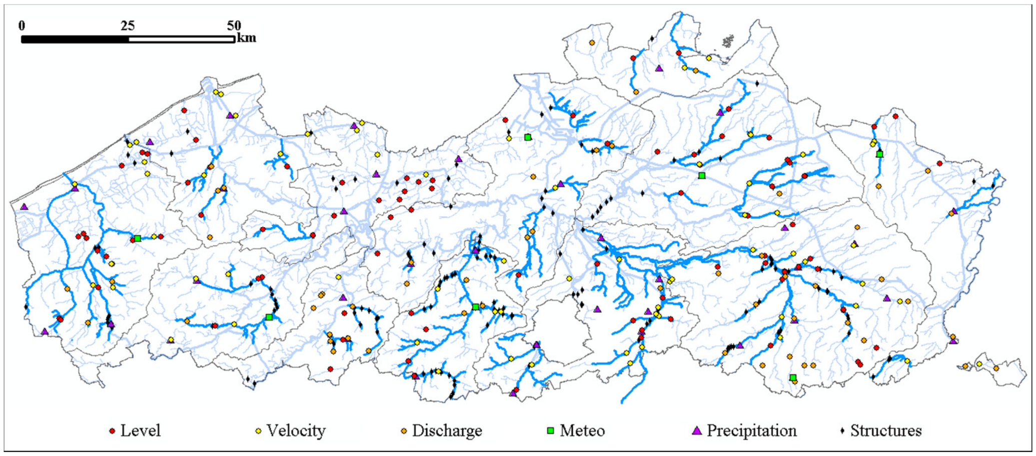

Figure 1. Extent of hydrodynamic models used in the operational flood forecasting system (blue lines) and overview of the gauging network operated by the Flemish Environment Agency

This paper describes the hydro-meteorological input data, the technical details of the flood forecasting system and its importance for a solid decision support. Finally, the paper discusses the data flow and the widget based portal website through which all data is presented.

HYDRO-METEOROLOGICAL INPUT

Rainfall

Rainfall observations

The Flemish Environment Agency maintains 43 rain gauges across Flanders (Figure 1). Nevertheless the rain gauge network is insufficiently dense to provide the hydrologic models with accurate rainfall estimates since their subcatchment areas vary from 1 to 500 km². Radar rainfall is known to give a better spatial resolution of the rainfall pattern and is thus a very helpful tool in real-time flood forecasting. Currently the flood forecasting system makes use of a pseudo-CAPPI radar composition of three radars with a spatial resolution of 1 km and new radar images available every 5 min. Even with the use of state of the art radar technology, error propagation can make radar rainfall data sometimes spurious. The use of rain gauge data to correct the retrieved radar rainfall is therefore necessary as illustrated by De Jongh *et al* [1]. The recalibration of raw radar rainfall with the available rain gauge data is performed every 15 min according to the algorithm of Moore *et al.* [2]. Adjustments made by Martens *et al.* [3] to optimize this method for the specific situation in Flanders will be employed in the near future.

Rainfall forecasts

Table 1 provides the spatial and temporal resolution, the simulation interval and the lead time for each of the available rainfall forecast products. Each of the daily 42 simulations uses different rainfall data sources or a combination of these as shown in Table 2.

Table 1. Properties of the different rainfall data sources used by the flood forecasting system

Rainfall forecast source	Spatial resolution [km]	Temporal resolution [min]	Simulation interval [min]	Lead time [h]
INCA-BE	1	10	10	4
ALARO	7	60	360	60
EURO4	12	15	360	48
ECMWF-det	16	360	360	240
ECMWF-EPS	32	360	720	240
GLAMEPS	11	180	720	54

Table 2. Lead time and rainfall data source for different types of simulations

	Lead time	Rainfall forecast source	
		0 - 4 h	4h - 48 h
Short-term deterministic (ST-det)	2 days	INCA-BE	Alaro (EURO4)
Short-term probabilistic (ST-%)	2 days	GLAMEPS percentiles	
Long-term deterministic (LT-det)	10 days	ECMWF deterministic	
Long-term probabilistic (LT-%)	10 days	ECMWF-EPS percentiles	

The short-term deterministic simulations use the best available rainfall forecast being INCA-BE for a lead time up to 4 hours and ALARO for the 4 to 48 hours lead time. INCA-BE is a nowcasting system used by the Royal Meteorological Institute of Belgium (RMI). It provides a forecast of which the first 2 hours consist of an extrapolation of the recalibrated radar observations after which it blends with the ALARO forecast for the following 2 hours (Reyniers *et al.* [4]). ALARO is an operational limited area NWP model used by the RMI. It is based on the ALADIN model but further developed with a physics parameterization package to be run at convection-permitting resolutions (Gerard *et al.* [5]). EURO4 is a NWP model from the British Met Office and serves as an operational backup for ALARO in case its forecasts would be missing or considered less plausible.

The long-term forecasts with lead times up to 10 days are produced by the European Center for Medium range Weather Forecasting (ECMWF). Besides one deterministic forecast, the ECMWF Ensemble Prediction System (EPS) produces 50 different results by perturbing the initial states and stochastically varying the model's parameters (Persson [6]).
The Grand Limited Area Model Ensemble Prediction System GLAMEPS is a multi-model EPS prepared for pan-European, short-range probabilistic numerical weather prediction. It combines EuroTEPS with ensembles based on the ALADIN model and two versions of the HIRLAM model resulting in 48 perturbed and 4 control members. GLAMEPS has been proven to produce better results than ECMWF's EPS (Iversen *et al.* [7]).
The ensembles are reduced to 4 time series for each EPS-grid from ECMWF and GLAMEPS by calculating the 10th, 25th, 75th and 90th percentile. This reduction makes the hydrodynamic simulation of probabilistic rainfall series possible within acceptable computation time.

Hyrad

Hyrad is an advanced weather radar display system developed by the British Centre for Ecology and Hydrology (CEH [8]). It provides real-time reception of rainfall data, recalibration of radar data based on rain gauge observations, static and dynamic display of images in multiple windows, merging of different rainfall data in time, calculation of catchment average time series and exporting these time series to serve as input for the hydrologic models.

Gauging network

In addition to radar rainfall data and rainfall forecasts, observations play a crucial role in calibrating the hydrodynamic models and are used in a data assimilation scheme to improve the forecasts. Since the early 1960's, the gauging station network has grown to an operational network of the entire hydrologic cycle, ranging from rainfall and meteorological parameters over soil moisture to water levels and discharges. The current network consists of 43 rain gauges, 8 meteorological stations – with 3 of them measuring soil moisture at different depths – and 200 river gauges of which 94 also register discharges (Figure 1).

Meteorological parameters

The meteorological stations measure all parameters related to evapotranspiration (radiation influx, ground irradiation, soil temperature, air temperature at different heights, …).

Stages, discharges and structures

Historically, water levels were measured with floating devices. Since the beginning of this century most of these devices have been replaced by or complemented with radar devices. The radar technology allows contactless measuring of water levels with high accuracy and precision. Observations are made every 3 seconds and averaged over 15 minutes. At locations with extensive weed growth in the riverbed, pressure sensors are used for recording water levels. Traditionally, discharges were measured based on a rating curve calibrated through manual gaugings. During the last decade 69 gauging stations were equipped with velocity sensors to tackle the inadequacy of a rating curve at locations where backwater effects due to weed growth, tides or hydraulic structures strongly influence water levels. Two types of velocity sensors are used: acoustic Doppler current sensors and contactless radar sensors.

All measurements are locally stored and are retrieved by data acquisition software to a central database. Communication for most stations is still through telephone (either fixed line or mobile), but the network is quickly evolving towards digital GPRS communication. Standard data calls are executed based on the urgency either with a 3 h, 1 h or 15 min interval.

Hydraulic structures such as pumps, weirs, sluices, etc. are automated and mostly controlled based on nearby measured stages and flows. These logical rules are configured in a Supervisory Control And Data Acquisition system (SCADA) allowing to monitor the levels nearby the structure and adapt the control parameters.

FLOOD FORECASTING SYSTEM

Each simulation with a flood forecasting system involves the import of time series, the simulation of the hydrologic and hydrodynamic models and the export of results. Time series of evaporation, recalibrated radar and forecasted rainfall are used to feed the hydrologic models that convert this input to discharge time series. These serve as upstream boundaries for the hydrodynamic models which, in turn, produce results for export. An evaluation of the forecast results allows to indicate the severity of the forecasted floods and to send out automated warnings. The software FloodWorks (Innovyze [9]) plays a key role in this entire model chain.

Hydrologic model

The hydrologic model used in the flood forecasting system is the Probability Distributed Model. PDM is a lumped conceptual hydrologic model that is suitable for continuous simulations (Moore [10]). The model translates rainfall and potential evapotranspiration data to flow at the catchment outlet based on a probability distributed soil moisture store population. The soil moisture stores generate direct runoff and groundwater recharge. Direct runoff is routed via two linear surface storages and groundwater recharge by a cubic subsurface storage. The sum of the outflow from surface and subsurface storages is the total flow generated by the PDM model. The Flemish Environment Agency has calibrated PDM models for approximately 100 monitored catchments (Cabus [11]). These PDM models serve as a basis for the calibration of the usually smaller and often ungauged subcatchments of the hydrodynamic model.

Hydrodynamic model

Stage and flow computations by the hydrodynamic models, fed by the hydrologic models, are executed with the 1-dimensional InfoWorks River Systems software (Innovyze [13]). It solves the Saint-Venant equations, which express the conservation of mass and momentum, by the implicit Preissmann numeric scheme (Preissmann [14]).

The hydrodynamic models are built from detailed topographic information such as transverse profiles of the riverbed every 50 m along the river and of all structures (bridges, weirs, sluices, etc.) and longitudinal profiles of the river bank along the entire modeled trajectory. The floodplains are modelled by reservoirs or cross sections across the valley. By defining flood compartments InfoWorks allows a comprehensive visualization of the extent of flooding by comparing the simulated water levels with the underlying Digital Elevation Model (DEM). The DEM has a horizontal resolution of 5 m and an average vertical accuracy of 7 cm (AGIV [15]).

FloodWorks

The FloodWorks software (Innovyze [9]) manages the import and evaluation of real time data, the simulation of hydrologic and detailed hydrodynamic models with updating at gauging stations, the display and export of simulation results and an evaluation of threshold water levels indicating the severity of the forecast.

FloodWorks imports time series of observed rainfall, evapotranspiration, water levels, discharges, rainfall forecasts, … Quality checks prevent the use of inaccurate data and the operator can manually adjust the time series at any time. In case of missing data FloodWorks allows the models to fall back on the best available data.

Aiming at more accurate flood forecasts, the system has the ability to update forecasts based on observed values at gauging stations and structures. A simple error correction method adjusts the hydrodynamic model by adding or abstracting the difference between measured and simulated flow at gauged locations. Updating is restricted to a range of levels or flows in which values are considered to be reliable and the model sufficiently stable. The correction discharges will slowly convert to zero when measurements are no longer available in order to prevent sudden changes causing model instability at time ‘now’ or in case of missing data. Often the measured flow is calculated by converting the measured level to a flow using the rating curve of the corresponding cross section in the model, resulting in the model being updated on water level. For those gauging stations where only simple hydrologic forecasts are available, the hydrologic models are updated through state updating. The flows out of the surface and groundwater storages of the PDM model are adjusted based on the difference between simulated and observed flows through an empirical state adjustment scheme as described by Moore [10].

The logical rules controlling hydraulic structures are implemented in the flood forecasting system where they can be overruled in case of a manual intervention in the SCADA system. The flood forecasting system also allows for updating the position of hydraulic structures.

FLOOD WARNINGS AND DECISION SUPPORT

In order to retain a continuous real-time overview and to carry out necessary notifications and communication in time, different forecasting modes are delineated with corresponding colors as presented in Table 3.

Table 3. Forecasting modes with corresponding color and interpretation

Mode	Color	Interpretation
Basic	Green	No actual or expected floods
Pre-alert	Yellow	Non-critical floods (farmlands and meadows) expected
Alert	Orange	Actual non-critical floods (farmlands and meadows)
Pre-alarm	Red	Critical floods (buildings) expected
Alarm	Red	Actual critical floods (buildings)

By evaluating threshold levels at gauging stations the condition of the current and forecasted flood situation is continuously assessed and the corresponding color is assigned to the station. Apart from these monitored locations forecast points are defined at strategically chosen reference points, usually bridges. These forecast points have local alert and alarm thresholds or are linked to the first locations along the upstream trajectory where non-critical and critical floods occur. The alert thresholds are determined by the DEM while the alarm thresholds correspond with the elevation of the lowest doorstep. More than 3 000 topographically surveyed doorsteps have been found to be representative for their neighborhood and are configured as such in the flood forecasting system. When a threshold is exceeded, the system switches to the corresponding mode and emphasize the triggered events by flashing circles, coloring nodes, etc.

Measurements from the gauging stations are retrieved every 3 hours to 15 minutes depending on the telemetry mode. Each of the flood forecasting subsystems has a separate telemetry mode which is evaluated by FloodWorks and triggered by the exceeding of telemetry threshold levels at strategically chosen gauging stations. Observations at rain gauges and hydraulic structures can change suddenly and are therefore always retrieved with an interval of 15 minutes.

A customized emergency response system translates FloodWorks' mode switches to warnings to the team members. This team consist of more than 50 people such as hydrologists, electromechanical engineers, field supervisors and maintenance staff, who are available 24/7 to monitor and interpret forecasts and intervene on-site. The warnings can be issued as phone calls or text messages, depending on the severity of the situation. The emergency response system also serves as a telephone switch system that redirects calls from professionals, such as firefighters and emergency planners, to the appropriate person available at that time.

DATA FLOW

Different data sources are directed to and from the flood forecasting system in different ways. Figure 2 gives an overview of this data flow and its sources.

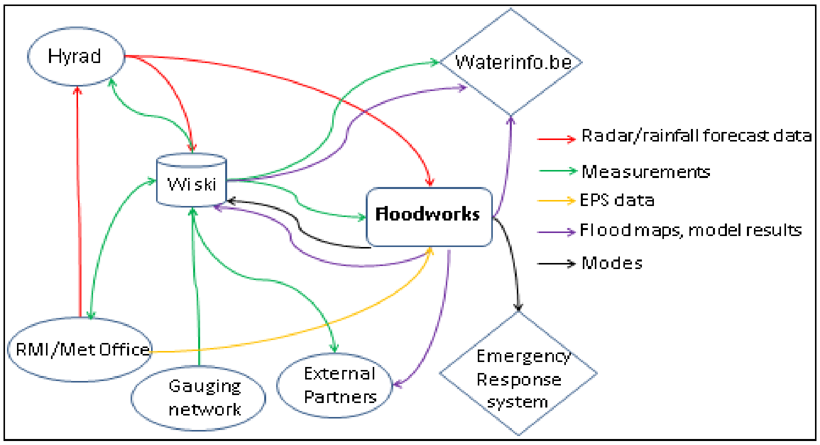

Figure 2. Dataflow of the flood forecasting system

The central point of the data flow is an oracle database, accessed with WISKI software (Kisters [16]). This is a GUI where all available data can be consulted, adapted and exported. Calculation servers run specific applications for the calculations within the database and the import to and export from the database. Real-time measurements from the Flemish Environment Agency enter the database directly via the telemetry software or the SCADA export service. Before being imported into WISKI, data from external partners are placed on an ftp folder, arrive attached to e-mails, are picked up from external ftp folders or are retrieved by a query on the database of a third partner.

OUTPUT: WWW.WATERINFO.BE

In association with other Flemish water managers, the Flemish Environment Agency has launched a widget based web portal www.waterinfo.be, combining all real-time measurements and flood forecasts generated by the forecasting systems for the navigable and unnavigable rivers in Flanders. The data are presented as animated, forecasted flood maps and graphs of water levels, discharges,… and displayed on an interactive map of Flanders. In addition to floods, the website provides information on 3 other themes: tides, precipitation and drought. Within the flood theme the model results are presented in three subpages according to the time frame for which the information is provided. The first subpage presents the actual flood situation with the color of each gauging station coinciding with its current status (green, orange or red). On the short- and long-term forecast subpages the gauges are colored green, yellow, orange or red according to their status. Clicking on a gauging station generates a graph displaying the measured and forecasted parameters. A time slider allows to view the sequential flood maps or to display the maximum flood extent over the entire forecast period. Professional users get extra options such as the possibility to consult the expected flood impact and to build their own dashboards as a collection of any available widgets that are interesting to them.

CONCLUSION

The real-time flood forecasting system of the Flemish Environment Agency provides detailed short- and long-term forecasts for nearly 2 000 km of unnavigable rivers in Flanders. The system uses observations from both rainfall radars and a dense gauging network, and forecasts from several European weather services. Up-to-date forecasts are computed hourly using the most recent observations and rainfall predictions, while 12-hourly forecasts give an indication of forecast uncertainty. A customized emergency response system issues automated flood warnings to the Agency's personnel. Flood forecasts, displayed as animated flood maps and graphs of water levels and discharges, in addition to manually interpreted flood information, can be consulted online through the widget based portal www.waterinfo.be. This provides both public and professional users with clear and crucial information to prepare for upcoming floods.

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