High-resolution ensemble flood forecasting: a case study in Höje Å, Sweden

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Abstract The number and impacts of pluvial floods are likely to increase with the growth of our cities and as extreme weather is anticipated to intensify with climate change. Improved preparedness is needed which may be attained owing to recent development of high-resolution hydro-meteorological observations and forecasts as well as geographical data.

This paper investigates the capacity of the HYPE model for rainfall-runoff modelling and ensemble forecasting at hourly resolution. The analysis includes evaluation and application of several new high-resolution data sources: radar-based precipitation (HIPRAD), urban land-use data (EEA Urban Atlas) and high-resolution ensemble forecasts (MEPS). These components are finally integrated in a forecasting prototype for a catchment in southern Sweden.

The results showed that HYPE, forced with HIPRAD and with land-use from Urban Atlas, performed well with a long-term Nash-Sutcliffe Efficiency > 0.8 at hourly level. Analysis of selected pluvial-type high-flow events close to an urban area indicated a good representation of fast runoff. The application of MEPS forecasts has been demonstrated for a few single events with promising results. Overall it is concluded that the 1-hour forecasts provide added value compared with the 1-d step and that an increased resolution in time and space is important to accurately forecast pluvial-type events.

Keywords: high-resolution, rainfall-runoff modelling, HYPE, forecasting, pluvial flooding

1. Introduction

Floods in urban areas bring potential risks for human lives, health and environment and the destruction can be severe and expensive to reconstruct. Urban flooding can be caused by either increased water levels at sea (coastal flooding), from a river that is overflowed (fluvial flooding) or when the rainfall intensity exceeds the ability of the ground to infiltrate (pluvial flooding). The latter may occur from short intense rainfalls in combination with a large fraction of impervious surface and a limited capacity of storm water sewer systems. The frequency and severity of this type of flooding is likely to increase in a future climate (Houston *et al.*, 2011). There is an ongoing growth of our cities creating larger areas of impermeable ground and at the same time human activities such as carbon-dioxide emissions are resulting in climate change and global warming (IPCC, 2013) which is anticipated to cause more intensified precipitation (European Environmental Agency, 2012).

In order to limit the consequences from pluvial flooding, models can be used to forecast the event. Since the intense rainfalls which cause pluvial floods usually are generally short and local, it is important that the resolution in time and space of the model is high enough to catch rapid variations. This paper investigates the capacity of The Swedish Meteorological and Hydrological Institute's (SMHI) runoff model, called HYPE, for rainfall-runoff modelling at hourly resolution. The analysis includes evaluation and application of several new high-resolution data sources: radar based precipitation (HIPRAD), urban land-use data (EEA Urban Atlas) and high-resolution ensemble forecasts (MEPS). Finally these components are integrated in a forecasting prototype for a catchment area in southern Sweden. The study is a part of the development of an hourly national flood forecasting system at SMHI.

2. Models and data

The study is based on the latest development of two models; HYPE at 1h resolution, and MEPS, as well as newly obtained data sets of high resolution precipitation (HIPRAD) and areal data for urban areas (EEA Urban Atlas). Below the models and data are described further.

HYPE is a hydrological runoff model developed by the hydrological research team of SMHI (Lindström *et al.*, 2010). HYPE stands for Hydrological Predictions for the Environment and can be used to model flow and circulation of water and nutrients from precipitation through the soil to the river discharge. It provides the ability to forecast matters related to water resources and water with high spatial detail, even for catchments with few gauges. The current operational model uses a daily time-step, but the temporal resolution has recently been increased with an aim to perform equally well in urban areas as in rural areas. An increase in temporal resolution would allow catching also the short intensive rainfall causing pluvial flooding, which cannot be captured with a 1-day time step. The performance of high resolution HYPE-model is evaluated within this study.

MEPS is a numerical weather prediction (NWP) system for high-resolution ensemble forecasts by the HARMONIE model (Seity *et al.*, 2012), developed in a cooperation between Sweden, Finland and Norway. MEPS has an hourly time step and a high enough spatial resolution (2.5×2.5 km²) to catch short and local precipitation events which can result in pluvial flooding. Instead of making a single forecast of the most likely weather, within ensemble forecasting an ensemble of forecasts are produced. These are called members. The amount of spread between the members should be related to the uncertainty of the forecast. The ensemble system of MEPS consist of 10 members all run on different surface assimilation's and forecasting 36 hours ahead (Andrae, 2017).

HIPRAD is a gridded national precipitation data set with a 2.5×2.5 km² spatial and 15 min temporal resolution now under development at SMHI (Berg *et al.*, 2015). It uses radar data adjusted to gridded gauge data (PTHBV) to combine the high accuracy of the gauge data with the nearly full spatial coverage of the radar data. High resolution hourly data is needed to catch quick events for urban modeling and to initiate forecasting models at a real-time update.

3. Method

The data and models are evaluated in a catchment area in the South of Sweden called Höje Å. Within this 316 km² catchment, the town of Lund is located as well as the discharge gauge Trolleberg situated just downstream of Lund. The gauge in Trolleberg is one of few gauges in Sweden situated close to an urban area. The impermeable surfaces of urban areas result in quicker and increased runoff which is what we want the model to catch and this is why this catchment is chosen as site for this study.

The precipitation data of HIPRAD is investigated by comparing with local precipitation gauges from the regional wastewater organization VA Syd at hourly resolution as well as a station from the national SMHI network at daily resolution. VA Syd has two gauges in Lund (referred to as VA Syd North and VA Syd South). These are compared to the corresponding grid cells from HIPRAD overlaying the same spot (referred to as HIPRAD North and HIPRAD South). The following comparisons are undertaken: standard deviation, annual precipitation, wet days, monthly variations, monthly mean and maximum values and correlation. The size of the VA Syd tipping-bucket rain gauges was upgraded in 2012, why the correlation after this year was also examined closer.

The runoff model HYPE at hourly resolution is calibrated with special emphasis on catching short intensive rainfall resulting in quick peaks. Initially the model is improved by increased spatial description of the area using the EEA Urban Atlas (European Environmental Agency, 2010). The calculated runoff from the HYPE model at 1-h resolution is compared with the outcome from the model at daily time-step.

Finally, the calibrated model is applied to re-forecast the discharge during a rainfall event in October 2016 by using the MEPS ensemble forecasts. The result from the model is compared with the observed runoff at the event.

4. Results

HIPRAD is compared to the local gauges from VA Syd and SMHI, and overall the agreement is good. Some of the results are presented here. The annual total precipitation in HIPRAD is on the same level as both VA Syd and the SMHI gauge (Figure 1). The correlation between the data is investigated for the summer months 2012-2014 (Figure 2 and Figure 3). The correlation is evaluated both by scatter plots comparing values from the same time-step (Figure 2) and by quantile-quantile plots comparing sorted data (Figure 3). Comparing the sorted data will show if the stations show the same statistical distribution.

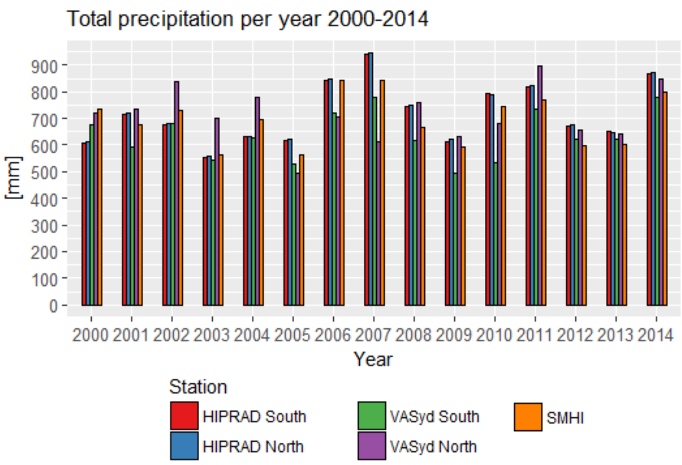
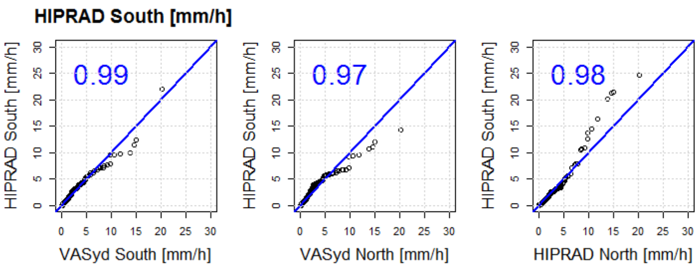


Figure 1. Annual precipitation. Comparison of precipitation data over Lund. HIPRAD grid cells (South and North) are compared to local gauges VA Syd South and North and SMHI



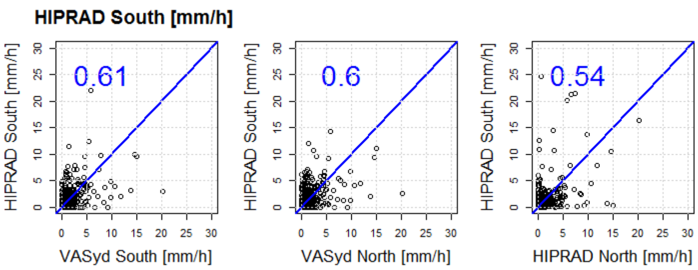


Figure 2. Correlation between the precipitation at HIPRAD South grid cell and the other stations at hourly time-step. In the upper plots data at the same time step are compared. The lower plots consists of sorted data and thus indicates if the statistical distributions are similar.

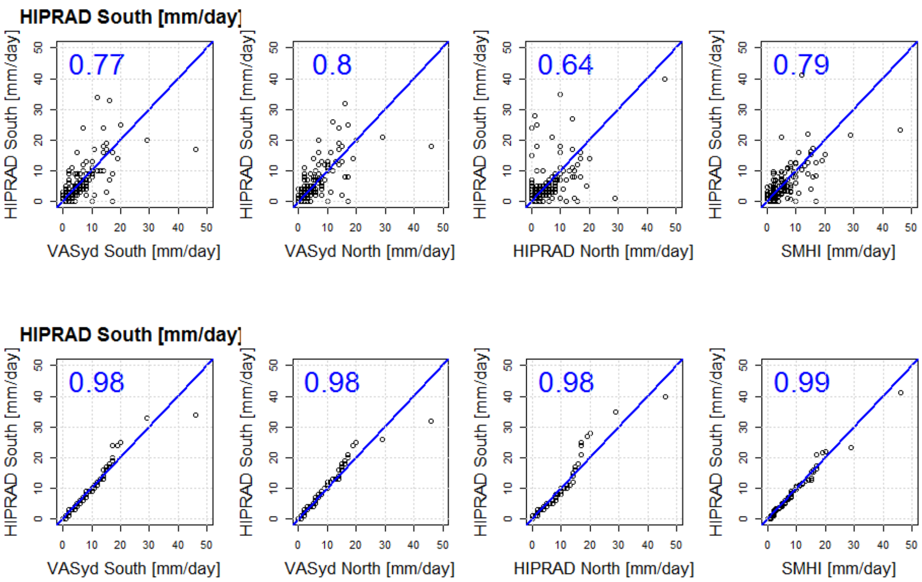


Figure 3. Correlation between the precipitation at HIPRAD South grid cell and the other stations at daily time-step. In the upper plots data at the same time step are compared. The lower plots consists of sorted data and thus indicates if the statistical distributions are similar.

Figure 4 show a comparison of HYPE simulations for two events modelled at hourly and daily resolution, respectively. The efficiency criteria of the models over the period 2006-2014 are compared (Table 1) with good result for both models. However, the model at daily time-step (1-day HYPE) is evaluated to runoff at a daily time-step. The Nash-Sutcliffe Efficiency (NSE) is a measurement of goodness of fit between calculated and observed runoff, developed especially for hydrological models. A NSE value of 1 corresponds to a perfect fit. The relative error (RE(%)), describes the volume error of the calculated runoff. Positive RE indicates that the model is systematically overestimating the water volumes. A negative value indicates the opposite - that the volumes are underestimated on average.

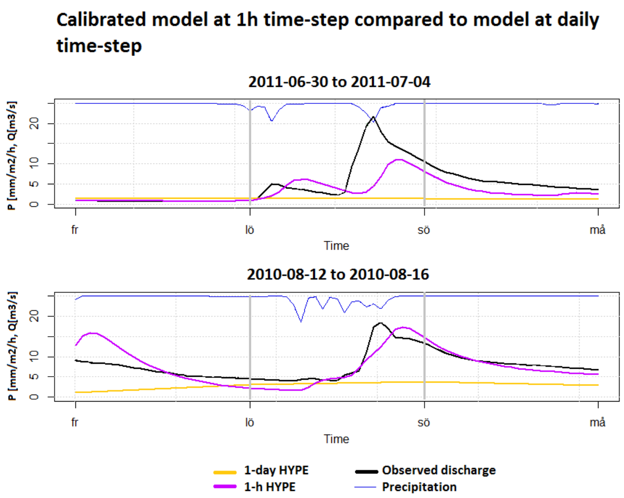


Figure 4. Two discharge peaks in Höje Å modeled at hourly and daily resolution. Black line represents the observed runoff. Purple line represents the calculated runoff from 1-h HYPE model and yellow line from 1-day HYPE. Blue line is mean precipitation over catchment upstream discharge gauge.

Table 1. Efficiency criteria for HYPE models in Figure 4, for period 2006-2014

HYPE model	NSE	RE(%)
1-h HYPE	0.83	-3.7
1-day HYPE	0.80*	-17.9*

*OBS these values are in compare to a daily runoff.

The calculated runoff from the forecasted event at 2016-11-04 is compared with observed runoff in Figure 5. One day prior the rain event all members show an increase in flow. However, 12 hours prior the event the members exhibit a larger spread, implying a higher uncertainty.

5. Discussion

The annual precipitation (Figure 1) from the different sources corresponds well. The result is improved after 2012 when the accuracy of the VA Syd gauges are improved. The correlation at daily timescale (Figure 3) is better than the correlation at hourly scale (Figure 2). This is expected as the exact time of ground rainfall is difficult to capture with radar, which HIPRAD is based on. This is also evident from the difference between correlations using same time step and sorted data, respectively. Comparing the correlation of the sorted data, HIPRAD shows variance similar distribution as the local gauges from VA Syd and SMHI. This is an encouraging result. It should be remarked that data from the SMHI gauge (daily values) are used in the production of the PTHBV-grid that HIPRAD is correlated to, but the VA Syd gauges are completely independent from HIPRAD. The sorted data also show how HIPRAD has a tendency to underestimate the highest intensities compared to VA Syd, which is expected in light of the spatial averaging in the HIPRAD data.

Comparing the HYPE simulations at 1-h and daily resolution, the advantages of using a 1-h time-step is evident (Figure 4). Sub-daily discharge peaks may be entirely missed with a daily time step.

The dynamics of the forecasted event in 2016-11-04 correlate well in comparison with observed runoff (Figure 5). The initial levels of the forecast are overestimated which is due to errors in the HIPRAD data used to initiate the model. The current version of HIPRAD is valid until end of 2014. The equation of adjustment to the gridded gauge data does not fit at the present time, probably due to updates in measuring equipment. The forecasts exhibit overall good dynamics considering the short-duration nature of the event, indicating that a 1-h national HYPE model coupled with high-resolution meteorological ensemble forecasts could be a valuable tool.

6. Conclusions

The main results from this study are the following.

- HIPRAD showed generally good agreement for long accumulations and statistical distributions. For short time step (1 hour) there were however temporal deviations. The correlation to point-scale data is affected by HIPRAD being gridded and therefore has a tendency to underestimate the highest intensities.
- HYPE at 1-h temporal resolution could be overall well fitted to the 1-hour observation in terms of efficiency criteria with a NSE above 0.8. The advantages of using an hourly time step when modeling sub-daily events were evident.
- The result from the forecasting was promising and the dynamics of the observed runoff was captured reasonably well in the forecast. A relatively early signal of rapid flow increase was obtained.

We conclude that the evaluated components performed overall well, which supports their applicability for high-resolution flood forecasting. This study is a part of the development of an hourly national flood forecasting system at SMHI, aiming at an improved support for pluvial flooding and other events producing rapid flow changes on sub-daily time scales. Within the study the data that enables such increase in time resolution is evaluated, the model is upgraded spatially and a test-forecast is produced with promising result. The goal of having a national early warning system for pluvial floods does not seem too far away.

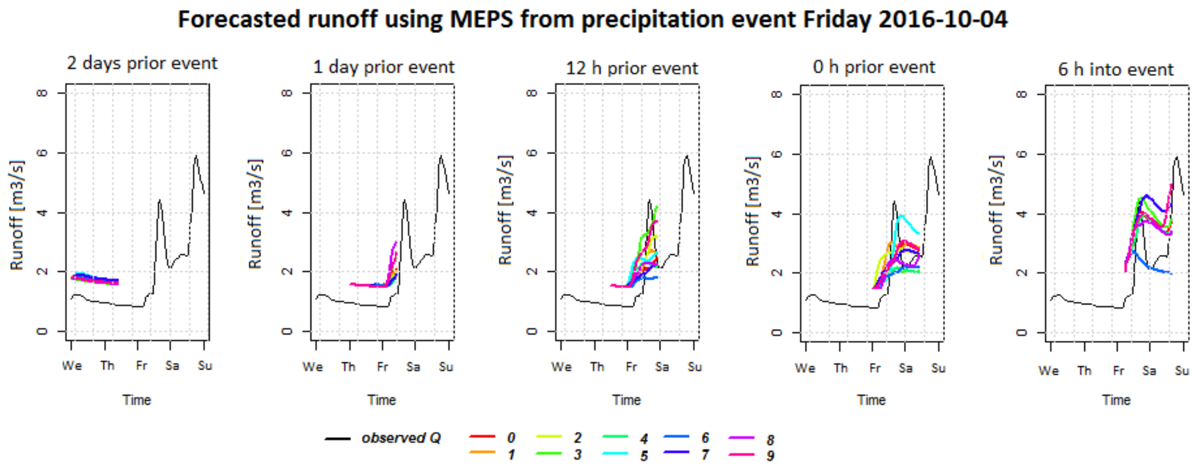


Figure 5. Forecasted event on Friday the 4th of November 2016. The precipitation event continued from 00:00 to 18:00.

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