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High resolution ensemble flood forecasting

Development and demonstration of a system for Höje å

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Division of Water Resources Engineering
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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.

Terminology

Convective precipitation	Intensive short precipitation events. Formed when a small area of the earth is heated leading to quick up-rise in air.
Ensemble forecast	A number of equally probable projections based on small differences in initial conditions.
Field capacity	The amount of water that the soil can hold - what is retained in the soil after the excess water has left.
Fluvial flooding	Flooding in a water course caused by rainfall or snow melt that infiltrates over a long period of time.
Hydrograph	A graph of the discharge as a function of time at a specific point in a river.
Member	Term used within ensemble forecasting. A set of forecasts are produce and each forecast is referred to as a member of the set.
Pluvial flooding	Local flood created by a rainfall intensity which exceeds the ability of the ground to infiltrate / discharge.
Saturation	When all the pores in the soil that can be filled with water are filled.
Stratified precipitation	Large scale frontal precipitation.
Wilting point	The amount of water not accessible for the plants retained in the soil when the plants wilt.

	HYPE:
Forcing data	Input data to the model. In HYPE: precipitation and temperature.
SLC (class)	The areal soil and land use are combined into Soil and Land use Classes. The classes are given as a percentage of each compartment/sub catchment.
Static data	Data that are specific for the area the model represents and adapted during calibration of model. In HYPE: Land cover, soil type, lakes and reservoirs, (crop dynamics and point sources)

	Abbreviations:
EC	Efficiency Criteria, quantitative estimation of the performance of the model
EEA	The European Environmental Agency
EPS	Ensemble Prediction Systems
EU	The European Union

EWS	Early Warning Systems
HIPRAD	**HI**gh-resolution **P**recipitation from gauge-adjusted weather **RAD**ar (precipitation data base by SMHI)
HYPE	**HY**drological **P**redictions for the **E**nvironment (hydrological model by SMHI)
KGE	Kling-Gupta Efficiency (efficiency criteria)
MetCoOp	Cooperation between Sweden, Finland and Norway around NWP
MSB	The Swedish Civil Contingencies Agency (Myndigheten för samhällsskydd och beredskap)
NSE	Nash and Sutcliffe Efficiency (efficiency criteria)
NWP	Numerical Weather Prediction
SMHI	The Swedish Meteorological and Hydrological Institute

Contents

1 Introduction

Floods in urban areas forms a threat to our societies. They 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 occurs from short intense rainfalls. The impact and quantity of this type of flooding is likely to increase. (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(Qin et al., 2013) which is anticipated to cause more intensified precipitation (European Environmental Agency, 2012).

In order to limit the devastation from pluvial flooding models can be used to forecast the event. For the last 50 years a variety of hydrological models have been constructed for this purpose. Since the intense rainfalls which cause pluvial floods usually are 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.

1.1 Background

HYPE is a hydrological model developed to simulate how water and nutrients move within the environment, specialized in large scale prediction in un-gauged basins. It has been in development since the beginning of the 21-century, when the European Union's water framework directive (WFD) urged improved monitoring of the Swedish water bodies. The original model uses daily time steps. This is enough to model large scale changes but is highly limiting in areas with limited infiltration, where also shorter weather events can have large impact on the runoff. SMHI have for the last few years been working for an upgrade of the original HYPE model to a model with higher resolution in time and a more detailed description of area fractions.

The HYPE model is upgraded as follows:

Temporally: Increase the resolution of the time step from 1-day to 1-hour. The forcing data will change from being only weather station based to also being based on radar data from a model called HIPRAD.

Spatially: A more detailed source for soil-and land use categorization is used for a more precise description in urban areas.

Weather-forecasting models have a long tradition of being used as forcing data for rainfall-runoff models. The models are now of high enough resolution in time and space to also catch short local rainfalls. Following this progress, operational national 1 hour time-step forecasting prognoses are under development at SMHI.

1.2 Aim and objectives

The project aim is to develop and evaluate the current state of a high resolution HYPE-model and its potential to produce flood forecasts.

1. HIPRAD precipitation data is evaluated:
   HIPRAD (radar based precipitation data at 15 min resolution and 2x2 km^2 grid) forcing data is compared to local weather stations from VA Syd. How well does the data correspond?

2. The impact of using 1h forcing data is evaluated:
   The HYPE model is updated in soil and land use categorization using a more detailed source for spatial description and the model is calibrated using the HIPRAD data. How much is the model improved in compare to using daily time step?

3. The possibilities to produce real time update forecast will be evaluated:
   How well does the calculated runoff from a forecast using HYPE at 1h time-step with high resolution ensemble forecasts match the observed runoff?

1.3 Limitations

HYPE can be viewed as an extension of the original model set up for all of Sweden (S-HYPE). These two models will work intervened and S-HYPE is to represent rural areas surrounding the urban areas. Consequently the set up for S-HYPE forms the foundation of the model and changes in the high resolution model must be able to operate within S-HYPE as well.

Lack of data. The high resolution meteorological forecasts have been saved for October 2016 which limits the evaluation of the forecasting to events occurring during this month.

1.4 Method

The precipitation forcing data is investigated by comparing with additional precipitation gauges from VA Syd as well as SMHI. Furthermore HYPE is calibrated to fit the observed data as good as possible with special emphasis on catching short intensive rainfall resulting in quick peaks. The model is improved by adjustment of the model parameters and by increased spatial description of the area. Finally, the model is run using precipitation data based on a high resolution ensemble forecast for the most sever event in October 2016. The result from the model is compared with the observed runoff at the event.

The procedure of this project can be summarized like this:

1. Evaluation of HIPRAD data for Höje å catchment.

2. Evaluation of the catchment where typical *pluvial events* are located. These are of interest when calibrating the model since this is what we want the model to catch.

3. Calibrate the existing model for Höje å catchment.
4. Force the model with new high-resolution meteorological ensemble forecasts and analyse the results.

2 Theory

2.1 Pluvial floods and flash floods

Pluvial floods are surface water flooding originating from direct extreme rainfalls. As opposed to fluvial floods - which is flooding caused by water infiltrated over a long time period eventually causing the water level in rivers to rise and over-topping the banks - pluvial floods appears when the rainfall intensity exceeds the ability of the ground to infiltrate. This typically occurs when a convective rainfall fall over an area with limited infiltration.

Convective rainfalls appears when a surface of the Earth is heated more than its surrounding, causing a significant increase of evaporation in this area, and an upward directed air movement at a high speed. When the air has reached high enough in the atmosphere it will cool dopwn and the vapor will fall down, usually in the form of short and intense precipitation over a small area. Examples of areas with limited infiltration are urban areas, small steep areas or areas with a thin layer of soil (SMHI, 2011). An increased number of surfaces with limited infiltration will impact the runoff in the following way:

Faster runoff: Limited infiltration make the surfaces fast-tracks for the water to runoff. In urban areas the runoff is accelerated by a pipe-network. Drainage inlets are placed at low points to avoid flooding and the water is then led off to either a combined or a separate sewage system.

Increased runoff volumes: Rapid runoff limits the retention time. This decreases the evaporation and hence also increases the volumes of the runoff downstream.

Increased peak of runoff: The combination of rapid runoff and limited retention time makes the hydrograph from urban areas higher and steeper than from a rural area, which result in a concentration of water masses. (Figure 7.2.1)

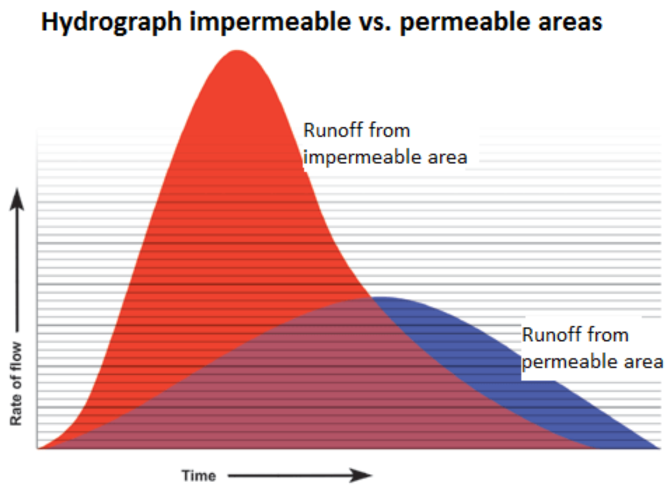

Figure 2.1: The difference in volume (area below the curves) and rate of flow between impermeable (surfaces of no/limited infiltration) and permeable areas

The intensity of extreme rainfalls are anticipated to increase with the expected temperature rise caused by global warming (Qin et al., 2013) (European Environmental

Agency, 2012) making pluvial floods the flood type most likely to increase in severity in a future climate (Houston et al., 2011). This is mainly due to the increase in atmospheric temperature which will increase the water-holding capacity of the air according to the Clausius-Clapeyron rate; approximately 7% per degree Celsius, but the increase in intensity of extreme rainfalls might even exceed the Clausius Clapeyron rate (Berg et al., 2013). There are also consequences originating from the ongoing urbanization. The greater extent of impermeable surfaces in urban areas increases the risk of pluvial flooding while the increased density of people and buildings also increase the vulnerability of the same areas by exposing more people for the flooding hazard (Houston et al., 2011). The amount and intensity of rainfall in Sweden is expected to rise. A 10-year rainfall today is expected to appear twice as often in the future (SMHI, 2011). In Skåne, where the catchment area of this study is located, the maximal intensity could increase with up to 20% by the end of this century (Ohlsson et al., 2015).

After several major floods occurred in Europe in 2007, the European Union (EU) adopted a directive on flood risk which regulates the handling of the floods, called the EU Floods Directive. The intention is that member countries should work to reduce the negative impacts of floods and thus protect human health, the environment, cultural heritage and economic activity (EU, 2007). The EU Floods Directive is to be implemented in cycles of 6 years. The first cycle was based on existing and historical data which in Sweden only included floods from lakes and rivers, since there has not until now existed any national systematical structure to record flooding from intense rainfall. However, in the next cycle (starting in 2016) all possible floods relevant for Sweden are to be included.(MSB, 2014) The Swedish Civil Contingencies Agency (MSB) are responsible of assembling information to facilitate implementation of the EU Floods Directive in the Swedish County Board and the Swedish municipalities.

2.2 Rainfall-runoff modelling

Rainfall-runoff modelling is the art of modelling the runoff and stream flow routing from rainfalls. By extrapolation from existing measurements, a rainfall-runoff model can fill the gap between undense measurements in time and space. This is especially useful in ungauged catchments (Beven, 2012). However, the environment is complex, and thereby difficult to describe in mathematical terms. Hence, every model will include simplifications. Which simplifications that best describes the reality is discussable and this opens up for numerous different models. Using a model of a higher resolution than that of the input data and the required estimations is pointless, hence the quality of the model is heavily dependent on the data available.

Design models are used for example in flood mapping within city planning, where a design rain in the form of a 100- or 200-year rain is entered in the model to evaluate the worst possible outcome that is needed to be accounted for. These kinds of models are used to implement the EU Flood Directives as were described in section 2.1. The other type of model are the *Operational models* which are used in Early Warning Systems (EWS) and facilitates decision making. Within this study we will evaluate the use of Urban HYPE model as an operational model.

Within this study, runoff modeling in partially urbanized areas will be evaluated. The difference between urban and rural runoff is foremost the absence of impermeable surfaces in the latter. This will affect the runoff in such a way that even an spatially small rainfall can cause flooding, why higher spatial and temporal resolution is needed in the input data as well as within the model. If the model is too coarse, for example if it is using daily time step, these intensive short rainfalls are smeared out over the day and the model will hence produce an equally smeared discharge curve.

2.3 Measuring rainfall

Precipitation is most commonly rainfall but also includes snow, hail, sleet, and other forms of liquid and frozen water falling to the ground. It can be measured by a weather station, a so called *rain gauge*, or by using radar.

A rain gauge is a small cylinder open at one end. The rain is funneled into a narrow tube. Using a tipping-bucket, the time period of the rainfall can be measured accurately. In this case the rain travels down the funnel and drips into one of two very carefully calibrated 'buckets' balanced on a pivot. The top bucket is held in place by a magnet, and when the bucket has been filled to the calibrated line, the magnet will release its hold, causing the bucket to tip. The water then empties down a drainage hole and raises the other bucket to sit underneath the funnel. When the bucket tips, it triggers a sensor sending a message to the display or weather station. In this way, the intensity of the rainfall is can be measured (ThoughtCo.).

The data from a tipping-bucket rain gauge contains the time notation for each time the buckets has filled to the calibrated amount. This data can be assimilated to any time-step needed, for example hourly by adding all ticks within an hour and multiplying by the calibrated amount of the bucket. The resolution of the data hence depends on the size of the tipping-bucket.

Radar-derived precipitation data is also available. The data is based on disturbance in radar signals which is converted to rain intensity. Depending on the type of rainfall the signals of the event can differ, hence the conversion from radar signals to rainfall intensity is sometimes wrong. By adjusting the data to local gauge measurements within the catchment of the radar, the intensity of the rainfall will match better with the reality. This will also provide a more complete image of the rainfall as it combines the full areal coverage that the radar provides with the point source real measurements of the gauges.

Measuring precipitating using both a tipping-bucket rain gauge and radar images are prone to several errors. A tipping bucket is typically sensitive to wind as it affects the catch (Beven, 2012). The placement in relation to wind conditions at the site, as well and design of the gauge can help limit this influence. Snow is neither measured well with a tipping bucket nor with radar. Other common error sources in precipitation estimation by weather radar are presented in Figure 2.2.

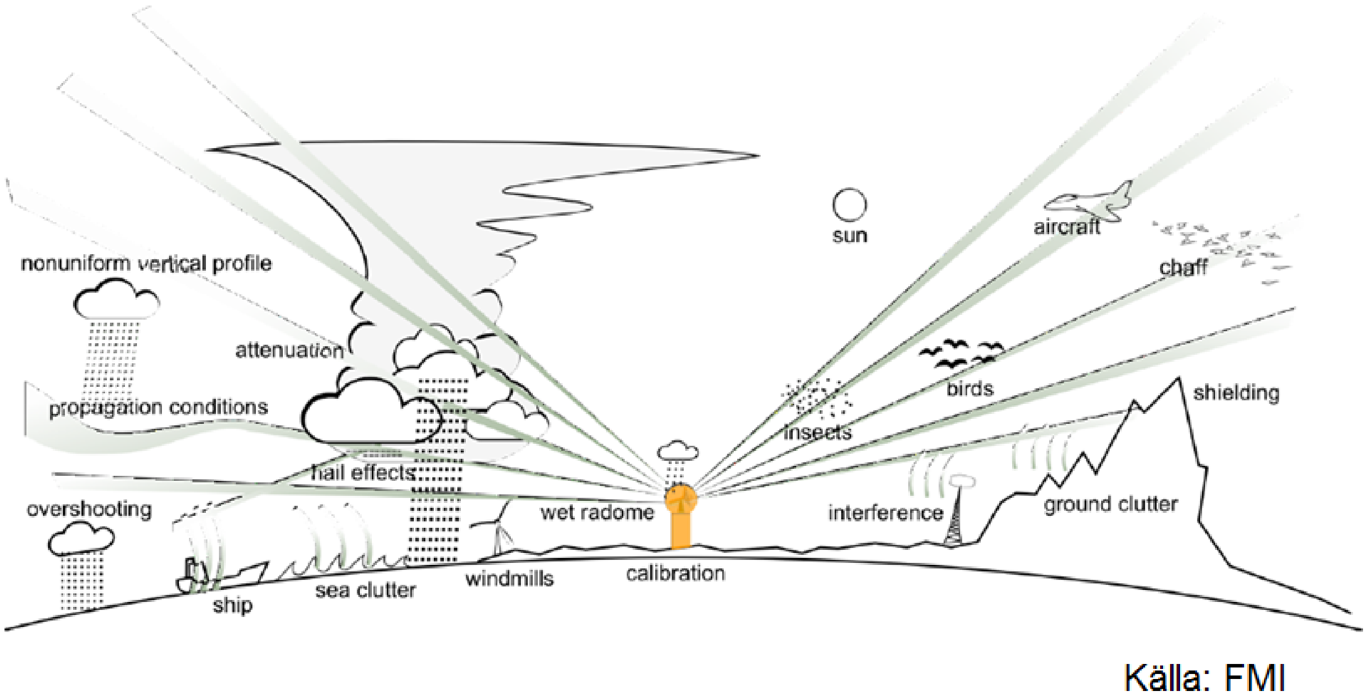

Figure 2.2: Example of what can disturb the radar image. Source: Finnish Meteorological Institute

3 The models and data

This thesis is based on the latest development of two models from SMHI; HYPE at 1h resolution, and MEPS. It is also based on a newly obtained data set of high resolution precipitation data (HIPRAD) and areal data for urban areas (EEA Urban Atlas). These components are further described and summarized below:

Models

HYPE: The core model of this study is HYPE, a hydrological model used to calculate rainfall-runoff.

MEPS: Recent development of high resolution meteorological ensemble forecasting model called MEPS has opened up for the possibility to use HYPE in ensemble forecasting of rainfall-runoff at a hourly resolution.

Data

HIPRAD: Radar based precipitation data integrated to gridded gauge data.

EEA Urban Atlas: High resolution land use data for urban areas.

Table 3.1: Summary of the models and data used within this project.

Product	**Description**	**Time step**	**Spatial resolution**	**Available time period**
HYPE	Rainfall-runoff model	1h, 1d etc	size of subcatchments	-
MEPS	Precipitation forecasting model	1 h	2.5x2.5 km^2	-
HIPRAD1	Precipitation data	15 min	2x2 km^2	2009-2014
HIPRAD2	Precipitation data	15 min	2x2 km^2	2005-2014
Urban Atlas	Land use data			

3.1 HYPE

HYPE is developed by the hydrological research team of SMHI in Norrköping Sweden (Lindström et al., 2010). HYPE stands for **Hy**drological **P**redictions for the **E**nvironment and is a hydrological model for integrated simulation of flow and circulation of water and nutrients. It provides the ability to forecast matters related to water resources and water with high spatial detail, even for catchments with few gauges. The first model, called S-HYPE 1.0, was developed in 2009 to cover Sweden. In 2011 SMHI took the initiative for a HYPE Open Source Community to strengthen international collaboration in hydrological modelling. Today there is a model set up for Sweden, the Baltic Sea basin, the Arctic, Europe, Niger river, India and La Plata in South America with more to come. The various uses are for example EWS, research, public awareness, retention calculations, climate change impact studies, input to hydraulic models etc.

In the beginning of 2011 SMHI investigated the possibility to increase the resolution of the HYPE-model, with an aim to preform equally well in urban areas as in rural areas (MSB article). An increase in temporal resolution would allow catching also the short intensive rainfall causing pluvial flooding. These rapid events are lost when accumulated to 1 day-data. For rural areas this is an acceptable simplification since the water will be sustained at different areas, but in urban areas, with limited infiltration, the impermeable areas will cause a quick runoff which is what we want the model to catch. This high resolution HYPE-model is evaluated within this thesis.

Sewer network is not included in the HYPE-model. This introduces the risk of overestimating flood risks, since some will be retained in the sewage system. Advantages with not including the pipe network is that it will speed up the calculations and need less data, which makes it cheaper and easy to handle. It has been shown that during these extreme rain events the management system capacity is limited in relation to rainfall volume and intensity and hence could be excluded. It is recommended, however, to take account of storm water system to assess capacity and soil infiltration capacity, eg. by flat-rate deduction from the rainfall volume(MSB, 2014).

3.1.1 Technical description

The set-up of the model and catchment area are stored in several text files. HYPE simulates both water flow and substances, and depending on the usage of the model different information needs to be provided. The core files of the set-up are presented in table 3.2.
Precipitation- (Pobs.txt) and temperature observations (Tobs.txt) are needed as *forcing data*. The catchment is divided into subcatchments (SUBIDs), and categorized on the terms of land use, soil type *static data*). These are later combined into Soil and Land Use Classes (SLC classes)(GeoClass.txt). Typical land uses can be forest, lake, open land and different crops.

During the calibration of the HYPE model, the characteristics of the SLC classes are adapted to values that provide the best result (par.txt). The classes are not linked to a geographical location within the subcatchments but are given as an areal percentage of the subcatchments (GeoData.txt). The classes can also differ vertically with three depths. The performance of the model can be determined at execution by providing observed discharge values (Qobs.txt).

Table 3.2: Description of the files needed to run the HYPE model

TEXTFILE	DESCRIPTION
Pobs.txt	Precipitation over each SUBID [mm/time step]
Tobs.txt	Mean temp. at each SUBID [Celcius/time step]
Qobs.txt	Observed runoff at SUBID [m3/time step]
par.txt	Characteristics of the land and soil use and general parameters used in the modeling. Altered during the calibration.
GeoClass.txt	Classification of SLC-classes
GeoData.txt	Percentage of SLC-classes per SUBID
info.txt	The specifications of the run of the model are set. The time step used within the model as well as *warmup period* and *modeling period* is defined here.
Warmup period	Period to set model at initial stage (1 year is recommended for hydrological models)
Modeling period	During this period the outcome is registered

S-HYPE is the HYPE model set up that is calibrated to fit Sweden. It contains 13 land use-, 9 soil- and 65 SLC classes. The land use and soil types that are used in S-HYPE are listed below:

Land uses: 1=Lake, 2=Bog, 3=Fen, 4=Glacier, 5=Thin Soil, 6=Urban, 7=Coniferous forest, 8=Deciduous forest, 9=Grassland, 10=Other, 11=Agricultural land, 12= Clear cut, 13=Semi-urban

Soil types: 1=Peat, 2=Fine/Clay, 3=Course, 4=Till, 5=Thin soils or no soil, 6=Water, 7=Silt, 8=Urban, 9=Glacial sediment

Each catchment area in Sweden is divided into subcatchments (called SUBIDs within HYPE) according to the hydrological topography of that area (i.e. which courses excess water will take). For every subcatchment the areal percentage of each SLC-class is specified, as well as downstream subcatchment. The basic scheme of the model set up is illustrated in fig 3.1.

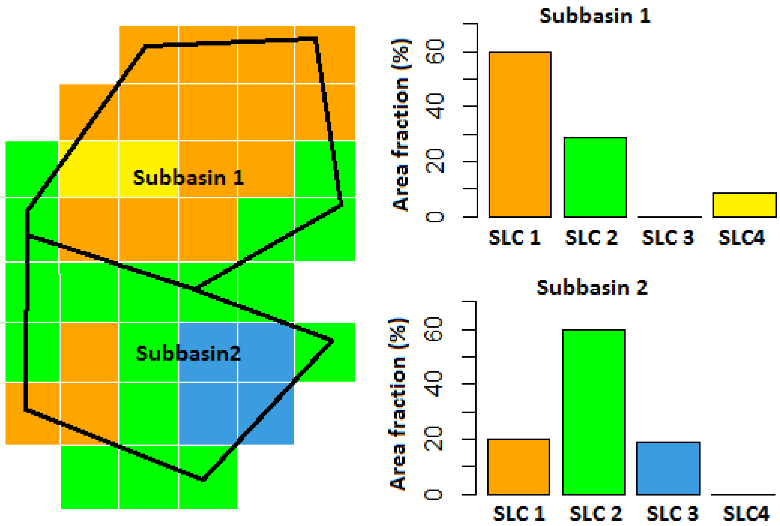

Figure 3.1: The subcatchmnets are divided into area fractions

3.2 EEA Urban Atlas

The spatial resolution needs to be upgraded in HYPE in order to catch the percentage of impermeable surfaces more precise. This is done within this thesis by using a more detailed source for classification of the soil- and land use of the catchment area, called EEA Urban Atlas (Urban Atlas). This is used in lieu of the Corine data base which is used originally.

EEA Corine (Corine) land cover data base was a prototype project initiated within the EU in 1985 to provide decision makers with access to clear and updated geographical data about the current state of the environment, consistent between the membership countries, in order to manage our environmental and natural heritage. The name stands for '**Coor**dination of **i**nformation on the **e**nvironment' and the database contains land cover information such as geographical distribution and state of natural areas, quality and abundance of water resources, land cover structure and state of the soil, the quantities of toxic substances discharged into environments and lists of natural hazards, etc. It is mainly based on satellite data using the satellites Landsat and SPOT as sources, which has provided a possibility to also cover vast areas and update the information frequently. Today the project is governed by EEA.(European Environmental Agency, 1994)

EEA is also a supporter of Urban Atlas, which provides a high resolution GIS map for each European town with more than 100 000 inhabitants. The resolution of Urban Atlas is 100 times higher than of Corine land cover. Just as Corine, Urban Atlas too was initiated to produce an inter-comparable land use data, but this time representing the European cities. Both are based on satellite data.(European Environmental Agency, 2010)

3.3 MEPS

MEPS stands for MetCoOp EPS, where *MetCoOp* is a cooperation between Sweden, Finland and Norway around numerical weather prediction (NWP) and *EPS* represent ensemble prediction systems. NWP uses mathematical models of the atmosphere and oceans to predict the weather, based on current weather conditions. It has a grid-size of 2.5 km in the horizontal and covers 65 point in the vertical.

Ensemble forecasting means that instead of making a single forecast of the most likely weather, a set (or ensemble) of forecasts are produced. These are called *members*. The amount of spread between the should be related to the uncertainty (error) of the forecast. Figure 3.2 shows an example. Ensemble forecast A has a small spread between the members in compare to ensemble forecast B. Hence, the ensemble forecast B is more uncertain.

The ensemble system of MEPS consist of 10 members all run on different surface assimilation's and forecasting 36 hours ahead (Andrae, 2017).

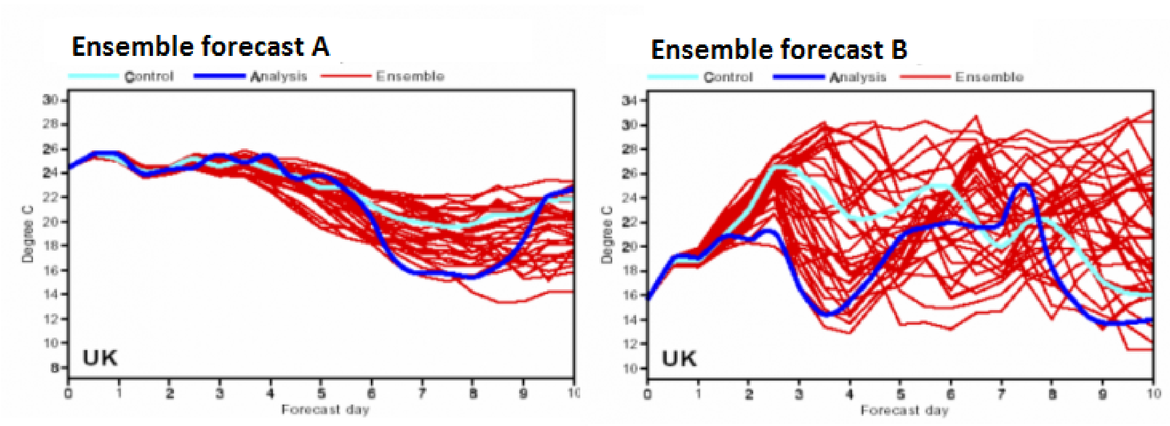

Figure 3.2: Example of ensemble forecasts of air temperature in United Kingdom, Source:Meteoblue. Ensemble forecast A has a small spread between the members in compare to ensemble forecast B. Hence, the ensemble forecast B is more uncertain.

3.4 HIPRAD

High resolution hourly data is needed to catch quick events for urban modeling and to initiate forecasting models at a real-time update (Berg et al., 2015). In recent years meteorological forecasting models have improved and can now deliver precipitation forecasts at a high resolution in time and space. This development enables usage within EWS to forecast runoff, however in order to run these predictions in a model the initial state of the model is required to be up-to-date.

At SMHI, a new data set called HIPRAD is under development in order to receive such hourly data at near real-time update. HIPRAD (**HI**gh-resolution **P**recipitation from gauge-adjusted weather **RAD**ar) is based on radar-observed precipitation merged with gridded gauge data. Since HIPRAD is based on radar data, which is delivered at only few minutes delay, the plan is that HIPRAD is going to be produced at real-time as well.

3.4.1 Gridded gauge data

The radar-observed precipitation data is delivered in a 2x2km^2 grid and it is interpolated to a 4x4km^2 gridded gauge data. The gridded gague data used for the interpolation is called PTHBV. PTHBV was introduced in 2003 to provide the SMHI-HBV model with precipitation (P)- and temperature (T) data. PTHBV-data is today also used to drive the S-HYPE model. It is produced by so called optimal interpolation from weather stations to a 4x4 grid. Information about altitude and wind speed- and direction are also utilized in the interpolation. (Olsson et al., 2013)

3.4.2 From radar signals to precipitation data

How the radar signals are filtered and converted to precipitation data is presented below (Berg et al., 2015):

1. At a regular time-step, e.g. every 15 minutes, the radar scans the sky at different tilt angles and measures the echoes of what is assumed to be droplets with a particular droplet size distribution (density). Depending on the precipitation type, this assumption may be more or less correct. Echoes with radial velocities less than 1 m/s are suppressed.

2. All radar signals that only appear at a single 15 minute data are removed since these are considered as spurious signals. The radar signals are then converted to precipitation intensity depending on the reflectivity. Any missing time periods are filled by interpolation and the 15 minute radar data is aggregated to hourly data, which is the time step of PTHBV.

3. The radar data is bi-linearly interpolated to the 4x4km^2 PTHBV-grid. The projection of the PTHBV-grid is slightly different which acts as a filter. Bilinear interpolation is used when interpolation in 2D (as a grid) and means that the interpolation is made in one direction first followed by an interpolation in the other direction.

4. Radar and PTHBV data are accumulated over a 30-day period and the ratio of monthly mean PTHBV and radar is calculated. This factor is used to scale all the radar data at every time step. This adjusts the mean value of the radar data to be identical to that of PTHBV, and by applying this for each grid point also spatial inhomogeneities are removed from the radar data.

5. The radar composite potentially has a bias in the precipitation intensity probability distribution function (PDF), due to errors in measurements and also due to the simplified conversion of echoes to intensities (step 1). Also if the factor calculated in the last step is a lot larger than one it will affect the higher intensities more. A bias-correction method called Quantile Mapping (QM) is applied to ensure bias-free long-term accumulations. This method is dependent on a calibration period of at least a couple of years, and is sensitive to changes in e.g. measuring equipment that appears after the calibration period.

6. The data is disaggregated back to hourly data by scaling.

The correction of the radar signals (described above) is adjusted to the current condition why an update in either software or hardware could have a negative effect on the result.

3.4.3 HIPRAD1 vs. HIPRAD2

HIPRAD2 is the latest version of HIPRAD (HIPRAD3 is under development). HIPRAD1 and HIPRAD2 are evaluated in this study. A few of the differences between them are:

- HIPRAD1 is implemented 2009-2014 while HIPRAD2 stretches over 2005-2014.
- HIPRAD1 is based on radar NORDRAD, which is the a cooperation between Sweden, Norway, Finland, Estonia, Latvia, and Denmark existing of 35 operational weather radars in total. HIPRAD2 on Baltrad network (http://se.baltrad.eu/)
- HIPRAD1 uses operational PTHBV-data while HIPRAD2 uses climatological PTHBV-data.
- HIPRAD1 uses a trailing monthly average for the scales, compared to the calendar month which are used in HIPRAD2

4 The catchment area

This chapter describes the catchment area used to evaluate the models, as well as the precipitation data available for the catchment.

4.1 The catchment area, Höje å

The models will be evaluated at Höje å catchment area which is situated in the South-West of Sweden in a region called Skåne. Within this catchment is the town of Lund located. Lund will represent an urban area and one runoff gauge called Trolleberg is situated just downstream of Lund. Trolleberg is one of few discharge gauges in Sweden that has a notable contribution from urban runoff which makes this area highly suitable for this study.

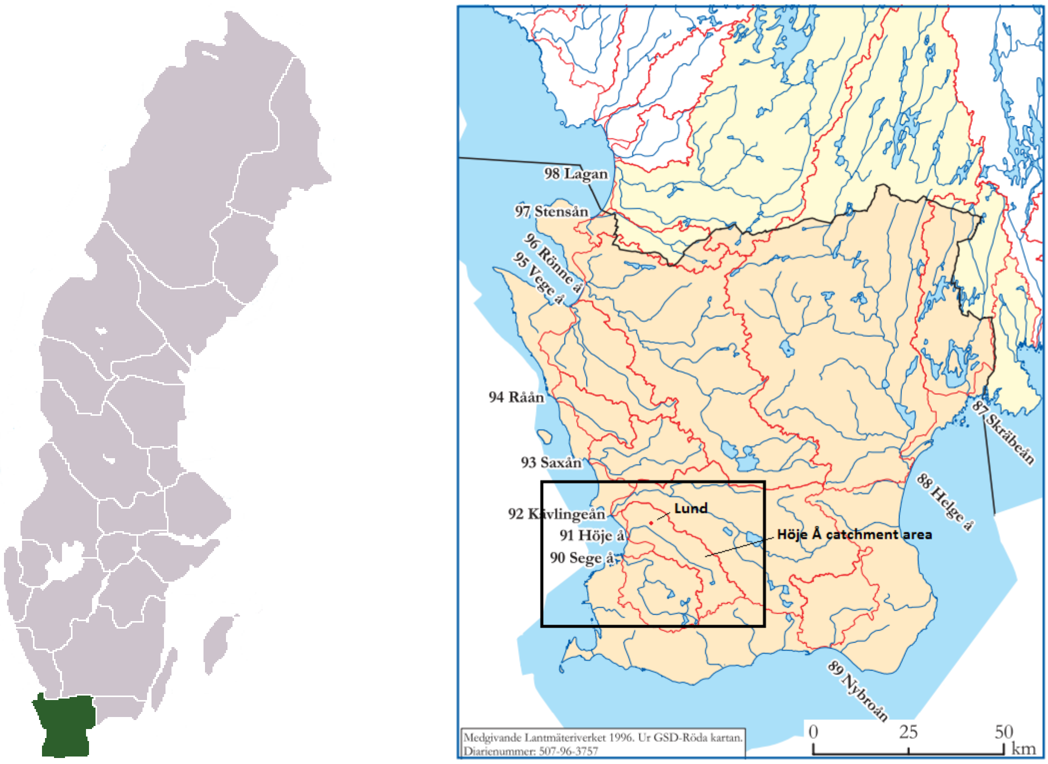

Figure 4.1: Höje å catchment is situated in the south of Sweden

The size of the area upstream the gauge is of main interest, since changes in the model downstream the gauge can not be evaluated. The area upstream the gauge covers an area of 273 km^2. Aforementioned Corine land use data base is used to categorize the land use and soil types within the area. This is needed for the HYPE model set-up, as different land and soil types will affect the runoff in different ways. The dominating land use class within the area is agricultural land, and the dominating soil types are till and fine materials (Figure 4.2 and 7.2.1).

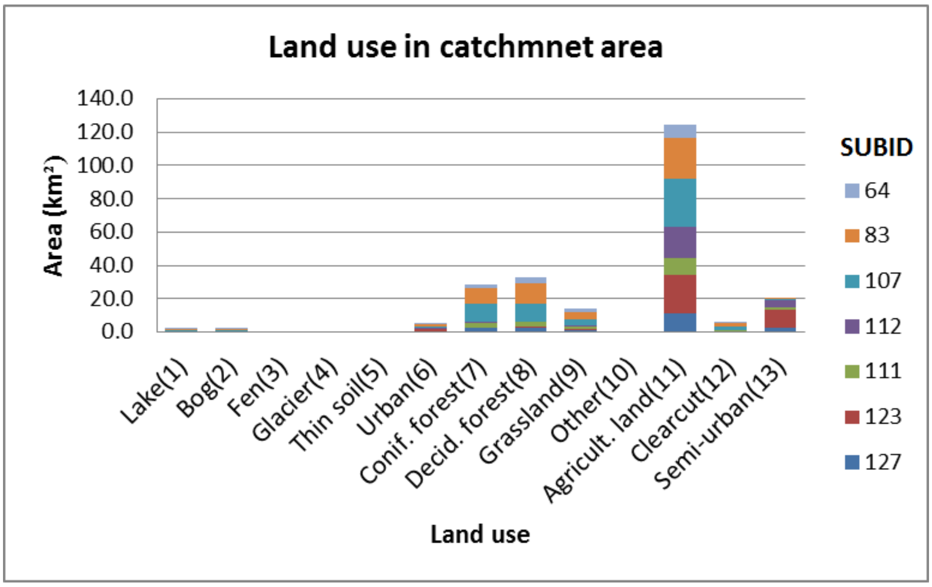

Figure 4.2: Land uses within Höje å catchment upstream Trolleberg gauge categorized with Corine. Agricultural land is the largest land use covering more than 2/5th of the area. The number behind the land uses are the number they are assigned in S-HYPE and the SUBIDs are the subcatchments of the area.

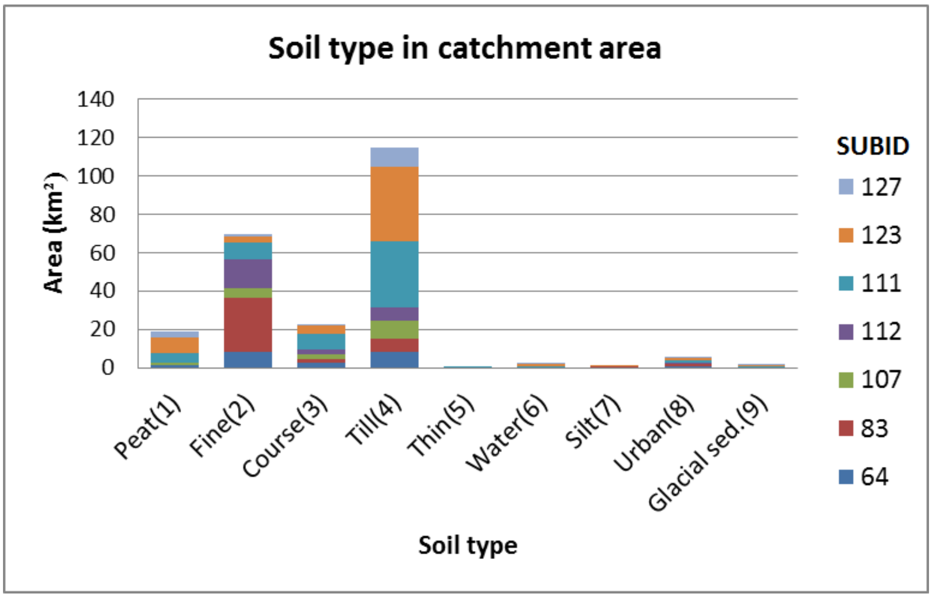

Figure 4.3: Soil types within Höje å catchment upstream Trolleberg gauge. Till is the largest soil type covering around 2/5th of the area. Fine is the second most dominating. The number behind the land uses are the number they are assigned in S-HYPE and the SUBIDs are the subcatchments of the area.

Within the HYPE model Höje å catchment is divided into 13 subareas (**64, 83, 107, 112, 111,** 118, 121, **123, 127,** 134,136,137,141 and 142), Figure 4.4. The seven catchments marked in bold are situated upstream of the gauge at Trolleberg. Subarea 127 has its outlet in Trolleberg. The main characteristics of the subcatchments upstream Trolleberg are presented Figure 4.5 and 4.6, and the size of the areas as well as urban fractions can be seen in in Table 4.1. The largest subcatchments are subcatchment 83 and 107. Subcatchment 123 and 127 covers the town of Lund.

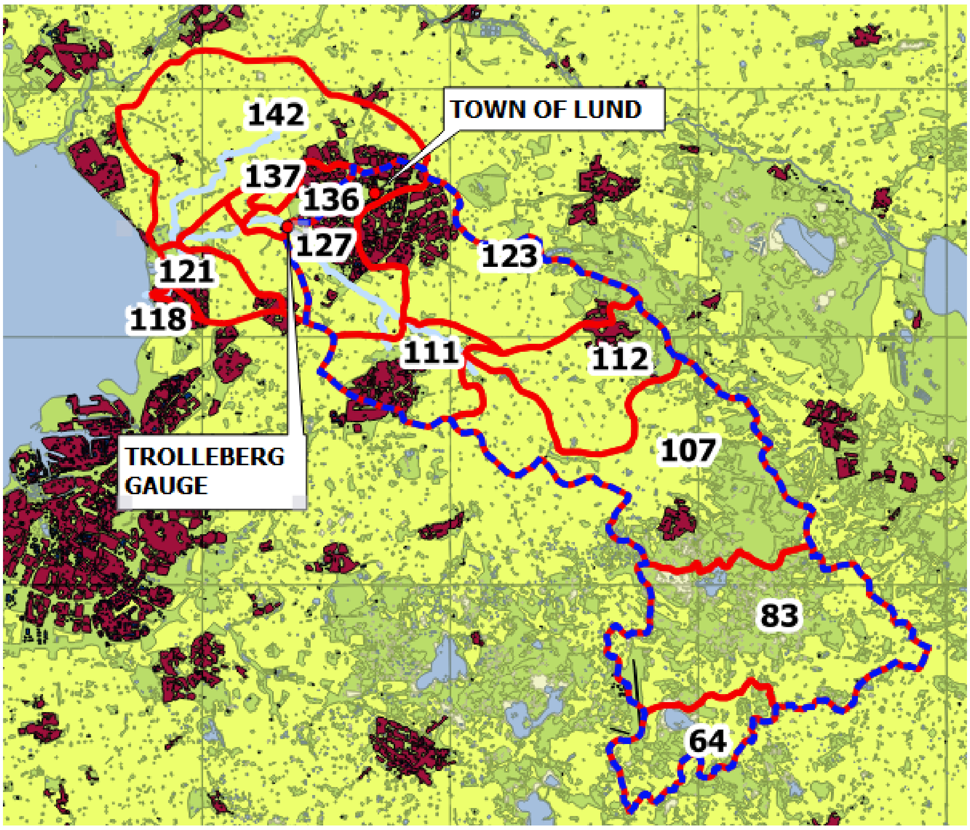

Figure 4.4: The catchment contains 13 subcatchment in total. There is one gauge situated in Trolleberg at the outlet of subcatchment 127. Red areas represent buildings e.g. the town of Lund.

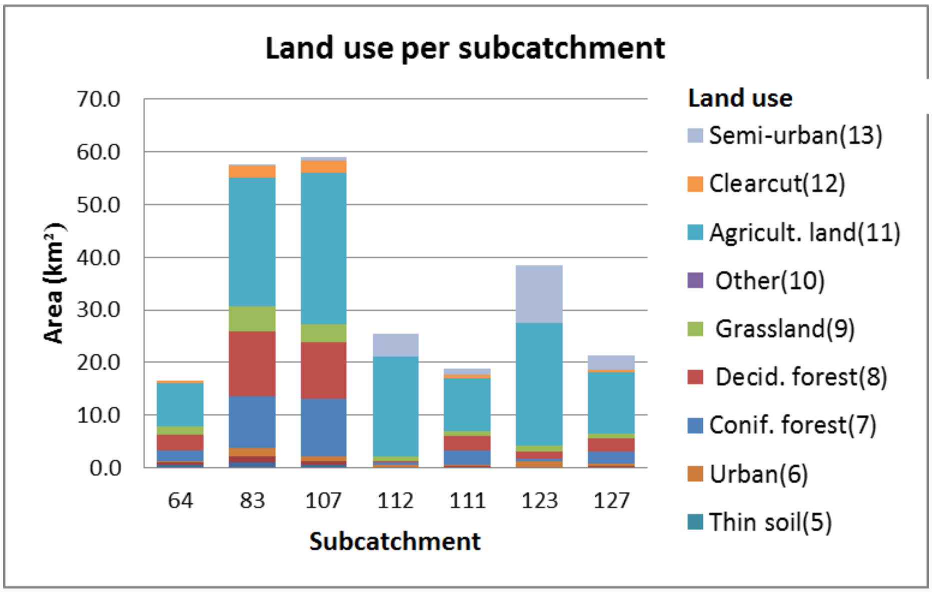

Figure 4.5: Land uses per subcatchment. The largest subcatchments are subcatchment 83 and 107. Subcatchment 123 and 127 covers the town of Lund.

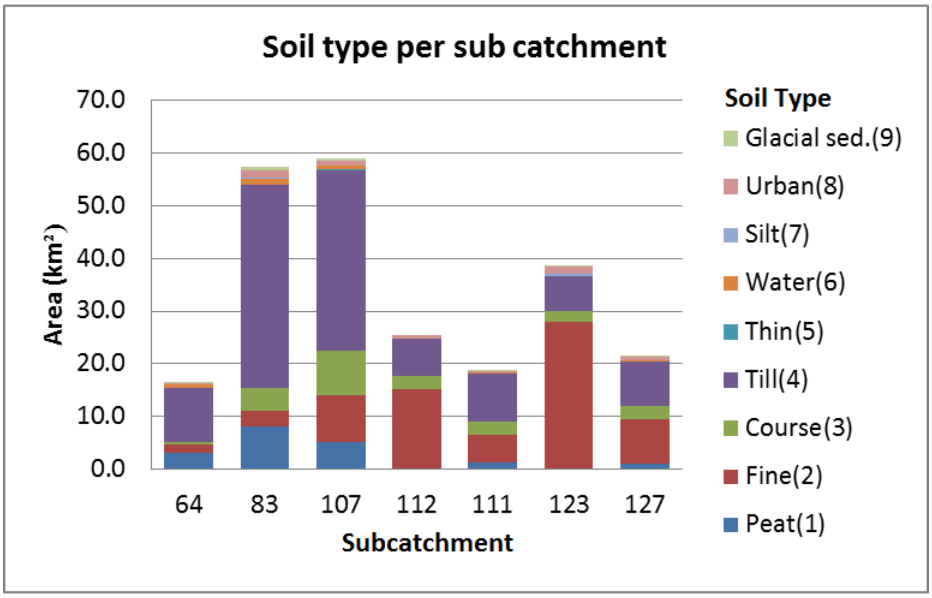

Figure 4.6: Soil types ber subcatchment. The largest subcatchments are subcatchment 83 and 107. Subcatchment 123 and 127 covers the town of Lund.

4.1.1 Urban areas

Since the main focus of this study is pluvial rainfall, areas with limited infiltration such as urban areas are of particular interest.

Subcatchment 123 and 127 contain Lund and are situated upstream the gauge 4.7. Lund covers an area of $25km^2$ with at least 2/3rds included within the area upstream of the gauge. However, when comparing the size of urban areas, semi-urban areas and urban soil categorized (using Corine) for all subcatchments (Table 4.1)- subcatchment 123 and 127 does not stand out in amount of urban areas. It seem like most of the urban land has been categorized as semi-urban. Also catchment 111 and 112, where Staffanstorp and Dalby is located, are categorized as containing more semi-urban areas. Figure 4.4 shows the location of the subcatchments.

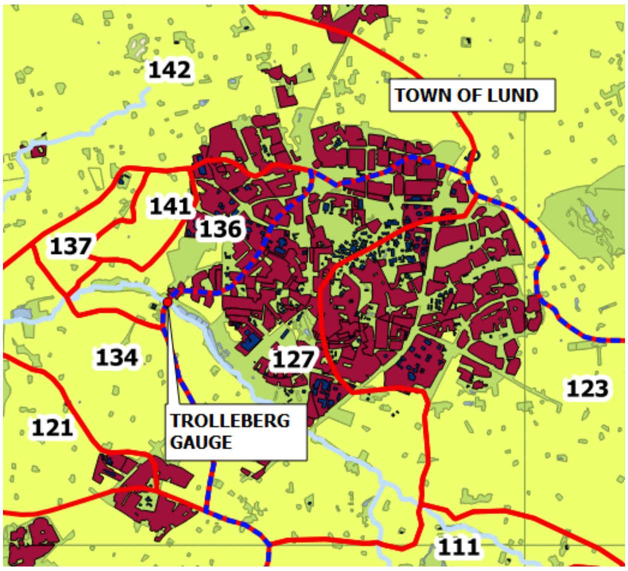

Figure 4.7: The subcatchments around Lund

Table 4.1: Characteristics of the subcatchments (SUBID) within the catchment of Höje å. Left column represent the area fraction (%) of the **subcatchment**. The right column is the area (km^2) this represent.

SUB-ID	**Area** (km^2)	**Main land use**	**Main soil types**	**Urban Land use**		**Semi-urban Land use**		**Urban Soil type**	
				(%)	(km^2)	(%)	(km^2)	(%)	(km^2)
64	17	Agr. land	Till	1.7	0.3	0.0	0.0	0.3	0.0
83	58	Agr. land	Till	2.6	1.5	0.1	0.1	1.5	0.8
107	59	Agr. land	Till	1.4	0.8	1.3	0.7	0.8	0.5
112	25	Agr. land	Fine	2.3	0.6	17.0	4.3	0.6	0.1
111	19	Agr. land	Till	2.0	0.4	6.4	1.2	0.4	0.1
123	38	Agr. land	Fine	3.3	1.3	28.5	10.9	1.3	0.5
127	21	Agr. land	Fine	2.9	0.6	13.3	2.8	0.6	0.1
Total area	**237** (km^2)				**5.4** (km^2)		**20.1** (km^2)		**2.2** (km^2)

4.1.2 Lund sewer system

10% of the sewage system is combined system and 90% is separated system. Combined sewage system means that both the rain water and the black water will go to the treatment plant. This retains the runoff but at intensive rainfall there is a risk of flooding the entire sewage system. The separated sewer system contains separate pipes for the rainwater and the sewage water. The rainwater will be led directly out of the city. This will increase the risks of flooding downstream but also facilitate dimensioning of the sewage system with more uniform need as the water consumption is easier to predict than the weather. Today most new systems are built as separated. There is a sewage treatment plant at Källby ARV (Avloppsreningsverk = ARV in Swedish) fig. 4.8.

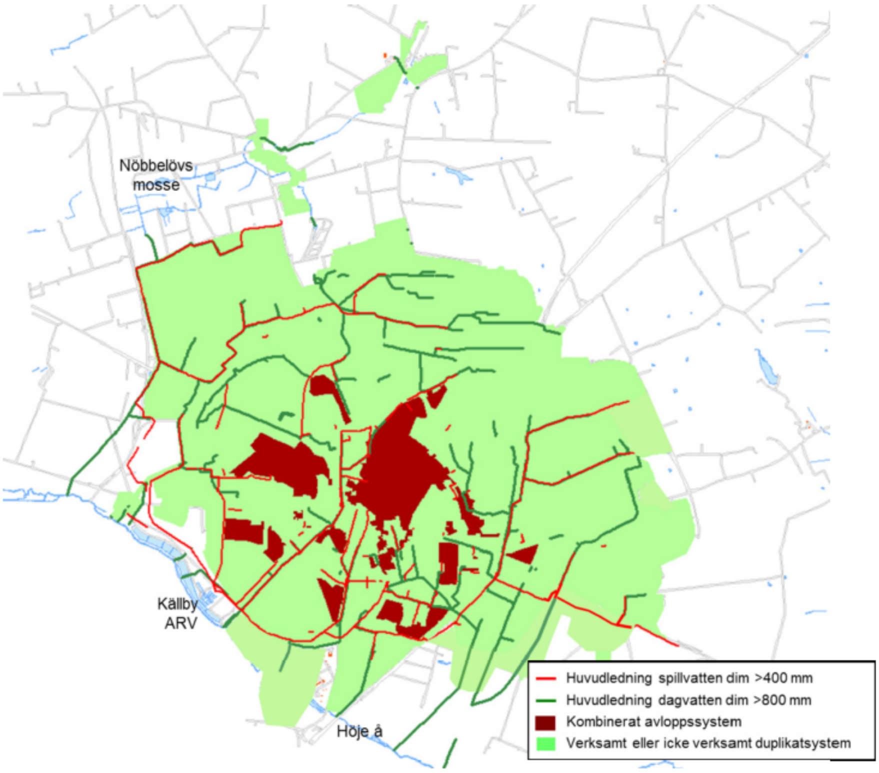

Figure 4.8: Part of Lund with combined sewage system (VA Syd, 2012)

The sewage system may affect the runoff, since it can retain the water. According to Patrik Nilsson at VA Syd (which are responsible for the sewage system in Lund) the influence in Lund should be negligible. Since 90% of the sewage system is separated he says most of the precipitation will pretty soon end up in a river. However, there is an overflow system within the sewage system in Lund which is not often used. There have been basement flooding within Lund at 2007-07-05, 2009-06-30, 2010-08-06, 2010-08-14.

4.1.3 Flow-duration analysis

The flow-duration curve is a plot that shows the percentage of time that flow in a stream is likely to equal or exceed some specified value of interest. It can be used to show the percentage of time river flow can be expected to exceed a design flow of some specified value, or to get a general view of the discharge characteristics of the stream and the ability of the basin to produce flows at different levels.

The median value in Höje å at Trolleberg discharge gauge is $1.5m^3/s$ and the percentage of time over 10 m^3/s is 2.55%.

The area below the curve represents the average of flow and the value at 50% represent the median value, see figure 4.9.

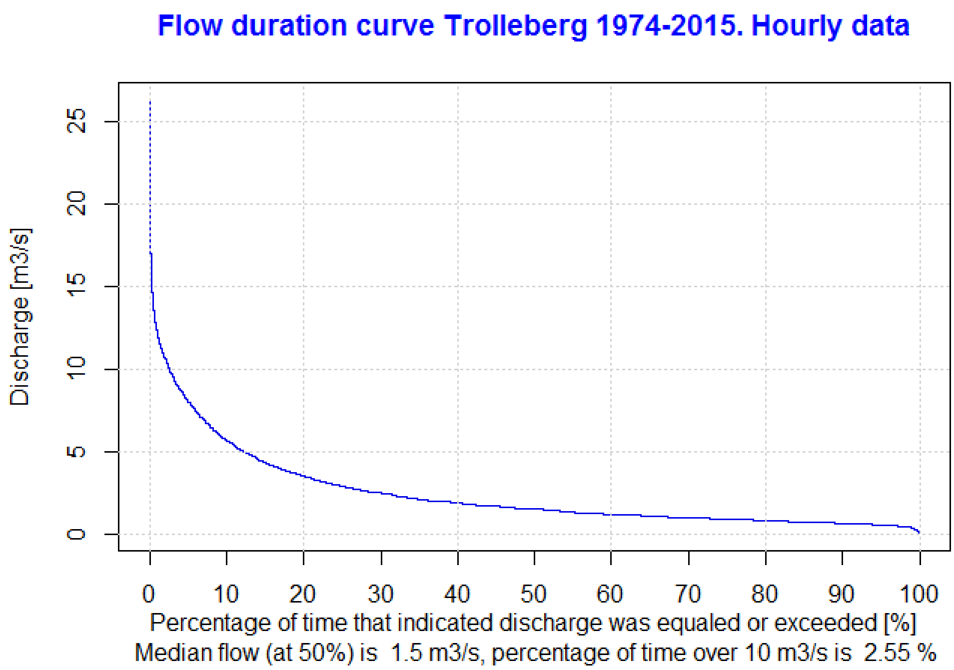

Figure 4.9: Flow duration curve at Trolleberg. Hourly discharge data from 1974-2015. Median flow is 1.5 m3/s and the percentage of time over 10 m^3/s is 2.55%

The shape of a flow-duration curve in its upper and lower regions is particularly significant in evaluating the stream and basin characteristics. The shape of the curve in the high-flow region indicates the type of flood regime the basin is likely to have, whereas, the shape of the low-flow region characterizes the ability of the basin to sustain low flows during dry seasons. A very steep curve indicated high flows for short periods which would be expected for rain-caused floods on small watersheds. Snow melt floods, which last for several days, or regulation of floods with reservoir storage, will generally result in a much flatter curve near the upper limit.

The time of the data has great impact on the result. Usually daily average is used but since this is a model for flood analyse I will use hour data to not risk loosing the peaks in averaging. It is calculated by first ranking the flow data from highest to lowest. The probability that a given flow will be equaled or exceeded is calculated according to equation 1. (Oregon State University, 2002)

$$P = 100 * [M/(n + 1)] \quad (1)$$

where:

P is the probability that a given flow will be equaled or exceeded (% of time)
M is the ranked position on the listing (dimensionless)
n is the number of events for period of record (dimensionless)

4.2 Precipitation data

Within this thesis, grid point HIPRAD data from the catchment will be compared with local gauges from VA Syd (hourly resolution) and from SMHI (daily resolution). HIPRAD is delivered as grid-cells covering an area of 2x2 km. The data from the grid-cell covering the location of the VA Syd gauges will be used in the comparison. The locations of the gridpoint and local gauges are seen in figure 5.2.2.

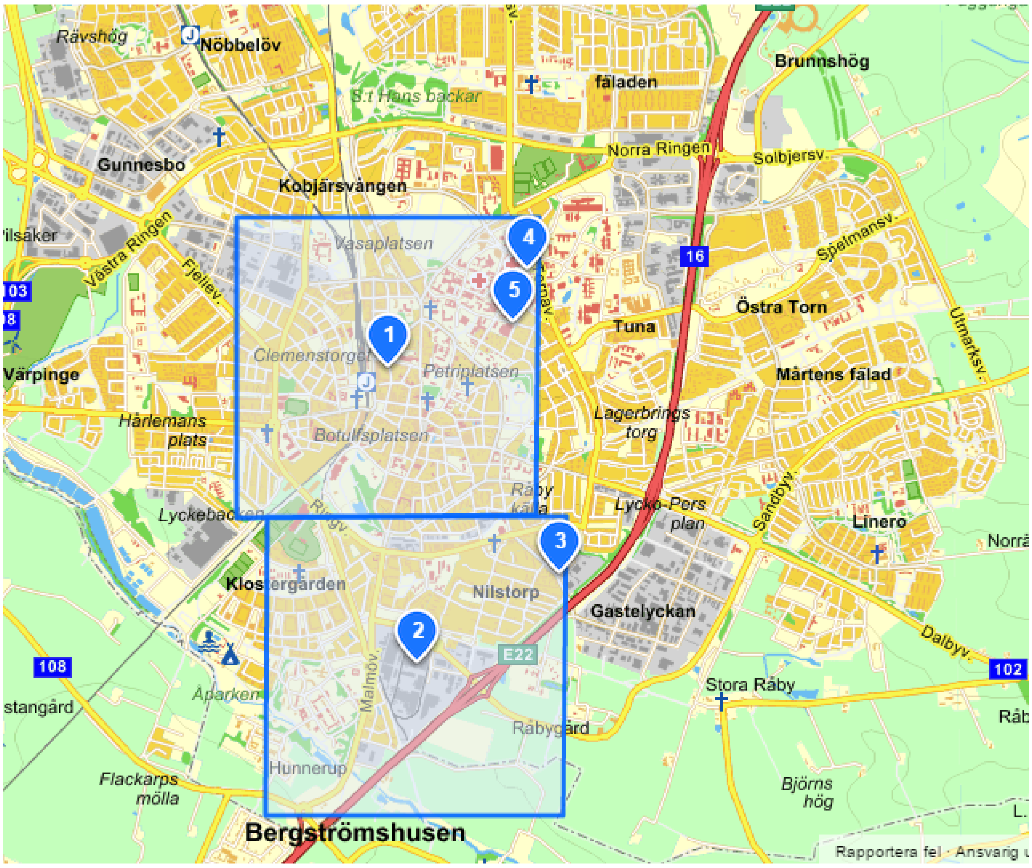

Figure 4.10: Location of grid cells and rain gauges in Lund.
1: Center of north HIPRAD grid, 2: Center of south HIPRAD grid, 3: South VA SYd, 4: North VA Syd, 5: SMHI gauge .

HIPRAD: (Nbr 1 and 2 in Figure 5.2.2) The gridpoint closest to the location of the VA Syd gages were chosen. The data is delivered every 15 minutes (HH:00, HH:15, HH:30 and HH:45) at UTC+0 timescale.
Time period 2005/2009-2014.

VA Syd: (Nbr 3 and 4 in Figure 5.2.2) Va Syd has two tipping-bucket gauges within this area. The size of the bucket was 0.5 ml before April 2012, when it was upgraded to 0.2 ml. According to VA Syd the data before 2012 is not as trustworthy as after the upgrade. The time of the measuring equipment is changed

to follow Swedish time including summertime (according to the logbook from 2012. The date for changing does not necessarily match with the national time of change).
Time period: (1998-07-22 00:00) 2012-04-01 00:00 to 2016-03-31 13:00

SMHI: (Nbr 5 in Figure 5.2.2) SMHI gage measuring at daily time step. This gague is probably also used when producing the PTHBV grid that HIPRAD is interpolated to. The daily precipitation is calculated between 06:00 -06:00.
Time period: 1976-12-31 00:00 to now

5 Method

The overall work of this thesis is summarized in flowchart 5.1. The goal is to produce a runoff forecast of pluvial flooding in the catchment of Höje å, using HYPE at 1h resolution.

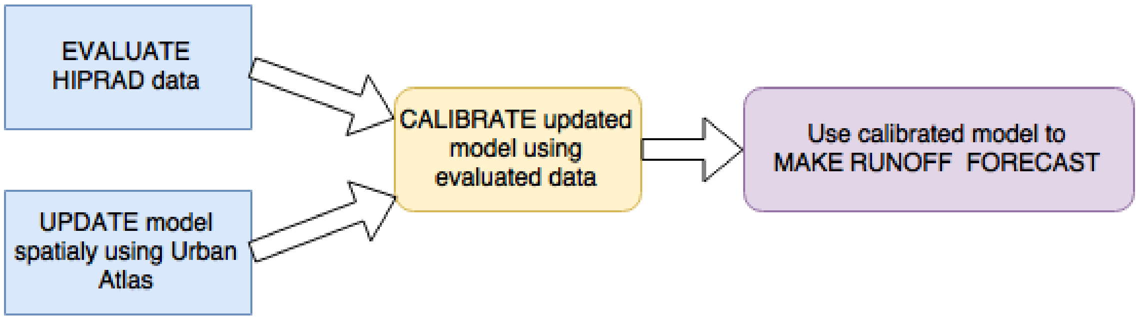

Figure 5.1: Flowchart

5.1 Interesting events

To reach the main goal, the historical data of Höje å catchment is investigated for events that have been of pluvial nature or resulted in high floods. This is needed in for the evaluation of the model. By examine the plot of an important event, information about how the model handle these events is gained. Interesting event were identified by the following terms:

Short and intense: Pluvial flooding originating from short and intense rainfall where the flood is induced by rainfall-intensity exceeding the infiltration level.

Initiated by a dry period: To evaluate the impact on runoff from impermeable ares it is preferable that the other ground is not already saturated at the beginning of the event. To assure this the period before the event should be more or less dry. However, to few event meet this criterion why it could not be strictly followed because.

Large impact: The event should have had a measurable impact on the area. This is investigated by looking at discharge in Trolleberg, situated just downstream of Lund, and by examine known situations where basement flooding were registered; 2007-07-05, 2009-06-30, 2010-08-06 and 2010-08-14.

Summer rain: Only events which occur during the summer are of interest in this study.

Rain over urban area: It is interesting to see if there are difference if the rain fell over areas with more urban/semi-urban surfaces as subcatchment 123 and 127.

Six events were recognized as interesting out of these terms. These are presented in table 5.1 and plotted in figure 5.2 and 5.3. The precipitation data is stored as mm rain per *subcatchment* in HYPE. Since the subcatchment varies in size, an average of the precipitation over the catchment is calculated (blue line in plots). This is compared with the precipitation at catchment 123 and 127 (red and green line).

An effort have been made to keep the same scales (also temporal) for all of the plots to facilitate comparison between the six of them. This might be misleading as some of the events are a lot longer than what is shown here, for example event A from 2007.

Table 5.1: Interesting events that are plotted and used to evaluate the model.

Fig.	**Start date plot**	**Stop date plot**	**Peak flow** [m^3/s]	**Duration of flow higher than 10** m^3/s	**Info**
A	2007-07-03	2007-07-07	26.3	167 h = 7 days	Major flood in area. 1:st higest flow within time period. Rain during 3 weeks prior flood. Basement flooding
B	2011-06-30	2011-07-04	21.7	10 h	4:th highest flow within time period. Rain one day prior flood
C	2010-08-12	2010-08-16	18.6	13 h	6:th highest flow within time period. Followed period with much rain and basement flooding. Rapid increase of flow from 1 to 11 m3/s in 5 h. Basement flooding
D	2013-08-12	2013-08-15	12.5	2 h	16:th highest flow but very short and intense event!
E	2014-07-31	2014-08-04	6.8	-	Large amount of rain over urban areas - Subid 123:17.4 mm/h, Subid 127:9.1 mm/h
F	2006-08-11	2006-08-15	8.5	-	Large amount of rain over urban areas - Subid 123:12.6 mm/s, Subid 127:4.1 mm/s. Long event

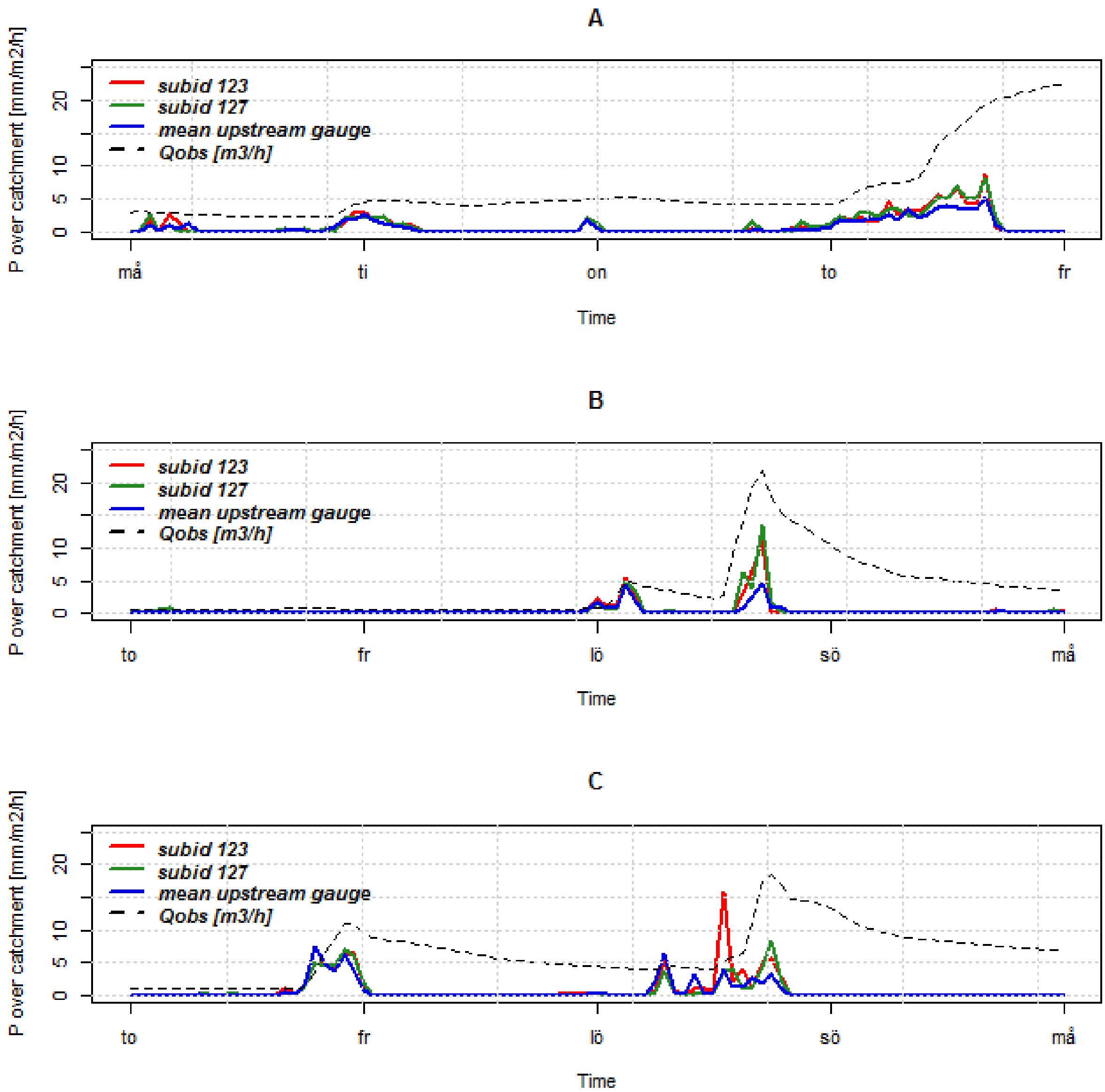

Figure 5.2: The characteristics of the event A, B and C.
Black line represent the observed runoff at Trolleberg [m^3/s].
Blue line is the mean amount of precipitation that fell over the entire area upstream the gauge that hour.
Read and green is the precipitation registered for that subcatchment

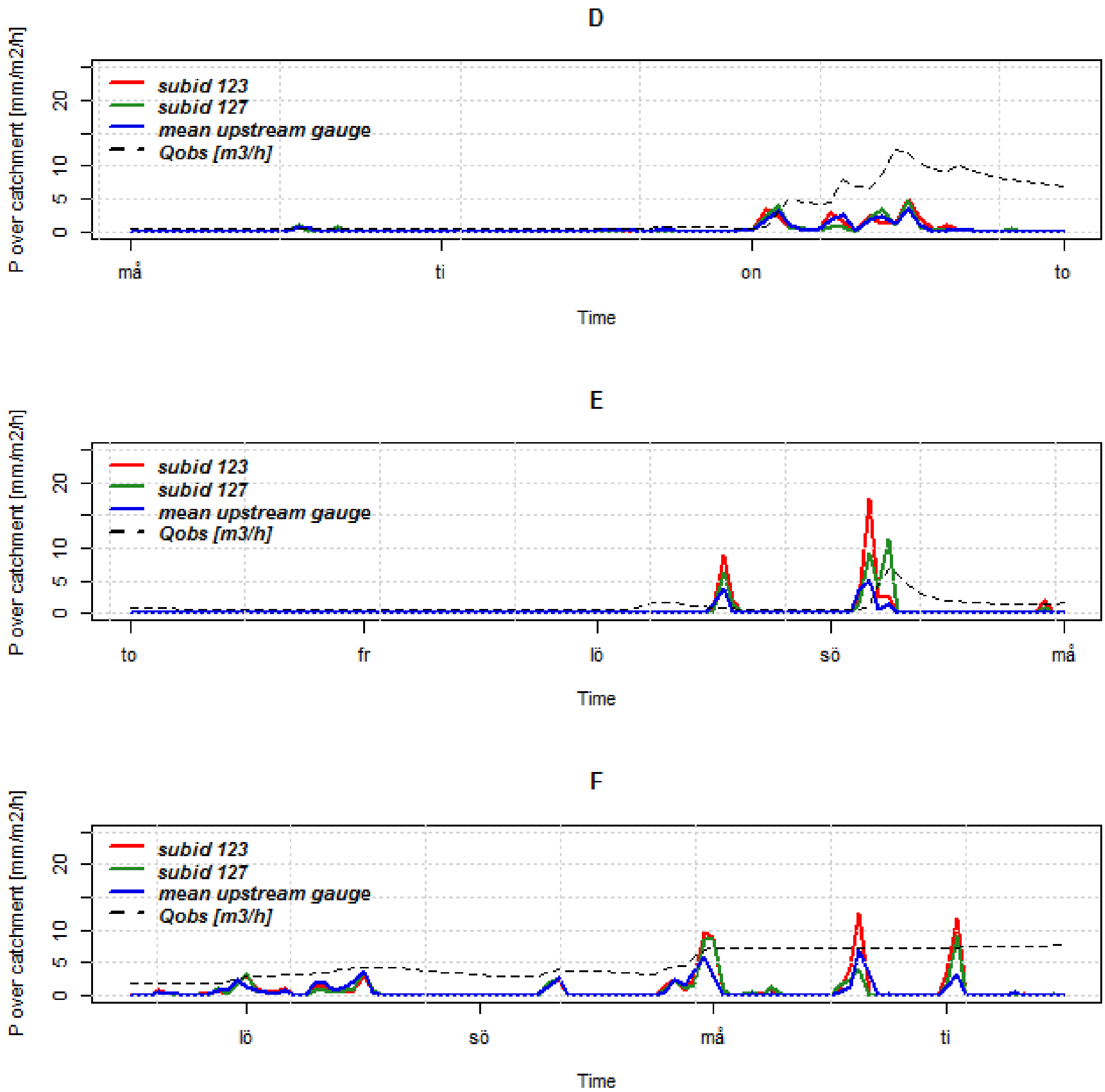

Figure 5.3: The characteristics of the event D, E and F.
Black line represent the observed runoff at Trolleberg $[m^3/s]$.
Blue line is the mean amount of precipitation that fell over the entire area upstream the gauge that hour.
Read and green is the precipitation registered for that subcatchment

5.2 Evaluation of HIPRAD precipitation data for Höje å catchment

Updated 1h precipitation data is needed to initiate the model prior a forecast is run. HIPRAD provides this and also has possibility of being real time updated. This is a great advantage when modelling for Early warning systems (EWS). Within this section the quality of HIPRAD data is investigated.

5.2.1 HIPRAD2 vs. HIPRAD1

HIPRAD1 and HIPRAD2 are produced at different time periods (table 5.2) why only the overlapping time can be compared (2009-2014). The data is compared by plotting the volumes and calculating the correlation according to Pearson correlation.

5.2.2 HIPRAD vs.VA Syd and SMHI rain gauges

HIPRAD is based on radar data interpolated with PTHBV-data, which in turn is based on local weather stations. In order to get a bias-free check of the data it need to be compared with external data which has not been used in the production of HIPRAD. VA Syd have two gauges within the area which will be used for comparison (see Figure for location).

The precipitation data from the HIPRAD2 is compared with data from VA Syd at the location of the VA Syd measuring gauges "Lund North" and "Lund South". A third gauge from SMHI is also used as comparison, "SMHI". However this gauge is measuring on a daily time step and is most probably used when the PTHBV-grid is made, hence not bias-free and HIPRAD is expected to show some similarities.

An overlapping time-period is used for evaluation which is 2000-01-01 to 2014-12-31. Initially, the north and the south stations were to be compared separately against each other. In the end there was no strong correlation between them, therefore all stations are compared to each other.

Plotting the data: The data is plotted for the "interesting events" (table 5.1) chosen for the catchment. This also illustrates the difference of using daily- or hourly time step.

Overall volume: The total precipitation per year is compared to give an overall view of the dynamics.

Frequency of wet hours and wet days: HIPRAD can register rain at a smaller level than the VA Syd gauges. From April 2012 the gauges at VA Syd is changed to collecting 0.2 ml instead of 0.5 ml as for previous period. All hours with registered rain at VA Syd is registered as wet. For HIPRAD hourly precipitation above 0.5 ml is calculated as wet until April 2012 were 0.2 mm is needed instead. Wet days per year is measured in two ways:

1. All days that were assigned wet according to hours are assigned as wet days.
2. The total precipitation during the day is summed and if this exceeds the threshold 0.5/0.2 that day is assigned wet.

Correlation between the stations: The correlation between all the station for total precipitation year, month, day and hour is compared by calculating the Pearson correlation coefficient.

The uncertainties in the data can be summarized like this:

- Both VA Syd gauge and HIPRAD radaner will handle snow badly, hence it could be preferable to only use the summer months in the comparison. Summer months are defined as May to September (5 months)

- HIPRAD is in UTC+0. According to the notebook over the gauges the VA Syd data after 2012 should be in Swedish time, including summertime from end om March to end of October. Before this year it is uncertain if the data follows the same pattern. Even during this period the time device is reset manually to summer- and normal-time so the consistence is not guaranteed. This is checked for (Table 5.3).

- The HIPRAD data also contains a correction for losses in the precipitation collection, i.e. it is expected that the gauges underestimate the intensity of the rainfalls. Therefore, the data from HIPRAD is expected to be a bit higher than the gauge data from VA Syd.

5.2.3 Correlation of data sets

HIPRAD data is compared to SMHI and VA Syd gauges. One way to compare data set is to compare dependency. Below follows of two different ways to check correlation of data sets.

Pearson correlation coefficient: This is probably the most commonly used correlation method. When two sets of data show a linear dependency they are called to have a strong correlation. A perfect positive linear correlation corresponds to a value of 1 and indicates that the two data sets contain the exact same values but the data set could also have a negative correlation where one data set increase as the other decrease (5.4). A correlation of 0 represents that the data sets show no correlation at all.

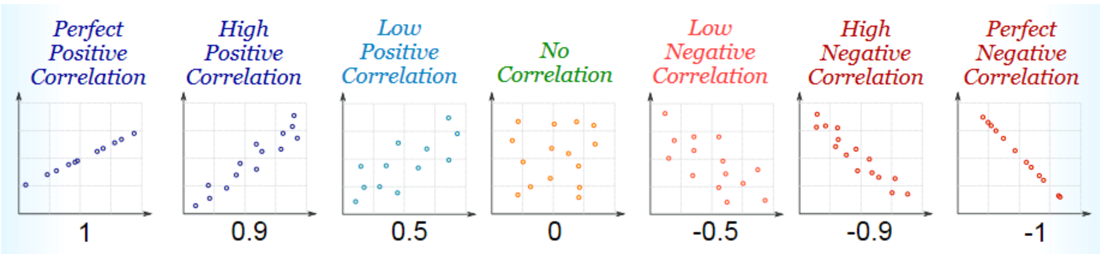

Figure 5.4: Linear correlation. Source: www.mathisfun.com

Visual examination: The importance of visually examine the correlation is here illustrated with the Anscombe's quartet(figure 5.5). The figure consist of 4 graphs with identical mean (7.5), variance (4.12) and linear correlation (0.816), but with totally different appearance. The first graph (x_1) contains what might we expect a correlation of 0.816 to look like. The second one (x_2) has a really strong correlations, but is not linear hence the low result. X_3 shows a great correlation (if not perfect for the first points but the last one breaks the suit while on the opposite at the final graph(x_4) the last outlier creates a linear dependency which is not found within the other points.

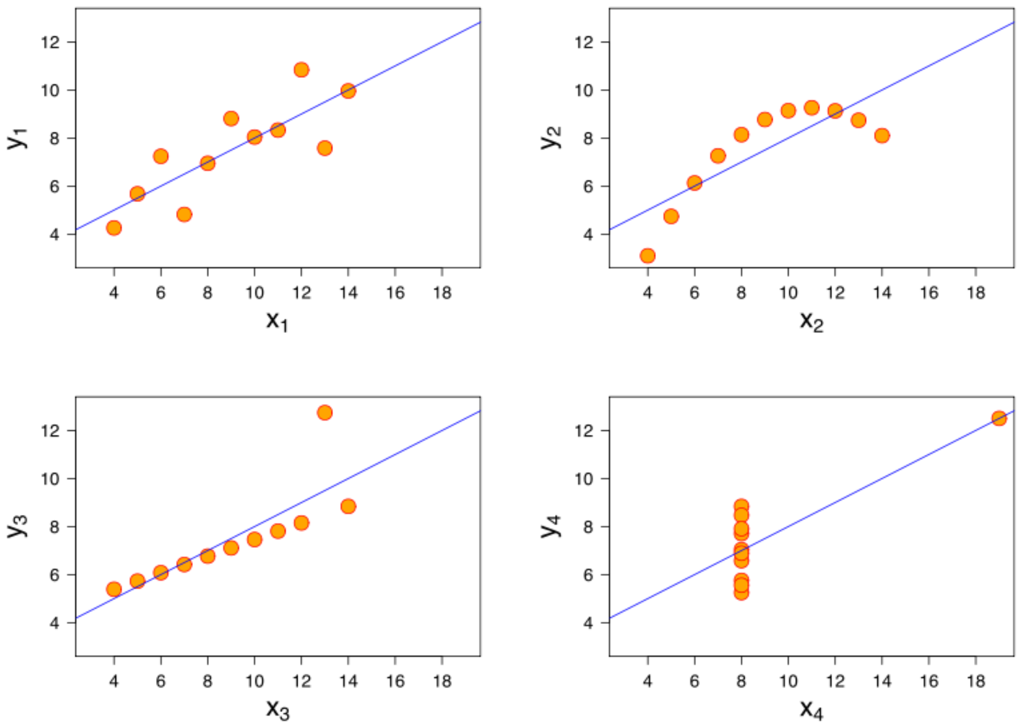

Figure 5.5: Anscombe's quartet. All four cases has a correlation between x and y of 0.816. (Anscombe, 1973)

5.2.4 Pre processing of data

The initial stage of the precipitation data is found in table 5.2. In order to compare the precipitation data it is preprocessed to fulfill the following criteria:
- The precipitation is measured at an hourly resolution
- The timezone is UTC +0 hour

Table 5.2: A summation of the data used within the evaluation

Station	**P reg.**	**UTC**	**Time period (start)**	**Timepreiod (stop)**
HIPRAD1	every 15 min	UTC +0	2009-01-01 00:00	2014-12-31 23:00
HIPRAD2	every 15 min	UTC+0	2005-01-01 00:00	2014-12-31 23:00
VA Syd	at full bucket	UTC+ 1-2h	1998-07-22 00:00	2016-03-31 13:00
SMHI gauge	every day	UTC+0	1976-12-31	now

HIPRAD: The data is delivered per every 15 min (HH:00, HH:15, HH:30 and HH:45) at UTC+0 timescale. According to conventions at SMHI the data is aggregated over the hour, i.e. any precipitation registered from 15:00-15:45 is re-registered at time 15:00.
Time period HIPRAD1: 2009-01-01 00:00 to 2014-12-31 23:00
Time period HIPRAD2: 2005-01-01 00:00 to 2014-12-31 23:00

VA SYD: The VA Syd data is collected by a tipping bucket of size 0.5 mm before April 2012 and 0.2 mm after this point in time. This could be inclusive of

summertime. To check if it is preferable to take account for summer time when converting the data to UTC+0, the VA Syd data is compared to the HIPRAD data, for the purpose of doing a small correlation test 5.3. Stronger correlation is seen in the data when summertime is taken into account in the conversion. The data is aggregated per hour.
Time period: 1998-07-22 00:00 to 2016-03-31 13:00

Table 5.3: Pearson correlation between VA Syd gauge and HIPRAD data at hour if summertime is accounted for or not when coverting to UTC+0 time. Both station shows better correlation when summertime is accounted for.

	HIPRAD North	**HIPRAD South**
VA Syd S No Summertime		0.32
VA Syd S Summertime accunted for		**0.52**
VA Syd N No Summertime	0.22	
VA Syd N SummertimeAccunted for	**0.36**	

SMHI gauge: The precipitation data from SMHI weather station is in UTC+0 at hourly basis and hence is not converted. The daily precipitation is calculated between 06:00 -06:00. Time period: 1976-12-31 00:00 to now

5.3 HYPE at increased resolution in time and updated spatially

The HYPE model is updated in soil and land use categorization using a more detailed source for spatial description, and the model is calibrated using the HIPRAD2 1h data. The impact of using 1h time-step of the forcing data is evaluated in compare to using a daily time step.

5.3.1 Impact of using Urban Atlas instead of Corine

There have been previous work on the advantages of updating the source of land cover data from Corine to Urban Atlas (Tanouchi et al., 2011) (see Chapter 3 for a closer description of Urban Atlas and Corine). The study resulted in an update of parameters of the national HYPE model describing urban areas. Within the study the subcatchment of Höje Å catchment was categorized in area fraction based on Urban Atlas land cover data. The same area fractions will be used within this thesis. In order to catch the more detailed description that Urban Atlas provides, two more land use classes were added in the Urban Atlas model; Urban Grass(14) and Urban Agriculture(15). Original S-HYPE does not contain these extra land use classes why it would be preferable to avoid including them. Within this thesis this was handled in the following way:

Land Use class Urban Grass(14) and Urban Agriculture(15) showed great similarities with Land Use class Grassland(9) and Agricultural land(11). The only variable differing was the *ttmp* which was for land use Urban Grass(14) and Urban Agriculture equals to 0 and for land use Grassland(9) and Agricultural land(11) equals to 0.2. *Ttmp* is the threshold temperature for snow melt, snow density and evapotranspiration (SMHI, 2016) and hence, this parameter should have low impact when calculating runoff from flash flood. The result of handling the extra land use classes as mentioned is evaluated, together with the percentage difference when changing from Corine to Urban Atlas

The evaluation of the model is obtained by plotting the outcome from the models based on Urban Atlas and Corine when running the model for event B and C, and by comparing the overall efficiency coefficients of the models over the period 2009-2014.

5.3.2 Calibration and model performance

When calibrating a model it is essential to be able to judge its performance and evaluate improvements. This can be done by a quantitative estimate of the model's ability, using an efficiency criteria (EC). Such EC are defined as a mathematical measure of how well a model simulation fits the available observations comparison (Beven, 2012). These variables can also be used to reproduce historic and future watershed behaviour or to compare current modeling efforts with previous study results. Improvements of the model can be done through adjustment of parameters, model structural modifications, the inclusion of additional observational information, or by representation of important spatial and temporal characteristics of the watershed (Krause et al., 2005).

However, there are differences in these variables that are of importance to know. For example; to avoid the canceling of errors of opposite sign, the summation of the absolute or squared errors is often used for many EC's. As a result large errors are emphasised (usually at intense water and high peaks) while small errors (usually when the water is calm at base flow) are deprecated, hence the impact of error at peak flows will have larger impact within this evaluation (Krause et al., 2005). Since the peak flows are generally more difficult to catch this could be an advantage depending on the use of the model, hence it is vital to determine which observations that will evaluate the performance of the specific model. The following EC's are considered within this thesis:

Nash–Sutcliffe efficiency (NSE)(1970): NSE is a measurement of goodness of fit developed especially for hydrological models. It is calculated according to equation 2 and ranges between -∞ to 1. An efficiency of 1 (E=1) correspond to a perfect fit between modelled and observed data. A NSE below zero tells the model is not better than just using the mean observation value. NSE is sensitive to extreme values and might exaggerate the poorness of the model if the data contains many outliers.

$$E = 1 - \frac{\sum_{t=1}^{T}\left(Q_o^t - Q_m^t\right)^2}{\sum_{t=1}^{T}\left(Q_o^t - \overline{Q_o}\right)^2} \quad (2)$$

where:

Q_o is the mean of observed discharge
Q_m^t is modelled discharge at time t
Q_o^t is the observed discharge at time t

Relative error (RE(%)) The relative error (RE), also refereed to as the volume error, is often used as a complement to NSE. It indicates how *incorrect* is the modelled value in relation to the observed one. It is based on the absolute error which shows how much the modeled value *varies* from the observed one. The RE is calculated according to equation3 as the ratio of the absolute error and the observed value. It is expressed in percentage. 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. A RE less than 10% is generally considered as good model performance.

$$RE = \frac{observedvalue - simulatedvalue}{observedvalue} \tag{3}$$

The calibrations are proceed by changing parameters in the par-file. The par-file contains over 100 parameters and with contribution from SMHI, and by examine the look of the runoff-graphs, a few parameter were chosen out of the 100 (5.4). Some of the parameters are specific for different land and soil use classes. Only the parameters of the dominating classes within the area according to the percentage (Figure 4.2 and 7.2.1) which is:

Landuse: Agricultural land(11)

Soiluse: Till(4), Fine(2)

Table 5.4: Table over the parameters changed during calibrations

Parameter	**Description**	**LINK**	**Unit**	**Reasonable size (day)**
wcfc:	Field capacity, fraction of soil available for evapotranspiration but not for runoff, same for all soil layers (used if wcfc1 not given)	Water content		0.05-0.5
wcep:	Effective porosity as a fraction, same for all soil layers (used if wcep1 not given)	Water content		0.05-0.5
rrcs1:	Recession coefficient for uppermost soil layer	Runoff		0.05-0.5
rrcs2:	Recession coefficient for lowest soil layer. Rrcs is suppose to decrease with depth!	Runoff		
rivvel: + **1-3**	Celerity of flood in watercourse – the waters maximum velocity in watercourse	River	m s-1	0.5-2
damp:	Fraction of delay in the watercourse which also causes damping	River	-	
srrcs:	Recession coefficient for surface runoff (fraction), should be set to 1 for lake and river classes with floodplains	Surface runoff	ts-1	

The calibrations the carried through by comparing the look of the outcome hydrograph and the EC when the parameters were increased and decreased. Three parameters does increase the performance of the model (srcc(4), rivvel, damp). These are examine more specifically. The calibration period were prolonged for the specific period to 2006-2012.

HIPRAD2 is the limiting data of the model, stretching over the time period 2005-2014. To avoid calibrating and validating for the same period the time period is divided like in table 5.5.

Table 5.5: Time period of the calibration

	Start	**Stop**
Warm up period	2005-01-01	2006-01-01
Calibration:	2006-01-01	2010-12-31
Validation:	2011-01-01	2014-12-31

5.3.3 Model performance

The aim is to compare the difference of using 1h- and daily time step. The calibrated model (at 1h time step) is compared to the calculated runoff from the national S-HYPE model (downloaded from VATTENWEB) and the daily HYPE model using aggregated HIPRAD2 data. The data is aggregated by hour. Two models at daily time step are used to limit the risk of oversee influence from either data or calibration of model.

5.4 Evaluation of 1h HYPE for forecasting usage

As a final stage the calibrated model is used to forecast a rain event. MEPS used in weather forecasting at SMHI have been saved for this purpose. These data take up a lot of memory so only one month of data were saved, covering the period of 2015-10-06 to 2016-11-04.

5.4.1 Update of forcing data

In order to run the model for the climate calibrations the forcing data needs to be prolonged:

Table 5.6: Available time period of the forcing data

	OLD period		**NEW period**	
DATA	**Start**	**Stop**	**Start**	**Stop**
Pobs (HIPRAD2)	2005-01-01	2014-12-31	2015-05-10	2016-12-08
Tobs (MESAN)	2005-01-01	2014-12-31	2015-01-01	2016-12-31
Qobs	1973-01-01	2015-07-26	2015-01-01	2016-12-31
MEPS	2015-10-06	2016-11-04	2015-01-01	2016-12-31

Pobs:
There are no hourly precipitation data developed for the period yet. Pobs is therefor produced by using the HIPRAD1 interpolation. Pobs are provided from in PTHBV to HIPRAD1 between the period: 2015-06-11 06:00 to 2016-12-08 06:00. The last hours of each month are missing (07:00-23:00). These are added and assigned a precipitation value of zero.

Between 2014-12-31 23:00 and 2015-06-11 06:00 there is no HIPRAD data available. This period is filled with the data from the same dates from year 2014. To ensure that this does not affect the model this period is only used as warm up period.

Tobs:
Temperature measurements are made through MESAN mesh. The additional data is from MESAN within the dates 2015-01-01 00:00 to 2016-12-31 00:00 This is attached to the previous file used.

Qobs:
The data is interpolated over the measurements to produce hourly data. Missing data are removed by interpolation using HiRes Data, delivered at every quarter of an hour (HH:00, HH:15, HH:30, HH:45). The main period of interest - 2016-10-19 21:00 to 2016-11-17 12:00 is such an absent of values with is filled. The comparing to two they have more or less similar values.

5.4.2 To model the event

The precipitation data and observed and calculated runoff for the time period of available MEPS (2015-10-06 00:00 to 2016-11-04 06:00), is plotted and searched for the most intense event (figure 5.6). In the end of the period there is a huge event according to the plotted precipitation. The calculated runoff is however a lot higher than the observed runoff (lower plot showing observed vs. calculated runoff)- almost three times higher, which could indicate that the precipitation data is erroneous. The observed runoff is, however, at its peak at this time. and there are MEPS available only for this period, hence this is the event that will be investigated.

Since the large difference in observed and calculated runoff, the precipitation data will be examined as well. This is done by aggregating the data aggregated to daily steps (06:00-06:00) and comparing with the SMHI rain gauge in the area.

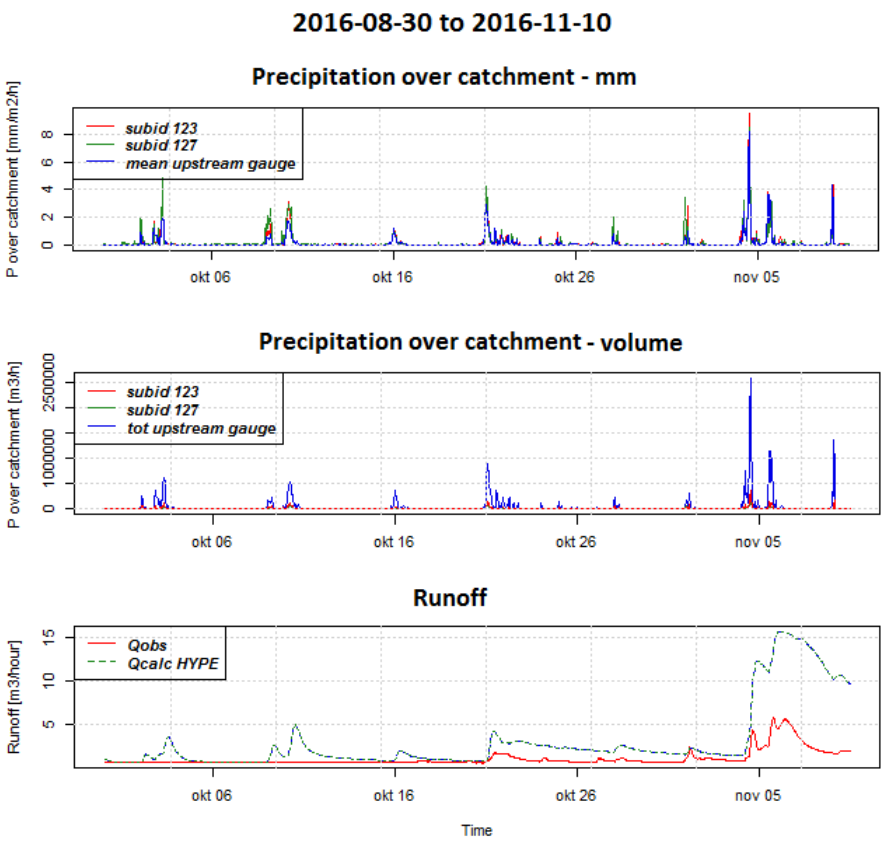

Figure 5.6: Image showing the entire period where there is MEPS

The event that is chosen starts at 2016-11-04 at around 00:00. MEPS data are only available up until 2016-11-04 06:00, so the runoff will be forecasted up to this time. Radar images from the time of the event shows that it was large and covers most parts of south Sweden. It also lasted for a long time (ca from 00:00 to 18:00) 5.7. This is not a typical flash flood but still interesting to model.

The 10 MEPS-members contain forecasted precipitation and temperature data over the next 36 hours. The runoff-forecasts based on the MEPS-members can either be produced by initiating the model until the time of the forecast using existing 1h data (updated HIPRAD2 in this case). This is to allow the correct starting conditions for the model. Secondly, the precipitation and temperature data from the MEPS members are used to model (i.e. forecast) the next 36 hours. However, since in this case all data is available already, it is also possible to only change the forcing data files of the precipitation and temperature at the 36 hours covering the forecast. By doing so, the model only need to be run one time.

The runoff-forecasts for this study are made at 2 days, 1 day, 12 h, 6 h, at the start of the event and 6 hours into the event. The model will have to be run for each member(10) and at each forecast(6), 60 times in total. This also includes updating the precipitation and temperature data for each forecast. The processes are automated by producing scripts.

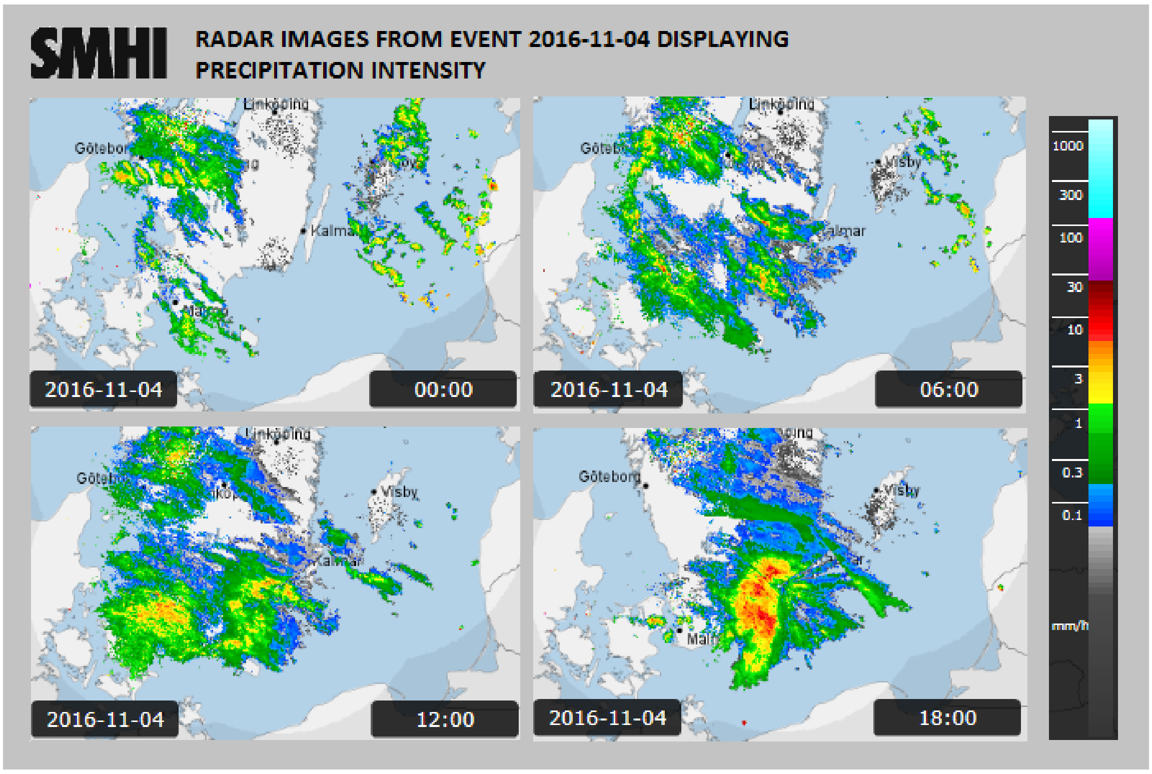

Figure 5.7: Radar images from the precipitation event 2016-11-04 elected for forecast using MEPS

6 Results

6.1 Evaluation of HIPRAD precipitation data for Höje å catchment

6.1.1 HIPRAD2 vs. HIPRAD1

HIPRAD1 and HIPRAD2 is compared in this study. HIPRAD2 is the latest version of HIPRAD but HIPRAD1 is available at up to date. Figure 6.1 shows that the difference between the two models in annual volume between 2009-2014 which seem to match well. The correlation is shown in figure 6.2 and it can be seen that it is also good, even when it is compared at hourly time step (0.95).

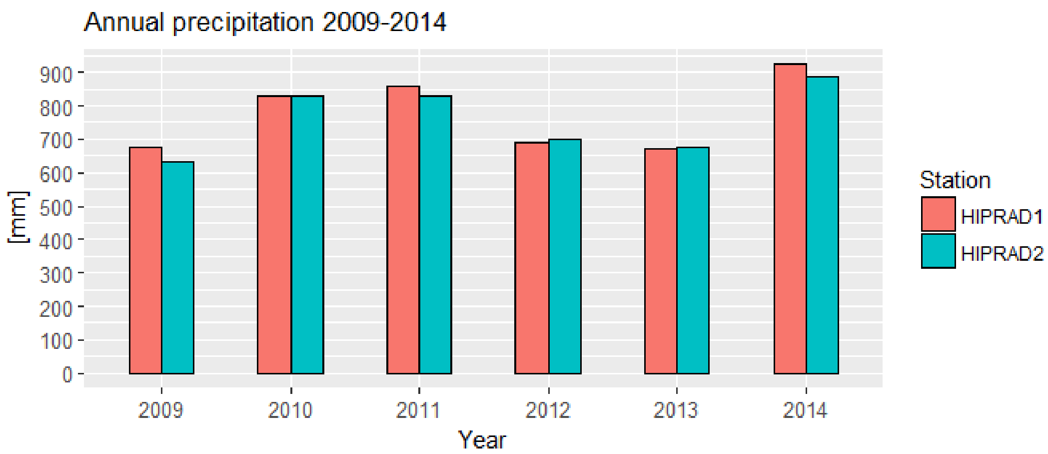

Figure 6.1: Total precipitation per year measured with HIPRAD1 and HIPRAD2

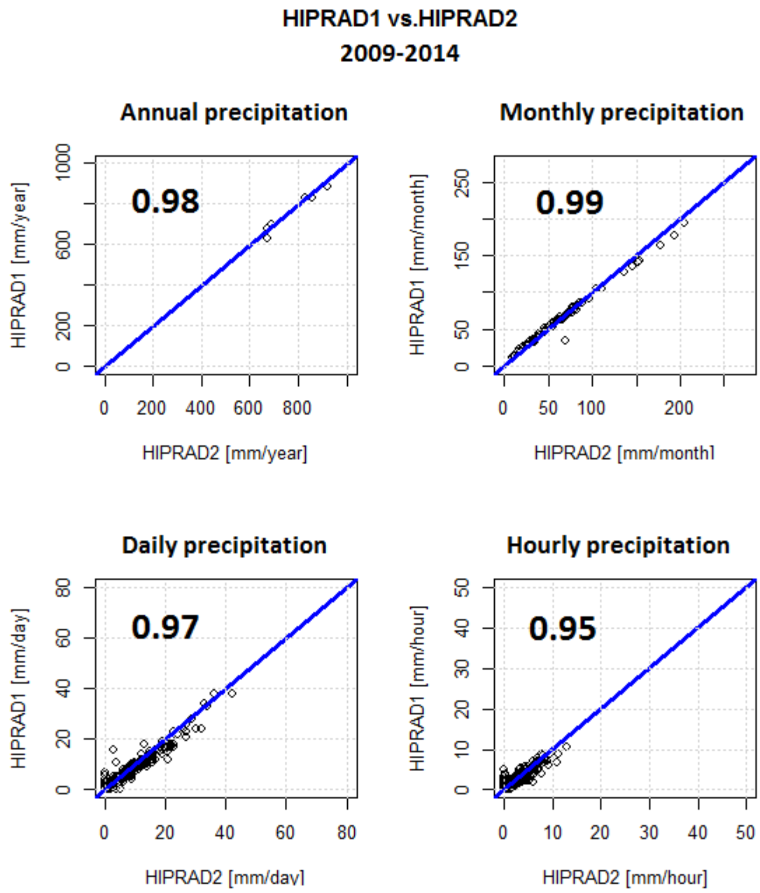

Figure 6.2: The correlation between HIPRAD1 and HIPRAD2 at time steps of hour, day, month and year. The precipitation is averaged over the entire catchment.

6.1.2 HIPRAD vs. VA Syd and SMHI rain gauges

To obtain an overall view of the data the station are plotted for the events A-F (6.3 and 6.4). This also visualises the difference of using daily (SMHI gauge) or hourly data.

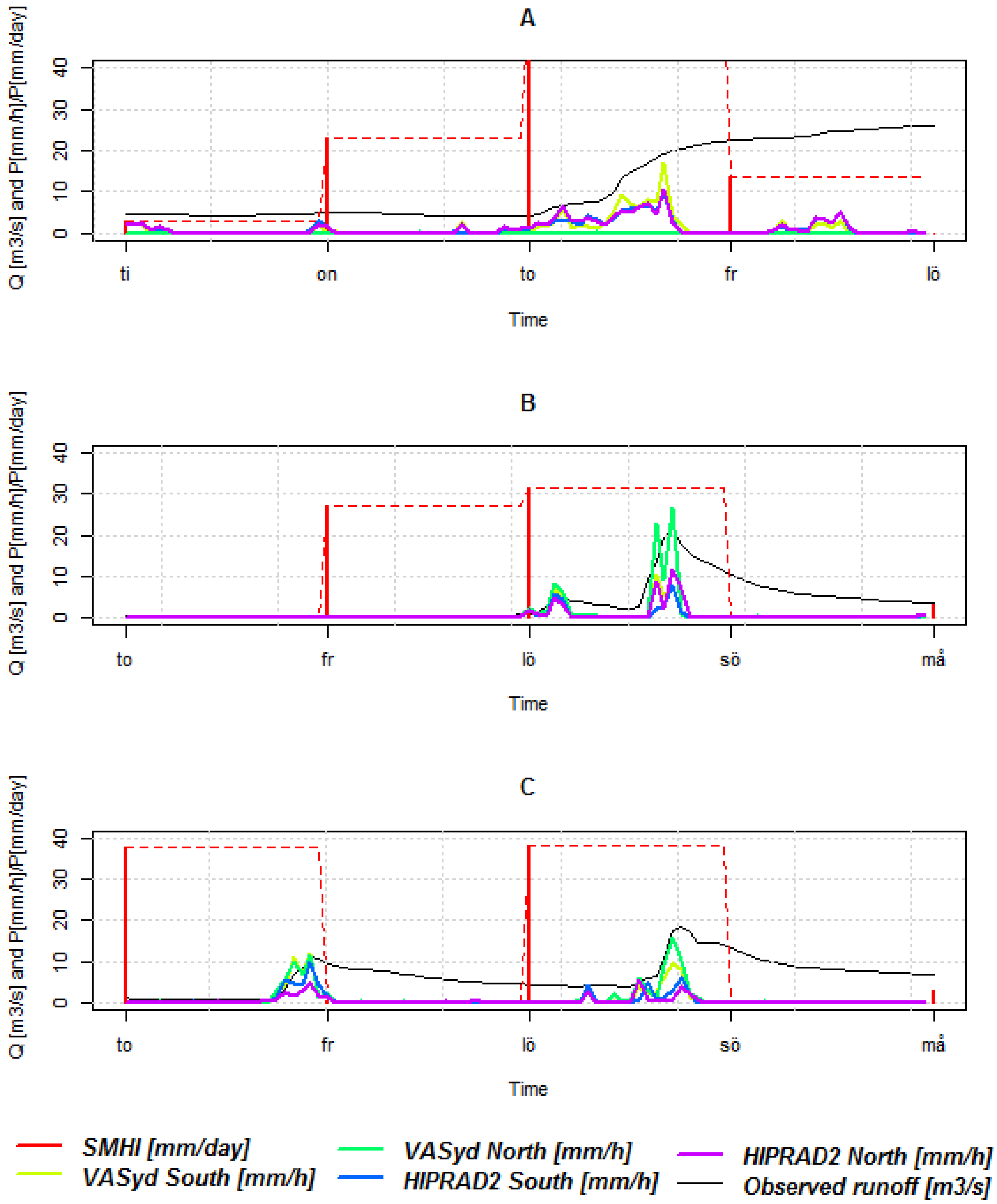

Figure 6.3: Precipitation registered at VA Syd South and North, HIPRAD2 South and North and SMHI gauge for event A-C, (SMHI gauge is measuring only on daily scale)

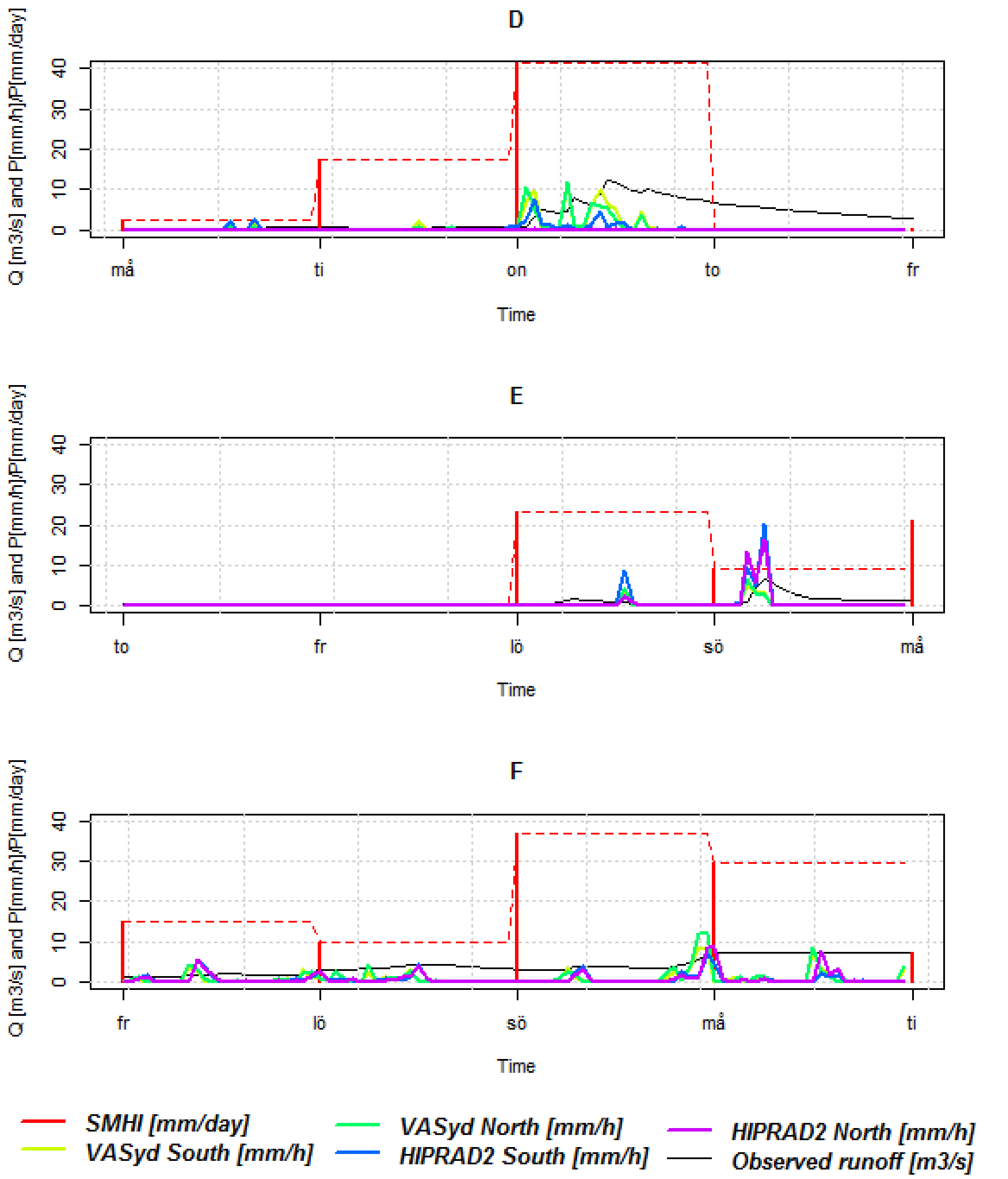

Figure 6.4: Precipitation registered at VA Syd South and North, HIPRAD2 South and North and SMHI gauge for even D-E, (SMHI gauge is measuring only on daily scale)

Annual and monthly precipitation

The annual precipitation 2000-2014 is visible in figure 6.5. HIPRAD data (red and blue) and data from VA Syd gauges (purple and green) are compared to SMHI gauge (orange).

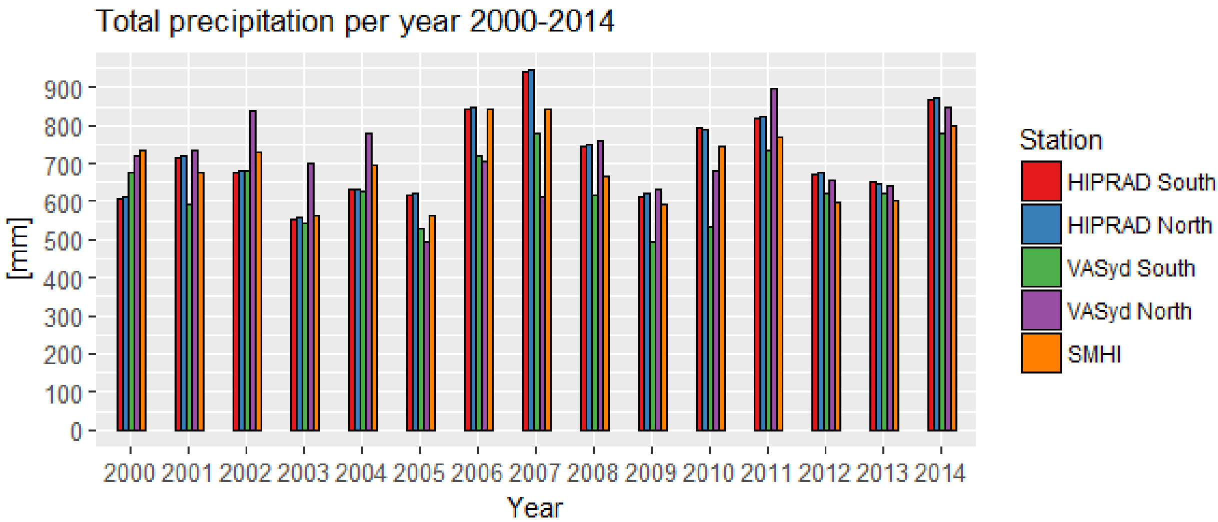

Figure 6.5: Annual precipitation, 2000-2014. Comparison between HIPRAD grid cells (north and south), VA Syd local rain gauges at hourly resolution (north and south) and SMHI rain gauge at daily resolution

Wet hours

Number of registered wet hours per year are compared. Since HIPRAD is based on radar it will register precipitation that is too small for the VA Syd gauges to catch. From April 2012 the tipping bucket at VA Syd is changed to collecting 0.2 ml instead of 0.5 ml as previous period. All hours where rain has been registered in the VA Syd data is counted as wet. For HIPRAD hourly precipitation above 0.5 mm/h is calculated as wet until April 2012 where an intensity of 0.2 mm/h is needed instead (figure 6.6). The result shows a higher frequency of wet hours for the VA Syd gauges than of HIPRAD.

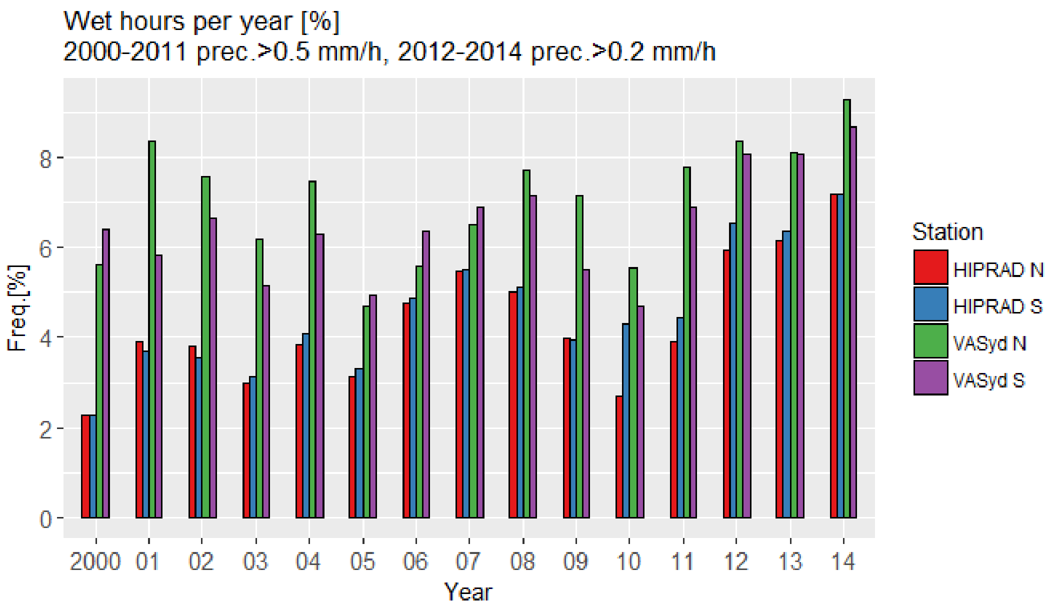

Figure 6.6: Frequency of wet hours per year. Before 2012-01-01 precipitation over 0.5 mm/h is considered a wet hour. After 2012-01-01 precipitation over 0.2 mm/h is considered a wet hour.

The number of wet days per year of the HIPRAD data is calculated in two ways. First; all days that contained a wet hour according to the criteria above are assigned as wet days. Secondly; the total precipitation during the day is aggregated **first** and if this value exceeds the threshold 0.5/0.2 mm/h then that day is assigned as a wet day.

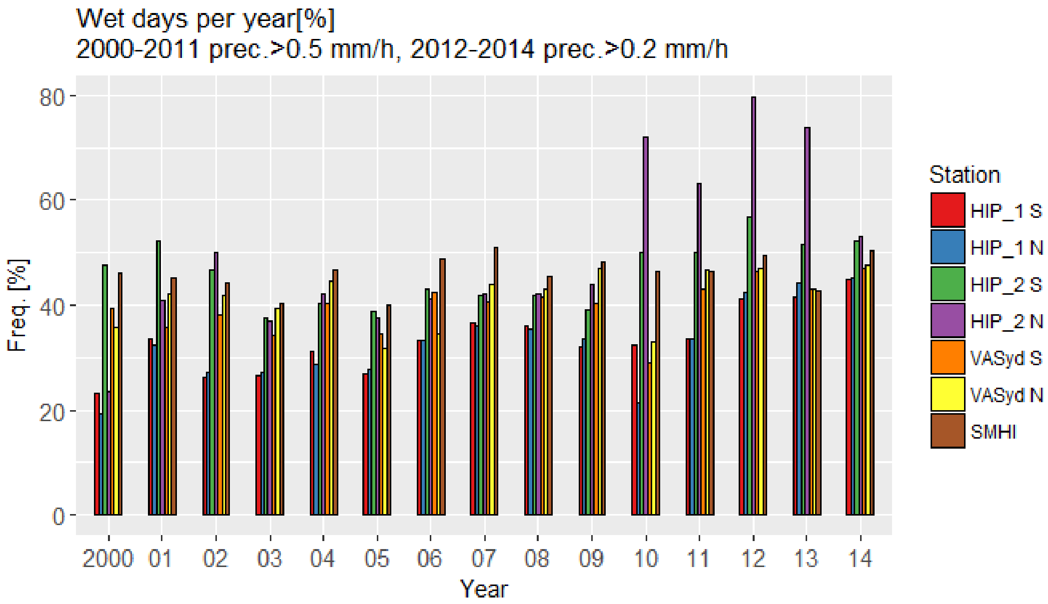

Figure 6.7: Frequency of wet days per year. ADD MORE

Monthly statistics

The monthly mean show clear seasonal changes (Figure 6.8).

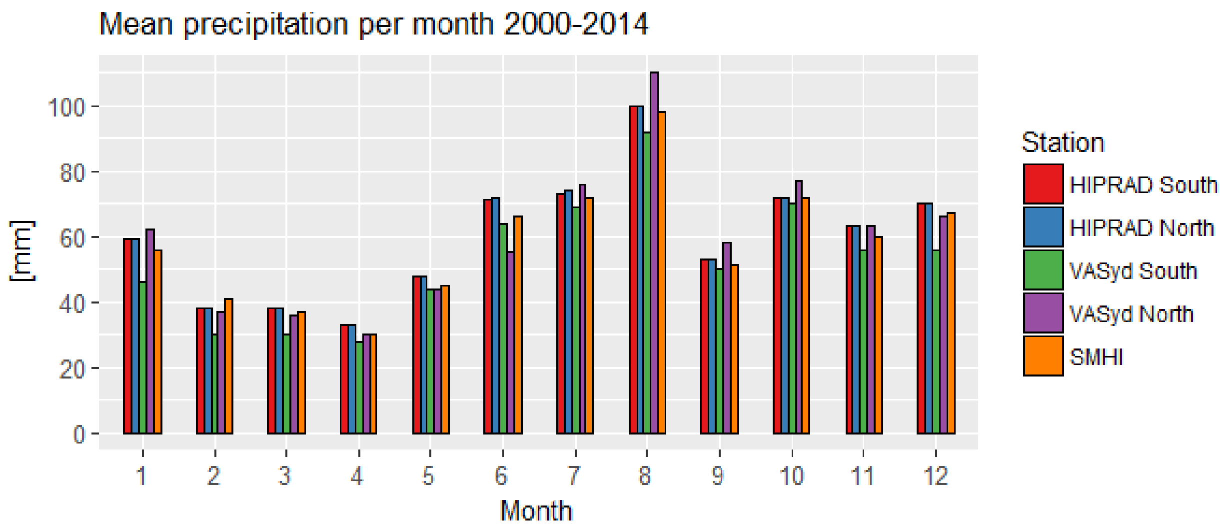

Figure 6.8: Monthly mean precipitation,2000-2014. Comparison between HIPRAD grid cells (north and south), VA Syd local rain gauges at hourly resolution (north and south) and SMHI rain gauge at daily resolution.

Table 6.1: Compilation of the total precipitation, std and max p per hour during June-August. All values are averaged over 2000-2014. The last rows show the maximal value measured for that station and month over the entire period. *Only wet hours where included in calculation of std.

Station	**June**	**July**	**Aug**
	Tot precipitation per month (mm):		
SMHI	45	67	72
VAS N	55	76	110
VAS S	64	69	92
HIP N	72	74	100
HIP S	71	73	100
	Standard deviation 1h (mm):		
VAS N	1.4	2.17	2.19
VAS S	1.66	1.71	2.11
HIP N	1.22	1.14	1.49
HIP S	0.97	0.99	1.39
	Max 1h (mm) (mean):		
VAS N	6	11	13
VAS S	8	8	12
HIP N	10	9	11
HIP S	7	8	12
	Total max 1h 2009-2014 (mm) :		
VAS N	14	28	36
VAS S	22	17	38
HIP N	26	25	24
HIP S	14	16	27

Compilation of the total precipitation, standard deviation and max precipitation per hour during summer June-August for 2000-2014 is seen in Table 6.1. During this period most intense rain are expected due to the increase in temperature.

Correlation 2000-2014

Table 6.2: Correlation between HIPRAD data, VA Syd gauges and SMHI gauge when using all year data 2000-2014

YEAR					
	SMHI	**HIPRAD North**	**HIPRAD South**	**VA Syd North**	**VA SydSouth**
SMHI	1.00	0.83	0.83	0.46	0.81
HIPRAD North	0.83	1.00	1.00	0.26	0.72
HIPRAD South	0.83	1.00	1.00	0.25	0.71
VA Syd North	0.46	0.26	0.25	1.00	0.51
VA SydSouth	0.81	0.72	0.71	0.51	1.00
MONTH					
	SMHI	**HIPRAD North**	**HIPRAD South**	**VA Syd North**	**VA SydSouth**
SMHI	1.00	0.94	0.94	0.86	0.95
HIPRAD North	0.94	1.00	1.00	0.80	0.90
HIPRAD South	0.94	1.00	1.00	0.80	0.90
VA Syd North	0.86	0.80	0.80	1.00	0.86
VA SydSouth	0.95	0.90	0.90	0.86	1.00
DAY					
	SMHI	**HIPRAD North**	**HIPRAD South**	**VA Syd North**	**VA SydSouth**
SMHI	1.00	0.69	0.79	0.80	0.89
HIPRAD North	0.69	1.00	0.82	0.59	0.67
HIPRAD South	0.79	0.82	1.00	0.68	0.76
VA Syd North	0.80	0.59	0.68	1.00	0.86
VA SydSouth	0.89	0.67	0.76	0.86	1.00
HOUR					
	SMHI	**HIPRAD North**	**HIPRAD South**	**VA Syd North**	**VA SydSouth**
SMHI	No data	-	-	-	-
HIPRAD North	-	1.00	0.68	0.36	0.41
HIPRAD South	-	0.68	1.00	0.46	0.52
VA Syd North	-	0.36	0.46	1.00	0.77
VA SydSouth	-	0.41	0.52	0.77	1.00

The correlation between the station for total precipitation year, month, day and hour is compared. The data from the SMHI gauge is only available per day i.e. can not be compared by hour (table 6.2). The result shows that VA Syd North has the worst correlation. At daily and hourly basis VA Syd South correlates better with VA Syd North than with the rest of the stations. However, at monthly and yearly aggregation of the data Va Syd South is better correlated with the other three stations.

Correlation 2012-2014

The VA Syd gauges were updated in 2012 and both rain gauges (VA Syd and SMHI) and the radar (HIPRAD) is expected to have less performance during wintertime. Further tests of correlation at daily and hourly time scale are performed when these possible error sources are excluded. Figure 6.9 and 6.11 show the correlation when the same time steps are compared. Figure 6.10 and 6.12 show the correlation when the data is sorted first.

Correlation at daily time scale

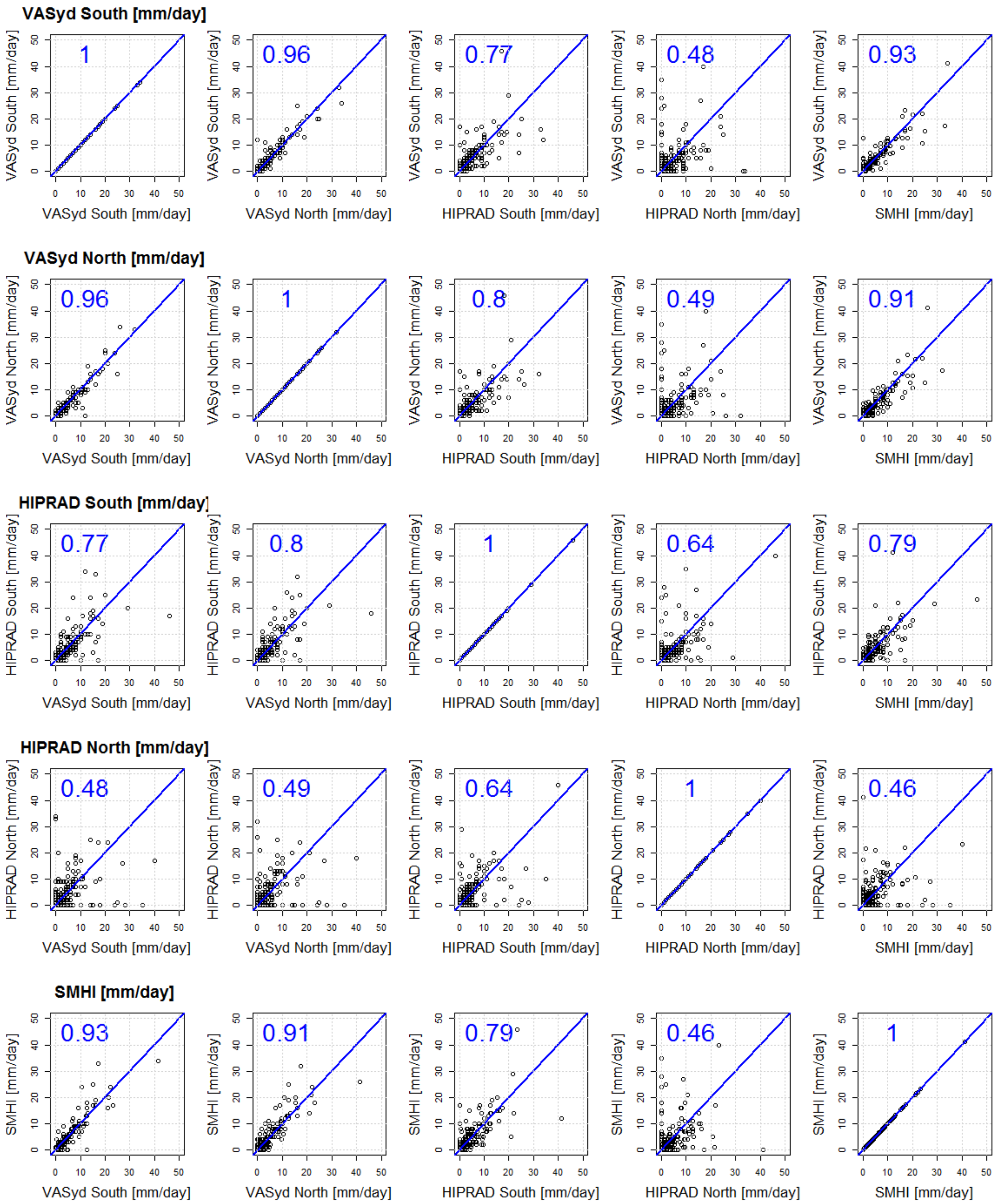

Figure 6.9: Correlation between VA Syd South and North, HIPRAD2 South and North and SMHI gauge at a daily time-scale May-Sep 2012-2014

Correlation at daily time scale, ranked data

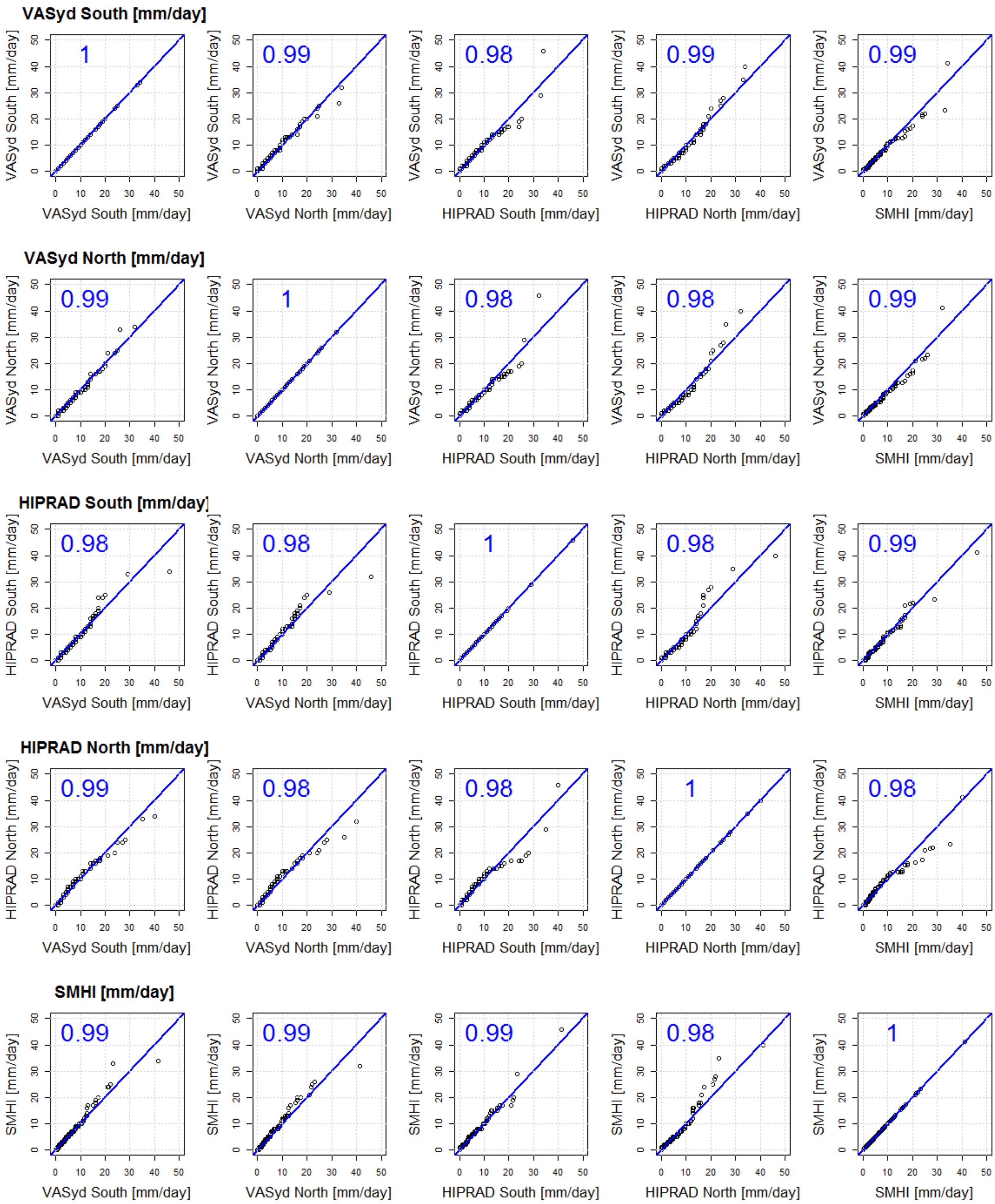

Figure 6.10: Correlation between VA Syd South and North, HIPRAD2 South and North and SMHI gauge at a daily time-scale May-Sep 2012-2014, using ranked data

Correlation at hourly time scale

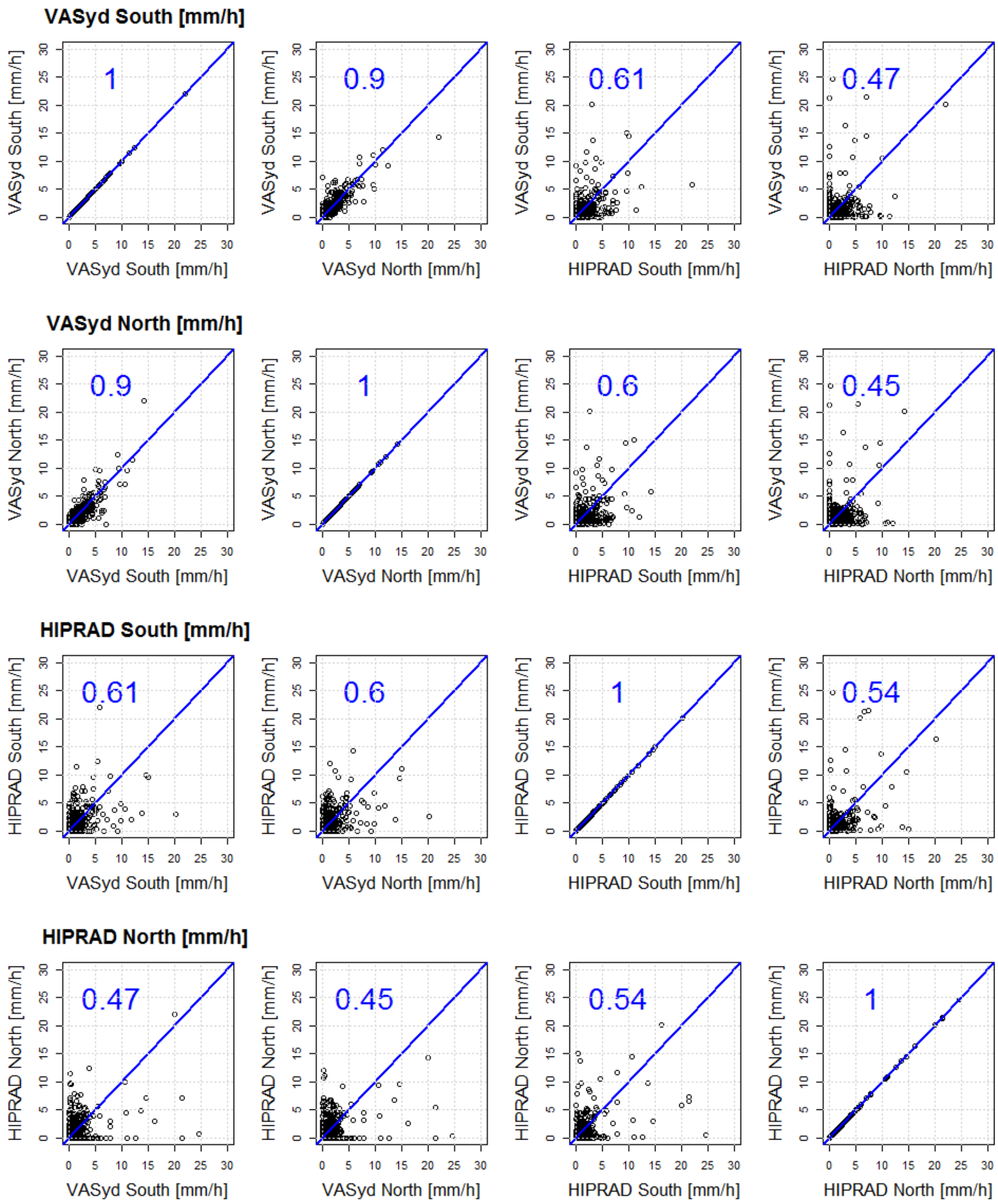

Figure 6.11: Correlation between VA Syd South and North, HIPRAD2 South and North and SMHI gauge at a hourly time-scale May-Sep 2012-2014 (SMHI gauge is only on daily scale)

Correlation at hourly time scale, ranked data

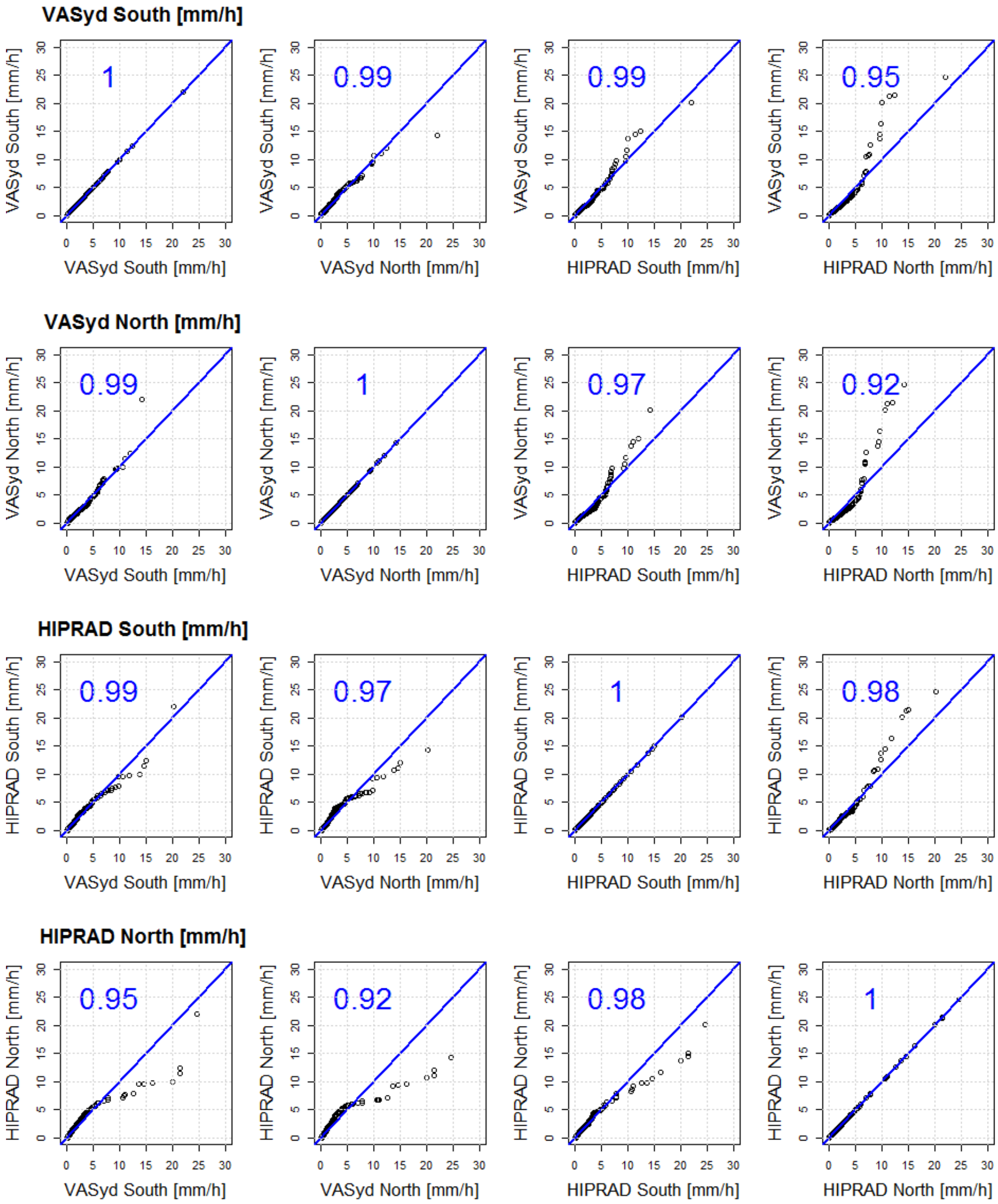

Figure 6.12: Correlation between VA Syd South and North, HIPRAD2 South and North and SMHI gauge at a daily time-scale May-Sep 2012-2014, (SMHI gauge is only on daily scale)

6.2 HYPE at increased resolution in time and updated spatially

6.2.1 Impact of using Urban Atlas instead of Corine

Impact of using land use Grassland(9) and Agricultural land(11) instead of Urban Grass(14) and Urban Agriculture(15)

After comparing the outcome when using land use Grassland(9) and Agricultural land(11) instead of Urban Grass(14) and Urban Agriculture(15), the negligible impact from parameter ttmp this is confirmed and hence, Grassland(9) and Agricultural land(11) is used instead.

Area fraction depending on source

The area fraction of four out of thirteen land use classes and three out of nine soil types change when the land cover data based on Urban Atlas instead of Corine. The changes in land use are Urban (mainly increase), Grassland (increase), Agricultural land (increase) and Semi-urban areas (decrease) (table 6.3 and figure 6.13) The increase of Grassland and Agricultural land origins solemnly from land use Urban Grass(14) and Urban Agriculture(15). The changes in soil type are Fine (mainly decrease), Till (mainly decrease), Urban (mainly increase) which is describe in table 6.4 and figure 6.14.

Table 6.3: Change in areal fraction (%) between using Corine or Urban Atlas as source of land use

SUBID	**64**	**83**	**107**	**112**	**111**	**123**	**127**
Urban(6)	-1.2	-1.8	-0.7	2.4	0.7	10.2	3.8
Grassland(9)	0.0	0.0	0.2	1.9	0.8	6.0	2.4
Agricultural land(11)	0.1	0.1	0.1	2.6	0.7	0.4	0.8
Semi-urban(13)	1.1	1.7	0.4	-6.8	-2.2	-16.6	-7.0

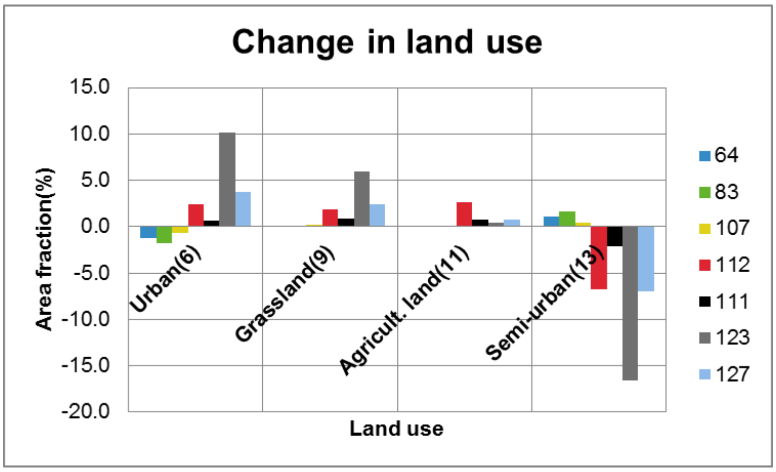

Figure 6.13: Change in areal fraction (%) between using Corine or Urban Atlas as source of land use

Table 6.4: Change in areal fraction (%) between using Corine or Urban Atlas as source of soil type

SUBID	**64**	**83**	**107**	**112**	**111**	**123**	**127**
Fine(2)	0.0	0.1	1.0	2.9	0.6	-8.7	-2.4
Till(4)	1.2	1.7	-0.2	-5.3	-1.3	-1.5	-1.3
Urban(8)	-1.2	-1.8	-0.7	2.4	0.7	10.2	3.8

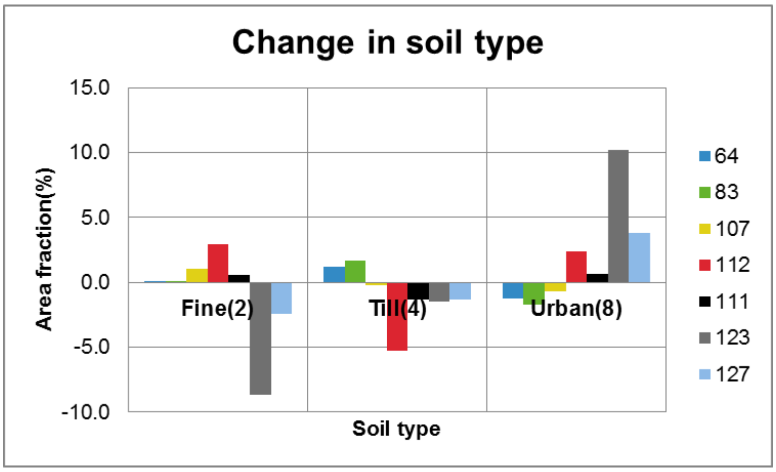

Figure 6.14: Change in areal fraction (%) between using Corine or Urban Atlas as source of soil type

Hydrograph

The models are compared over the period 2009-2014 when both HIPRAD1 and HIPRAD2 data is available. Initially both of the models were only evaluated at HIPRAD2 data. However,*Model Corine* is calibrated on HIPRAD1 so the change in data would decrease its performance. *Model Urban Atlas* is not calibrated so far. To be able to spot the influence of the data and the calibration of the model, both models are run on HIPRAD1 as well. The result is presented in table 6.5 and figure 6.15. The efficiency criteria is at acceptable levels for all models. Worth noticing is that the volume error (RE%) differs a lot depending on if HIPRAD1 or HIPRAD2 is used as forcing data. The best result is gained when HIPRAD1 is used as forcing data.

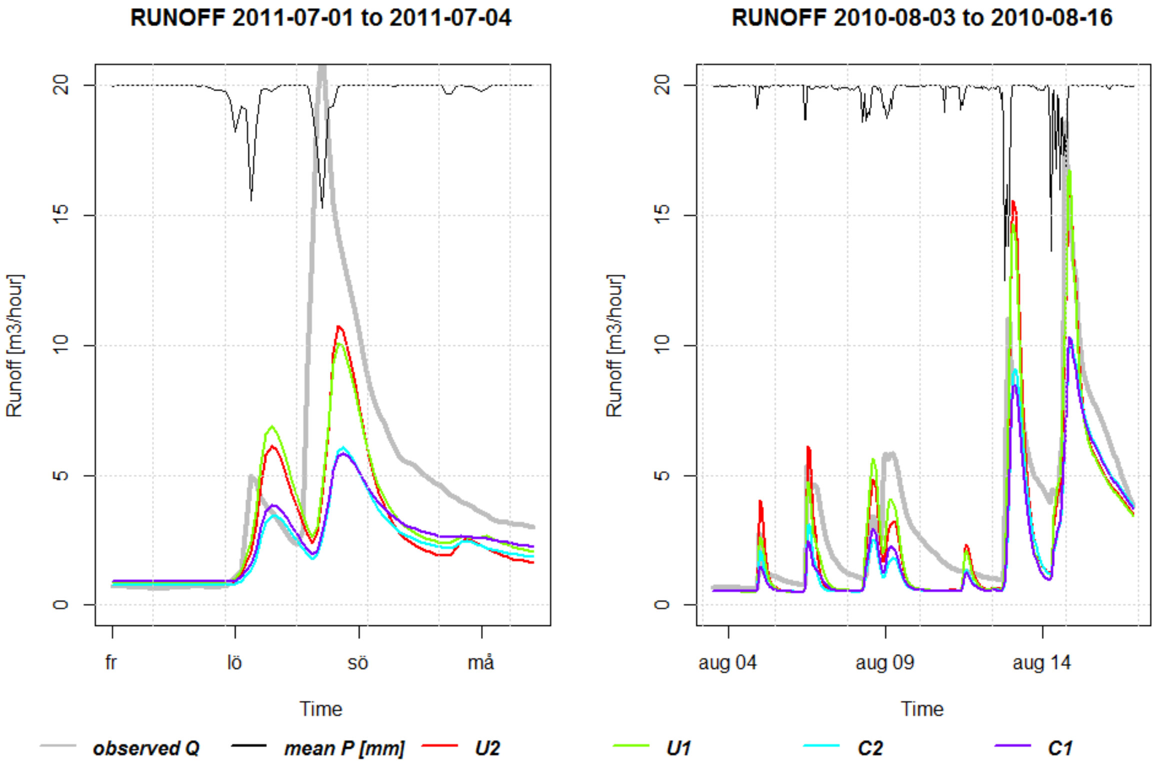

Figure 6.15: Calculated runoff using HIPRAD1 and HIPRAD2 as precepiation data where one model is based on Urban Atlas; U2 = Model Urban Atlas HIPRAD2, U1= Model Urban Atlas HIPRAD1, and one model is based on Corine C2= Model Corine HIPRAD2, C1= Model Corine HIPRAD1

Table 6.5: Efficiency criteria for models at time period 2009-2014

HYPE Model	**NSE**	**RE(%)**
Model Corine HIPRAD1	0.785	-2.10
Model Urban A. HIPRAD1	0.78	0.42
Model Corine HIPRAD2	0.78	-8.02
Model Urban A. HIPRAD2	0.78	-5.165

6.2.2 Calibration

The full result of the calibration is presented in Appendix 9.1. 3 parameters stood out in improving the EC and hydrograph of the model: rivvel, damp and srrcs (for description see table 5.4). These three where closer examined to find the best result (Table 6.6).

Table 6.6: Result from calibrations. The best result is marked in green

			NSE	RE(%)
DAMP	**m0**	0.5	0.814	-2.704
	m1	0.55	0.814	-2.705
	m2	0.6	0.815	-2.706
	m3	0.65	0.816	-2.707
	m4	0.7	0.816	-2.708
A	**m5**	0.75	0.817	-2.709
	m6	0.8	0.817	-2.71
	m7	0.85	0.817	-2.712
	m8	0.9	0.817	-2.712
	m9	0.95	0.818	-2.714
srrcs(4)	**m0**	0.00625	0.814	-2.704
	m1	0.0125	0.82	-2.5
	m2	0.01875	0.822	-2.396
	m3	0.025	0.823	-2.328
	m4	0.03125	0.823	-2.279
B	**m5**	0.0375	0.823	-2.239
	m6	0.04375	0.822	-2.207
	m7	0.05	0.822	-2.179
	m8	0.05625	0.822	-2.179
	m9	0.0625	0.821	-2.133
rivvel	**m0**	1	0.814	-2.704
	m1	0.95	0.815	-2.706
	m2	0.9	0.815	-2.708
	m3	0.85	0.816	-2.71
	m4	0.8	0.817	-2.713
C	**m5**	0.75	0.818	-2.715
	m6	0.7	0.818	-2.719
	m7	0.65	0.819	-2.722
	m8	0.6	0.819	-2.722
	m9	0.55	0.818	-2.731
combo	**m0**	AB	0.826	-2.284
	m1	AC	0.819	-2.722
	m2	BC	0.827	-2.291
	m3	ABC	0.829	-2.259
Validation	**2012-14**	ABC	0.841	-9.305

The calibrations resulted in two different recommendations of update in the par-file (table 6.7). The model called "1h-HYPE Calibrated 1" suggest for change in all of the parameters. To only the srrcs class according to the is also an alternative. This is referred to as model "1h-HYPE Calibration 2".

Table 6.7: Recommended updates after calibration

Model	Par	Original	Change
1h-HYPE Calibrated1	**damp**	0.5	0.75
	srrcs(4)	0.00625	0.0375
	rivvel	1	0.75
1h-HYPE Calibrated2	**srrcs(4)**	0.00625	0.0375

6.2.3 Model performance

Model 1h-HYPE Calibrated1 and 1h-HYPE Calibrated2 using HIPRAD2 as forcing data, are compared to the daily HYPE model using aggregated HIPRAD2 data (called "1day-HYPE aggregated"), as well as the calculated runoff from the S-HYPE model downloaded from VATTENWEB (called "1day-HYPE VATTENWEB"). Two models are used at the daily time step in order to limit the risk of oversee influence from either data or calibration of model.

The efficiency criteria of the models are represented in Table 6.8. The 1day-HYPE model performs well but notice that the calculated runoff is also compared to observed runoff at daily time step.

Table 6.8: Efficiency criteria at the two calibrated model as well as the daily HYPE model, 2006-2014

HYPE Model	NSE	RE(%)
1h-HYPE Calibrated 1	0.83	-3.7
1h-HYPE Calibrated 2	0.83	-3.7
1day- HYPE aggregated	0.80*	-17.9*

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

The models are plotted for the event A-F (Figure 6.16 and 6.17). The precipitation at the events are also included. The precipitation is plotted both as total mean over catchment as well as the precipitation for subcatchment 123 and 127 separately. These are the urban areas which are included to show if the location of the rain impacts the runoff.

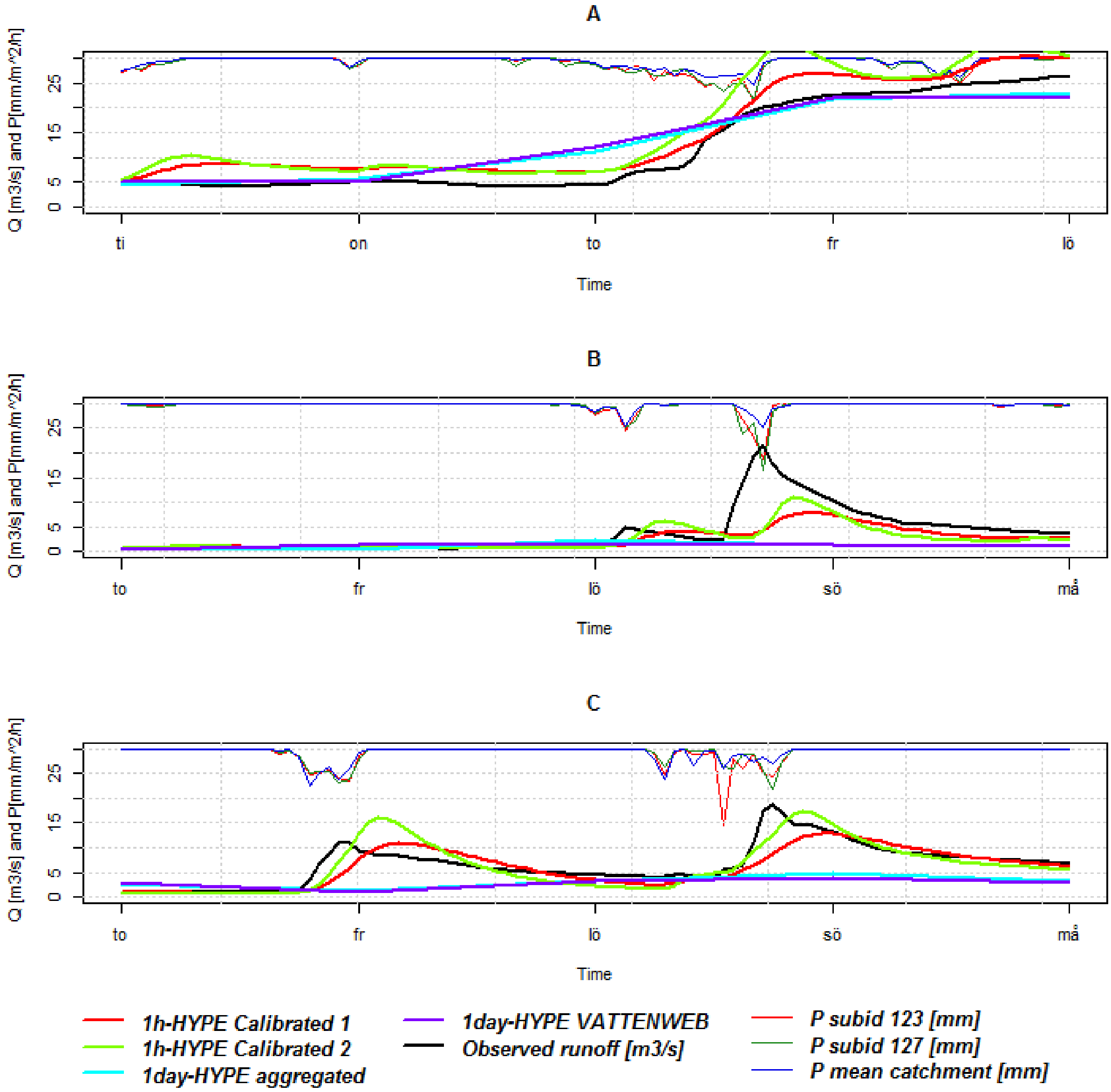

Figure 6.16: Comparison of the 4 models for event A, B and C

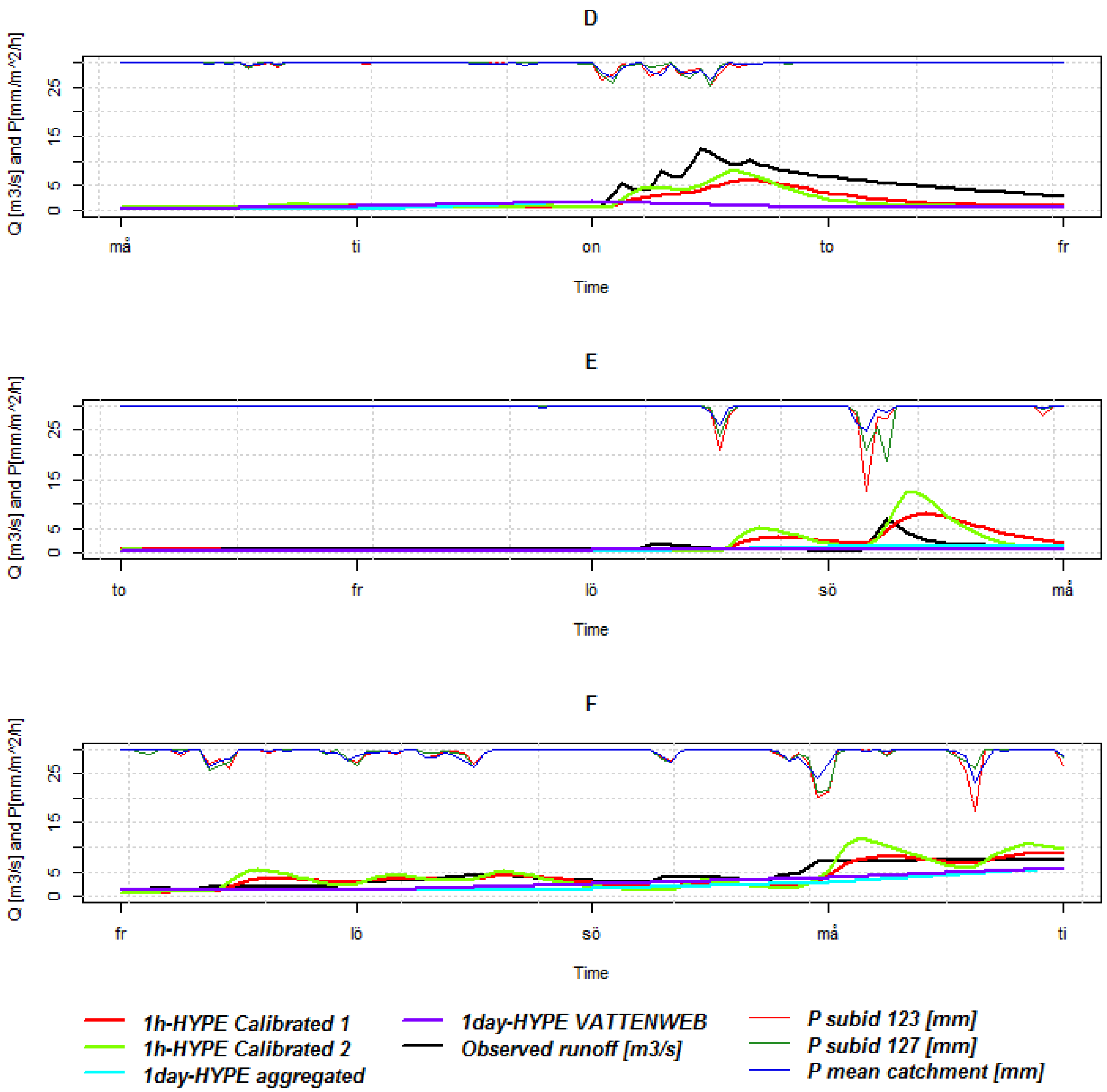

Figure 6.17: Comparison of the 4 models for event D, E and F

6.3 Evaluation of 1h HYPE for forecasting usage

The calculated runoff from the forecasted event at 2016-11-04 is compared with observed runoff in Figure (fig. 6.18). 1 day prior the rain event all members show an increase in flow. 12 hours prior the event the members are not as correlated hence the forecast is not clear.

The initial stage of the modeled runoff is too high in comparison to the observed runoff. This is due to the precipitation data used to initiate the model. Figure 6.19 show the model runoff for the event if only the HIPRAD1 data that was produced for the occasion is used. The runoff from the model is highly exaggerated. The examination of the data by comparing to the SMHI gauge in the area concluded that the data was probably not correct. 6.20.

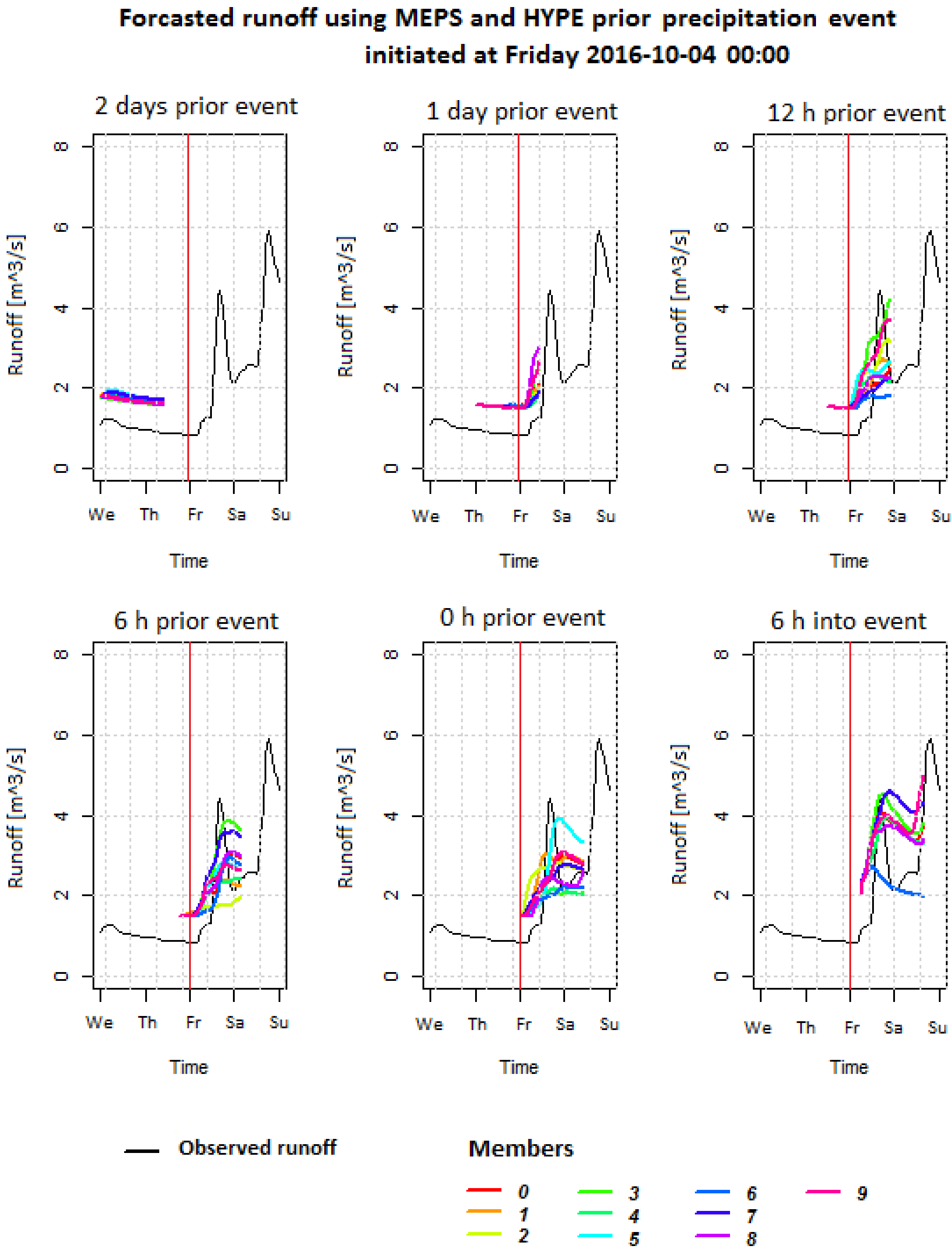

Figure 6.18: Forecasted event in 4th of November 2016. The precipitation event continued from 00:00 to 18:00. The vertical red line represent the start of the rainfall.

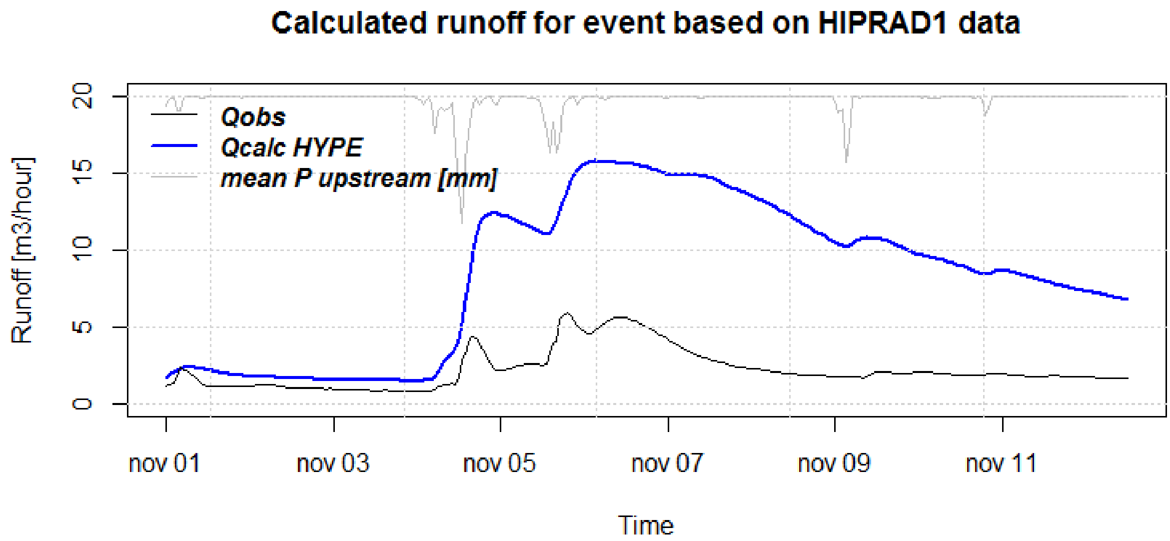

Figure 6.19: Plot the runoff from the HIPRAD original model

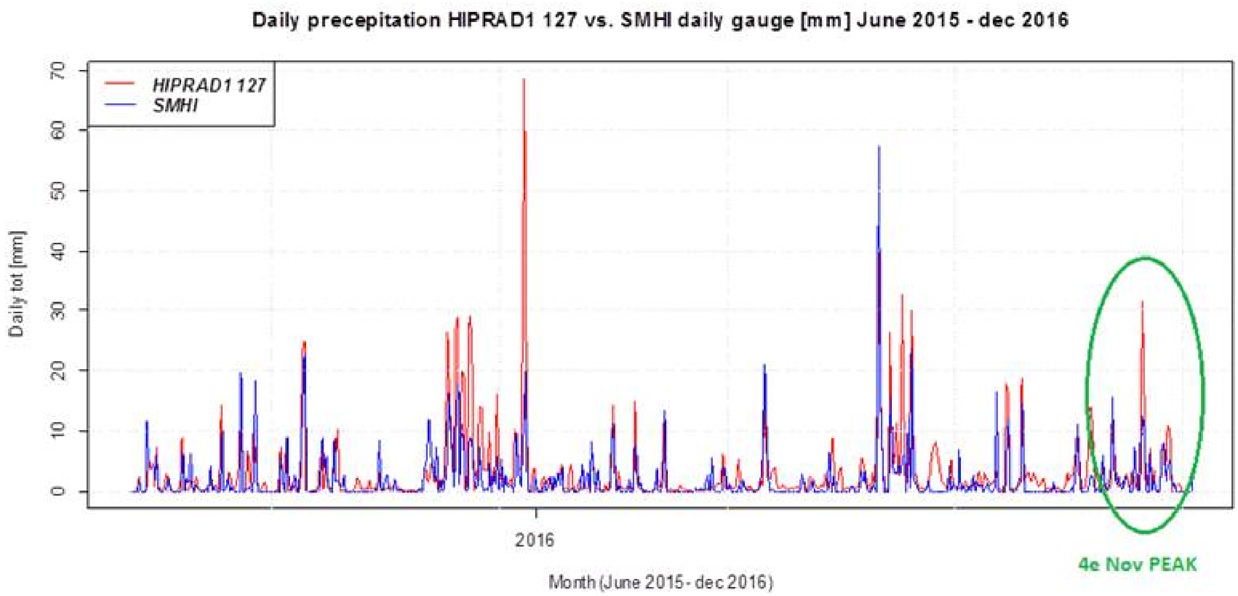

Figure 6.20: Plot illustrating that the data from HIPRAD is probably off.

7 Discussion

7.1 Evaluation of HIPRAD precipitation data for Höje å catchment

7.1.1 HIPRAD1 vs. HIPRAD2

HIPRAD1 and HIPRAD2 correlate well with an hourly correlation of 0.98 (Figure 6.2). A value of 1 correspond to a perfect linear correlation. This was a bit surprising because of the difference in interpolation (see chapter 3.4.3), but also since the efficiency criteria for HYPE differed a lot when the forcing data was changed between HIPRAD1 and HIPRAD2 (6.5). The efficiency criteria improved when the model was forced with HIPRAD1 data. The initial model used (based on Corine) was however also calibrated to HIPRAD1 data which could explain the increased performance. In that case, it indicates that the model is well calibrated to the data.

7.1.2 HIPRAD vs. VA Syd and SMHI rain gauges

HIPRAD data is compared to two VA Syd rain gauges at hourly resolution and one rain gauge from SMHI at daily resolution. HIPRAD is based on gridded radar data which means grid cells are compared to point source values.

The information stored at each grid cell represent the mean value over the cell area, hence it is important to not have grid cells whose size are exceeding the information that they are to represent. This strengthens the idea of using a high spatial resolution, as smaller grid cells will keep more information about the variations in the event. However, an increased grid size also need more memory and will slow down the execution of the model. When using the HYPE model in EWS for forecasting of runoff, as what is the aim of this study, short run-time of the model is an advantage.

The type of the rainfall matters, a precipitation front is usually homogeneous in the intensity and the value of the grid cell will usually represent the intensity of the rainfall. In a thunderstorm, however, the center of the storm is more intense and the areal spread is usually smaller. Hence, the intensity of the storm is underestimated when averaging it over the grid cell (SMHI, 2011).

The plots of precipitation for event A-F, Figure 6.3 and 6.4 indicates that the rain gauges have higher peaks than the HIPRAD data. This is could be a result from HIPRAD being grid cell data and VA Syd gauges are point-source.

The plot of the SMHI-daily precipitation data shows how much information is lost when a daily time-step is used.

Total precipitation:

The plot of the total annual precipitation (fig. 6.5) shows great similarities between the two HIPRAD grid cells. This could depend on the way in which the data is interpolated. During the production of the HIPRAD-grid the data from the radar stations are interpolated to a PTHBV-grid, both in intensity by a monthly value, and arealy since PTHBV uses a larger grid (4x4 km^2). It is possible that these two stations are interpolated on the same grid cell in the 4x4 grid. The PTHBV grid that HIPRAD is interpolated to include a correction for measuring losses. This might be the reason why the average annual precipitation is higher in the HIPRAD stations than in the gauging station.

The SMHI gauge is used for comparison and a higher correlation to the north VA Syd rain gauge was expected as they are closely situated. After 2012 the correlation between the stations are increased. This could be related to the increase in resolution of the VA Syd gauges in 2012.

In 2007 the catchmnet of Höje å was flooded. HIPRAD North and South as well as SMHI precipitation gage measures highest annual precipitation this year. VA Syd North and South show highest values after 2012, this could also indicate how the increased resolution of the tipping bucket improves the catch.

Wet hours and days per year:

The numbers of wet hours is difficult to compare since HIPRAD and the VA Syd data are gathered differently. What is classified as an wet hour will differ between the station (see 5.2.2). It is reasonable that the HIPRAD data show lower frequency of wet hours than VA Syd (Figure 6.6), since the VA Syd gauges collect precipitation in bucket during several hours and then result in a tick. For HIPRAD only a rain amount of more than 0.5 (or 0.2 after 2012) within *the same hour* will count as wet.

An interesting observation is the frequent rain events in the Höje å catchment area. Almost 50% of the days are wet. The number of wet hours are totally dependent on what limit is chosen as wet hour in the classification. When calculating wet days per year (Figure 6.7) an additional technique is used to categorize a wet hour. If the accumulated data over the day was above the limit (0.5/0.2 mm), the day was registered as wet. When this technique is used (see HIP_2S and HIP_2N in Figure 6.7) the frequency of the HIPRAD data correspond better to the VA Syd and SMHI rain gauges.

Monthly statistics:

The statistics over June-August is compiled in Table table:summerafacts. August is the wettest month seen over the entire year 6.8 and consequently also in compare to June and July.

The standard deviation represent the natural variation within the data. The standard deviation is generally higher in the VA Syd gauges, than for HIPRAD. This is expected because of the difference between grid cell(HIPRAD) and point sources (VA Syd). HIPRAD data represent the mean value over the grid cell where point-source values represent measurement in a much smaller area and hence should show an increased variation.

The max values at a monthly mean correspond well between the stations. Following the reasoning above the HIPRAD data is performing better than what is expected since it seem to be at the same levels as VA Syd. Usually HIPRAD is assumed to underestimate the peaks.

Correlation 2000-2014:

VA Syd North has the lowest correlation, especially the correlation over annual data is bad. This is unexpected since it seem to be situated right next to the SMHI gauge.

The data from VA Syd South matches VA Syd North at hourly and daily aggregation, but not for month and year.

It is interesting to see that the monthly correlation is a lot better than the yearly. This could be because of the seasons - the data show clear seasonal changes (Figure 6.8), it could be that the seasonal changes overrides possible internal differences between the data sets.

Correlation 2012-2014:

Since the VA Syd rain gauges where upgraded in 2012 the correlation after this year was examined closer. In this examination also only the summer month are included. The correlation at daily timescale 6.9, 6.10 is better than the correlation at hourly scale 6.11, 6.12. This is expected as the exact time of the event can be difficult to describe with radar, which HIPRAD is based on, since it measures over an area.

Comparing the correlation of the ranked data, HIPRAD shows the same statistical distribution as the local gauges from VA Syd and SMHI. This is an encouraging result. The SMHI gauge is used in the production of the PTHBV-grid that HIPRAD is correlated to, but the VA Syd gauges are bias free to HIPRAD. The ranked data also show how HIPRAD North (but also HIPRAD South) has a tendency to underestimate the highest intensities compared to VA Syd.

HIPRAD North show poorer correlation than HIPRAD South. In compare to correlation over the longer time period 2000-2014, Table table:corrTabel, the performance of HIPRAD North measurement's has decreased.

7.2 HYPE at increased resolution in time and updated spatially

7.2.1 Impact of using Urban Atlas instead of Corine

The impact of assigning Grassland(9) and Agricultural land(11) instead of Urban Grass(14) and Urban Agriculture(15) was negligible as expected. This is at the current state of Urban Grass(14) and Urban Agriculture(15). However, if the HYPE model is to be developed further for use in urban areas it might be wise to investigate if there are any main differences between permeable areas within urban areas. If so, an update of the characteristics for Urban Grass(14) and Urban Agriculture(15) included in the national model could be of interest

The land use fraction of Semi-Urban areas decreased in the subcatchments which initially contained the most (Figure 6.13). This was subcatchment 111, 112, 123 and 127. Initially towns within the catchment are mainly categorized as semi-urban but when Urban Atlas is used, it is possible to make a finer and more precise subdivision. As a result there is an increase of urban areas within the catchment.

The amount of urban areas have a large impact on the runoff. The parameters in HYPE describing semi-urban and urban areas differ in impermeability why an increase from semi-urban to urban have a large impact on the hydrograph (6.15).

All increase of Grassland(9) and Agricultural land(11) was initially categorized as Urban Grass(14) and Urban Agriculture(15). Further investigation is needed to tell the difference between such permeable surfaces in rural vs. urban areas, as described above. It is likely to assume that the infiltration could be limited in urban areas even if the land is permeable because it is "fractionated" between the impermeable urban areas and does not exist of large coherent surfaces.

The fraction of urban soil type in subcatchment 123 increased with 10% when Urban Atlas was used instead of Corine 6.14. Overall in the catchment there was an increase of urban soil. This areas were originally categorized as till or fine soil which could be explained by these being the dominating soil types within the area .

The increased peak of the calculated runoff when the amount of urban area increase can be seen in figure 6.15. This was expected since the amount of impermeable areas grow larger which will speed up the runoff.

Table 6.5 shows the correlation between the model when using two different data set as forcing data, HIPRAD1 and HIPRAD2, as well as the two different sources of runoff Urban Atlas and Corine. It is interesting to see that the change in forcing data has a larger impact on the efficiency criteria than the additional urban areas that are included when Urban Atlas is used as source of data. However, when comparing the hydrograph it looks like there is a greater difference between the Corine and the Urban Atlas model. There is an inherent difficulty in separating model, data and calibration. The model used is originally calibrated for HIPRAD1 this is one reason for result being in favour for HIPRAD1.

7.2.2 Calibration

The time period which is used for the calibrations will impact the efficiency criteria. If a extraordinary event occurs within the time period (as the large event of 2007), and this event is long enough, how the model handles this event will have great impact to the result. When the same model is run on a time series where the extraordinary event is not included or does not represent such a large part of the data, earlier benefits might e lost. This is one reason why it is important to have long data series for calibration of a model.

7.2.3 Model performance

Two difference changes are proposed as the calibrated 1h model - Model 1h-HYPE Calibrated1 and 1h-HYPE Calibrated2. Interestingly enough they have the exact same efficiency criteria 6.8 when compared over the period 2006-2014. For the calibrated period 2006-2011, Model 1h-HYPE Calibrated1 had slightly better efficiency criteria (it is called *combo -m3* in Table 6.6 in comparison to *srrcs(4) - m5* which is 1h-HYPE Calibrated2. This, again, show the influence of time period used for the calibration as mentioned above.

The event in 2007 was used as the main event to evaluate the result from the calibrations visually. This is unfortunate because 2007 is not a typical urban flash-flood, but rather it has been raining for several days when it occurs.

In Figure 6.16 and 6.16 the runoff from rain event A-F is modelled. 1h-HYPE Calibrated2 catches the extreme values better (B, C and D) but overestimate also overestimates a lot of the peaks (A, E and F). 1h-HYPE Calibrated1 on the other hand is more moderate but in the same time it misses a lot of the high peaks. This is a common problem when wanting the model to catch extreme events.

In comparison to the 1-day models, the advantages of using a 1h time step is evident. Only events A and F are captured within these daily models, the other events are overlooked when a daily time-step is used. The 1-day HYPE aggregated model correlates well with the 1-day HYPE VATTENWEB mode. This shows that the result is not being affected by the data or calibration of the 1-day models.

It is difficult to tell if increased precipitation in the "urban" subcatchments 123 and 127 impact the hydrograph differently. Event B has an large peak as well as more rain in these catchments, than what is average in the entire catchment. However, event E looks very similar in terms of precipitation but does not result in a great peak in observed runoff. The calculated runoff is very similar to the calculated runoff in event B.

7.3 Evaluation of 1h HYPE for forecasting usage

The forecast show good dynamics and there are great possibilities to use HYPE as a national forecast for pluvial rainfall. The initial data was poor which affected the forecast.

The dynamics of the forecasted event in 2016-11-04 correlate well in comparison with observed runoff (fig. 6.18). Already one day prior the rain event all members show an increase in flow. 12 hours prior the event, the members are not as correlated, hence, the forecast is not clear. At the beginning of the event the peak is underestimated by most members. Six hours into the event the members correlate well and forecast an increased peak. This was a long event lasting for over 18 hours.

The initial stage of the modeled runoff is however too high in comparison to the observed runoff. This is due to the precipitation data used to initiate the model. Figure 6.19 show the event if only the HIPRAD1 data is used to model the runoff. The calculated runoff is highly exaggerated.

The examination of the data by comparing to the SMHI gauge in the area concluded that the intensity of the precipitation was probably exaggerated within the entire time-period of new data, 2015-2016 6.20. The precipitation data used origins from HIPRAD1 but run on a new period. The error in data is probably because of that the new period (2015-2016) was not included in the period that the equation of the interpolation to PTHBV grid was built for. If HIPRAD generally underestimate higher intensities during 2009-2014, it is likely that this method will adopt the same behaviour later as well. If the radar errors has been modified, e.g. due to upgrades of individual radar, or changes in the composite, it will result in an overestimation of higher intensities in the latter period. There are currently many such modifications because both software and hardware are currently being replaced, starting in southern Sweden.

8 Conclusions

- HIPRAD1 and HIPRAD2 correspond well. However, the HYPE model perform better when HIPRAD1 is used as forcing data. This could be owing to that the model is calibrated to HIPRAD1.
- HIPRAD in comparison to the local gauges from VA Syd and SMHI show good performance. The overall variance of the data is in level with both the VA Syd and SMHI gauges. The correlation to point-source value is affected by HIPRAD being gridded data. Especially HIPRAD North but also South has a tendency to underestimate the highest intensities compared to VA Syd.
- Land use classes Grassland(9) and Agricultural land(11) are similar to Urban-Grass(14) and Urban Agriculture(15). Further updates of HYPE could include an updated version of UrbanGrass(14) and Urban Agriculture(15) to be able to better model urban areas.
- When changing from Corine to Urban Atlas, the number of urban areas increased and the semi-urban areas decreased. The amount of urban soil type increased as well.
- An increase of urban areas within the model lead to an increase of the peaks in calculated runoff.
- An increase in time-step in forcing data as well as in the model, allows for catching variations on a shorter time basis. This is important when modeling pluvial floods. Pluvial floods are too short to be modelled on a daily time step, but can have devastating consequences for an area.
- The result from the forecasting was promising and the dynamics of the runoff was clearly visible in the forecast.

This study is a part of a larger project at SMHI on developing a national warning system to forecast flooding at hourly resolution. By increasing the resolution in time, it is possible to capture also pluvial floods. 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.

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9 Appendix

Table 9.1: Summary of calibration

	Change	**Original value**	**New value**	**Result NSE**	**RE(%)**	**Bias**	**KGE**
0	**INITIAL MODEL**			0.851	-0.918	-0.024	0.856
1	**damp doubled**	0.5	1	0.858	-0.919	-0.024	0.851
2	**rrsc1 för (2) increased x10**	0.025	0.25	0.702	-0.629	-0.016	0.852
3	**rrsc1för (4) increased x10**	0.00625	0.0625	0.856	-0.314	-0.008	0.922
4	**rrsc1 för (4) decresed x10**		0.000625	0.834	-1.8	-0.046	0.797
5	**rrsc1 för (2) decreased x10**		0.0025	0.742	-1.405	-0.036	0.747
6	**(2) wsfc increased (all layers)**	0.15	0.3	0.84	-3.916	-0.1	0.833
7	**(2) wsfc decreased (all layers)**		0.05	0.824	3.537	0.091	0.873
8	**(4) wsfc increased (all layers)**	(0.3, 0.2, 0.2)	0.6	0.847	-3.506	-0.09	0.841
9	**(4) wsfc decreased (all layers)**		0.1	0.849	1.845	0.047	0.865
10	**(2) wsep increased (all layers)**	0.01	0.1	0.805	0.027	0.001	0.775
11	**(2) wsep decreased (all layers)**		0.005	0.852	-1.098	-0.028	0.864
12	**(4) wsep increased (all layers)**	(0.05, 0.05, 0.03)	0.1	0.844	-0.716	-0.018	0.813
13	**(4) wsep decreased (all layers)**		0.01	0.854	-1.009	-0.026	0.88
14	**rivvel halved**	1	0.5	0.859	-0.92	-0.024	0.845
15	**rivvel doubled**		2				
16	**srrsc (6)=1**	0.04167	1	0.844	-0.848	-0.022	0.856
17	**srrsc (11) doubled**	0.004167	0.008167	0.853	-0.913	-0.023	0.862