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Workshop Objectives and Proceedings

Extreme weather, and especially heavy rain, has a major impact on urban populations and landscapes. Urban flooding and the damage to infrastructure and society are problems in both developing and developed countries. Some key challenges in urbanized areas are to provide good quality detailed weather forecasts, to accurately measure high resolution space-time precipitation fields, to be able to predict impacts on urban drainage systems and their vulnerability, evaluate flood risk and potential practical counter-measures. Similar challenges apply to the effects of rainfall in natural landscapes, the triggering of floods, landslides, debris flows, and other natural hazards. Climate change provides a critical uncertainty to deal with when analyzing potential impacts of heavy rainfall in the future. All of these require the attention of a wider community of scientists, research managers, consultants and practitioners working in urban rainfall.

Following the tradition of previous UrbanRain workshops (1989, 1990, 1994, 1997, 2000, 2003, 2006, 2009 and 2012)\(^1\) the main objective of this meeting was to provide a focussed forum for exchanging ideas, experiences, and state-of-the-science in order to bridge the gap between novel research topics and critical issues that need to be addressed in practice. UrbanRain15 took place on 1-5 December 2015 in Pontresina, Switzerland.

This Proceeding collects the abstract or short papers of all 85 papers presented at the UrbanRain15 workshop. The abstracts/short papers cover the four key themes of the workshop: (1) Precipitation measurement, modelling and statistics; (2) Radar rainfall and precipitation forecasting; (3) Rainfall impacts in urban and natural systems; and (4) Climate change. They are organized in the Proceedings in alphabetical order by first author. The abstracts/short papers were not peer-reviewed or language edited. Each abstract/short paper is identified by a unique ID number and the Proceedings are available through the ETH Zurich E-Collection electronic open-access document repository. Further information about the UrbanRain workshops can be found on [http://www.ifu.ethz.ch/urbanrain](http://www.ifu.ethz.ch/urbanrain).

Peter Molnar, Nadav Peleg
ETH Zurich

(Editors)

Example of paper citation:


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Climate change impacts assessment on severe flood event in Kelantan River Basin

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Abstract

Continuous heavy monsoonal rainfall from 14th to 25th December 2014 over the east coast of Peninsular Malaysia had caused widespread floods especially in the state of Kelantan. The Kelantan river basin has an area of around 12,000km², however the flood peak was estimated about 30,000m³/s. Thirteen (13) deaths were reported and around 340,000 flood victims were evacuated with an estimated total loss about MYR1.7billion (DID, 2015). In general the state of Kelantan always experience annual floods during monsoon seasons, however this 2014 flood event is considered as the worst flood in the history of the state. Climate change is said to be one of the factors that contribute to the high rainfall magnitude and the extreme flood event. Thus this study is conducted to determine and quantify the contribution of climate change to the said flood event.

A comprehensive study has been conducted to assess the impact of climate change on the hydrologic conditions of Peninsular Malaysia (NAHRIM, 2014). Fifteen (15) climate projections for the 21st century by three (3) different coupled land-atmosphere-ocean Global Climate Models (ECHAM5 of the Max Planck Institute of Meteorology of Germany, CCSM3 of the National Center for Atmospheric Research (NCAR) of the United States, and MRI-CGCM2.3.2 of the Meteorological Research Institute of Japan) under four (4) different greenhouse gas emission scenarios (B1, A1B, A2, A1FI) were dynamically downscaled. The downscaled rainfall projections, amongst others, were ensemble averaged, and were compared against the corresponding historical simulation data for the 1970-2000 for the impact assessment. As a result, future frequency curves for 24, 48 and 72-hour accumulated rainfall over the Kelantan river basin were developed, as shown in Figure 1. The findings indicate that rainfall magnitude will increase under climate change for all durations and return periods, especially during the end of 21st century. However, decreases of rainfall extremes are projected during mid-century (2040-2070) for 50 and 100-year return periods, compared to the period of 2010-2040. Subsequently a regional rainfall analysis on the observed rainfall of the 2014 flood was conducted and compared with the future frequency curves. The 3-day maximum rainfall of the storm event of 499.6mm (22nd-24th December 2014) was analysed as 69-year return period, which is very close with the projected return period from the 2010-2040 curve. The whole storm event was estimated to be 180-year return period. Preliminary analysis has been conducted for 100-year return period that estimated an increase of rainfall about 36% in the future (NAHRIM, 2013), while the magnitude of the 2014 rainfall extreme will be further analysed.

In term of spatial distribution, from the isohyet map in Figure 2a, the storm is identified occurred at the upstream-southeast of the basin; with the maximum 1-day rainfall recorded on 23rd December 2014 was 507mm at Gunung Gagau rainfall station, whilst the projected maximum 1-day rainfall at the rainfall station based on climate change scenario A1B during the future period 2010-2040 is 612mm. Also shown in Figure 2b is the 1-day maximum rainfall values projected in the basin are up to 1,150mm, which could cause potential floods with higher magnitudes. However, it is found that the 2014 rainfall has exceeded about 200mm from the projected value and covered about half of the river sub-basin area (as highlighted red in Figure 2c), and caused a disastrous flood, spreading to the populated downstream areas.
Fig 1: Frequency curves during three periods of the 21st century over Kelantan river basin.

Fig 2: Spatial representation of (a) rainfall on 23rd December 2014; (b) projected A1B maximum 1-day rainfall (2010-2040); (c) difference between projected maximum 1-day rainfall and rainfall on 23rd December 2014 (all in millimetres).

References

DID (2015), December 2014 Kelantan’s Flood Report, Department of Irrigation and Drainage Malaysia.
Comparison between radar-derived precipitation estimates and rain gauge data in a sub-daily resolution

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Abstract

Radar-derived precipitation estimates can be substantially adjusted by rain gauge data. Whereas the real-time adjustment procedure is based on data from automatic gauges only, the retrospective analysis can utilize daily totals from much denser rain gauge network (Sokol, 2003; Sokol and Bližňák, 2009). This study verifies such estimates by sub-daily precipitation intensities from rain gauges for the warm seasons (May-September) of the years 2002-2012 in the area of the Czech Republic (CR). The length of accumulation period ranges between 10 min and 24 hours (10 min, 30 min, 1 h, 2 h, 3 h, 6 h, 12 h and 24 h) and the accumulations are continuous in time with a time step of 10 min. The rain rates were calculated using radar reflectivity data at 2 km above sea level measured by two Czech C-band Doppler radars (Brdy, Skalky) every 5 (since June 2009 onwards) and 10 min in 1 km by 1 km square boxes over the whole area of the CR.

Figure 1 illustrates comparison between rain gauge records from SYNOP observations at Milešovka observatory and adjusted radar-derived precipitation amounts in the corresponding 1 km² box with a time step of 10 min. It shows the time series of both data types for heavy convective rains occurred on 22 and 23 July 2010. Adjusted radar-derived precipitation product exhibits lower amounts at the beginning of the event but yields comparable values at the end of the event. Moreover, the structure of histograms and time of precipitation occurrence matches fairly well which indicates correctness of the applied adjustment procedure.

Objective verification of adjusted radar-derived precipitation amounts in various sub-daily resolutions will be performed with a limited number of corresponding rain gauge records for selected precipitation events. A quality of the calculated precipitation products will be expressed by traditional accuracy measures (mean error, mean absolute error and/or root mean square error) as well as by so called Taylor diagrams, illustrating together the centred root-mean-square difference, correlation coefficients and standard deviation.
Fig 1: Time series of 10 min precipitation intensities on 22-23 July 2010. The grey line shows observed precipitation amounts at the Milešovka observatory, the black line represents adjusted radar-derived precipitation estimates from the grid box, where the observatory is located.

References

Towards a radar-based precipitation climatology for Germany – the importance of surface precipitation observations

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Abstract

The necessity and demand for high resolution quantitative precipitation estimation (QPE) products for climatological issues is increasingly becoming a topic. With regard to climate change statistically reliable data for extreme events are of particular interest. Due to their high variability in space and time a systematic and comprehensive detection of small-scaled heavy rain events is still a challenge but of great importance for fields like urban planning, infrastructural design and civil protection. For this reason the Deutscher Wetterdienst (DWD) is currently working on creating a homogeneous and quality-controlled high-resolution precipitation reanalysis (RADOLAN-Klima) based on the RADOLAN (Radar Online Adjustment) algorithm which combines hourly rain gauge measurements and radar information. Since the number of rain gauge measurements significantly improves the quality of the product, a high density of measurements is desirable. In contrast to the operational running RADOLAN-online we have now the possibility to retroactively increase the number of rain gauges. We achieve this on the one hand by using daily DWD precipitation measurements and on the other hand by using data from external partner networks of DWD. To make the daily measurements available for the RADOLAN algorithm we developed a disaggregation method (DIAGG) to create synthetic hourly time series of precipitation. To demonstrate the improvement between RADOLAN-online and RADOLAN-Klima we show a comparison for one of the strongest heavy rain events in Germany in the recent years.

1. Introduction

Since 2005, the Deutscher Wetterdienst (DWD) operates a precipitation analysis algorithm called RADOLAN (Radar Online Adjustment; Winterrath et al., 2012), which combines weather radar data with hourly surface precipitation observations (RADOLAN-Online). The derived data are quality-controlled, hourly, high-resolution (1 km), quantitative precipitation estimation (QPE) products for real-time hydrological applications like flood forecast or water resources management. On the one hand, input data are provided by the national weather radar network, which is operated by the DWD and covers about 98 % of the German territory since the year 2000. Today it consists of 17 C-band radar systems, 16 of them with modern simultaneous dual-polarization technology. On the other hand, the DWD operates a network of automated rain gauges whose data are used for the online adjustment. In the meantime, approximately 15 years of radar data has been collected, which provides valuable information on short-term climatological questions. Particularly small-scaled heavy rain events which are highly variable in space and time are more and more challenges to policymakers of cities. They often occur on short notice, allow only short response times and demand fairly good preparation. The preparation includes a carefully considered urban planning and infrastructural design, as well as an elaborated strategy of civil protection. For its cross-cutting character, four federal institutes (Bundesamt für Bevölkerungsschutz und Katastrophenhilfe – BBK, Bundesinstitut für Bau-, Stadt- und Raumforschung – BBSR, Umweltbundesamt – UBA, Technisches Hilfswerk – THW) and DWD started a joint project to perform a homogeneous and quality-controlled high-resolution precipitation reanalysis (RADOLAN-Klima) based on the RADOLAN algorithm. The main goal is to identify hot spots of extreme precipitation events and recent changes in their patterns over Germany.
2. Data

For the RADOLAN algorithm the number of rain gauge measurements plays an important role for the quantification of the radar data, since the determination of precipitation amounts from reflectivity values leads to high uncertainties without any further information. Thus, the more representative gauge data are available, the better the adjustment gets, especially in the case of local extreme precipitation events that are usually only barely monitored by station based measurements. The reanalysis now opens up the possibility to increase the number of rain gauge measurements for the QPE. Especially before the year 2004 the online measurements have been based on less than 200 stations for the German territory increasing up to about 1300 stations nowadays (blue, Figure 1). Therefore the potential to improve the data basis with additional surface precipitation observations in order to increase the spatial resolution of the station network is especially valuable in the earlier years. However, Figure 1 shows also the potential to improve the recent data basis (green). For this purpose data from daily observations, which are available in the database only after days or weeks, has to be acquired. In total it is possible to provide the reanalysis with more than 2000 DWD rain gauge measurements at each time during the investigated period (2001 - 2014). Furthermore, hourly rain gauge measurements from external partner networks of DWD have the potential to increase the density of the rain gauge network, but the possible number of those stations has not yet been quantified.

![Fig 1: Availability of rain gauge measurements (DWD) for the time period 2001 - 2014 over Germany, hourly online measurements (blue), whole collective of measurements (green).](image)

3. Method

The adjustment within the RADOLAN algorithm between rain gauge measurements and radar data is done on an hourly time interval. While the automatic online measurements provide precipitation data on an hourly basis, the additional measurements are only available on a daily one. To harness this data we developed a disaggregation method (DIAGG) to generate synthetic hourly precipitation values for those stations. The DIAGG process uses the temporal distribution of precipitation obtained at one grid point from hourly radar data (RH-product, radar data after conversion in...
precipitation totals and summed up to one hour). Thus, the daily measurement of a conventional station can be disaggregated into synthetic hourly values. At first, for one station the corresponding grid point from the radar data is determined. Next a disaggregation factor $F_D$ is calculated from the ratio of the measured precipitation amount of the conventional station $R_{S,d}$ and the estimated 24 h sum of the radar $R_{R,d}$ (RH-product) at the corresponding radar grid point. Finally, the synthetic hourly precipitation value of the conventional station $R_{S,h}$ results from multiplying the hourly values from the radar $R_{R,h}$ with the disaggregation factor $F_D$.

$$R_{S,h} = R_{R,h} \cdot F_D = R_{R,h} \cdot \frac{R_{S,d}}{R_{R,d}}$$

In applying this method one should consider that the radar data should be nearly free of errors like clutter. Otherwise strong clutter is misinterpreted as a heavy rain shower for example. In this case an incorrect hourly time series of synthetic precipitation values is generated. There would be a significant overestimation for the time period in which the clutter has occurred and a clearly underestimation for the remaining period. To overcome such problems the preprocessing of the radar data is very important.

To clarify the method Figure 2 is showing the 24 h precipitation amount for the DWD station Altenberge (RR 60304) and the estimated precipitation amount of the corresponding radar grid point from 28th to 29th July 2014. Altenberge with 97.5 mm shows an approximately 20 % higher precipitation amount than the radar, which estimated 80.5 mm (Figure 2 a). Figure 2 b shows the application of the disaggregation factor on the hourly estimated precipitation of the radar and the resulting synthetic distribution of the hourly precipitation of Altenberge.

Fig 2: Example disaggregation method Altenberge (RR 60304) 28th July 2014 6:50 UTC – 29th July 2014 5:50 UTC, daily precipitation amount (a), hourly distribution of precipitation (b).
4. Results

Figure 3 illustrates the heavy precipitation event from 28\textsuperscript{th} July 2014 in Münster (northwest Germany) which produced heavy floods and regrettably caused two fatalities (Heuer, 2014). In this case, the event could only be poorly detected by REGNIE (regionalized precipitation amount) (Rauthe et al., 2013), a 24 h precipitation product for Germany which interpolates precipitation measurements from a station network (Figure 3 a). RADOLAN-online which used almost the same online stations in this region shows a much better result due to the additional highly resolved spatial information provided by the radar (Figure 3 b). In addition to the considerably more realistic precipitation distribution which corresponds to a deep convective event, a northern and southern maximum of precipitation is clearly visible. Moreover the total amounts of precipitation are significantly higher when radar information has been integrated (Figure 3 d). Figure 3 c shows the situation with three additional rain gauge measurements, including Altenberge (see Figure 2). While the amount of precipitation of the corresponding grid point for Altenberge increased from 69.4 mm to 90 mm the influence of the two other recently added stations is even larger. These stations are of external origin and have for this exemplary study already been implemented into RADOLAN. Especially the station HKA Münster (LANUV) which is located directly in the southern maximum is responsible for a huge increase in the total precipitation from 155.3 mm to 283.3 mm for the grid point with the highest amount of precipitation in RADOLAN-Klima (cf. Figure 3 b and c). Due to the still missing rain gauge measurements in the area of the northern maximum of precipitation the grid point with the maximum precipitation shows only a slight increase in total precipitation from 192 mm to 208.9 mm. However, it might be possible that the northern maximum had an even larger total precipitation than the southern maximum.

Fig 3: 24 h total precipitation amount at 28\textsuperscript{th} July 2014 05:50 UTC, pure station-based interpolation (REGNIE) (a), station and radar-based real-time precipitation analysis (RADOLAN-Online) (b), station and radar-based precipitation analysis with three additional gauge measurements (RADOLAN-Klima), REGNIE – RADOLAN-Online (d), REGNIE – RADOLAN-Klima (e), RADOLAN-Online – RADOLAN-Klima (f).
5. Conclusions

In this short paper we present a case study of an extreme deep convective precipitation event over northwest Germany and demonstrate exemplarily the importance of rain gauge measurements for the quality of a radar and station based QPE product (RADOLAN). Figure 3 d and e already show the significant difference of RADOLAN against a pure station based daily precipitation product (REGNIE). However, Figure 3 f shows the further improvement of RADOLAN, if additional rain gauge measurements are used. Further test runs show not only an improvement of the QPE for small scale deep convective precipitation events, but also for large scale flooding events like the June 2013 flood in Germany (not shown). In order to obtain additional rain gauge measurements we present the DIAGG method which allows the production of synthetic hourly precipitation values from daily rain gauge measurements. Currently we are also working on the development and implementation of error correction algorithms to minimize sources of errors caused by the nature of the radar measurements. In this context the preprocessing is going to switch to the POLARA (Polarimetric Radar Algorithms; Helmert et al., 2014) software framework. It comprises a set of about 35 detection and correction algorithms primarily designed for real time application that can also partly be used on single polarization data in reanalysis mode. Next steps are to realize a full RADOLAN-Klima run (2001-2014) with additional stations provided by the DIAGG method and to acquire as much external stations as possible.

References


Flash-flood warning in small basins using a rainfall thresholds based approach: a case study

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Abstract

Flash floods are an important problem in many European catchments resulting from severe thunderstorms typical of these regions. These phenomena can cause serious damages and economic losses and also pose a serious risk to people, as water depths and velocities can increase within a short time. One of the most important non-structural measure for flash flood damage mitigation is flash flood forecasting and associated real–time data collection systems. The importance of forecasting is the possibility it offers of alerting people of the forthcoming floods in sufficient time for them to act between the warning and the occurrence of the flood. For flash flood events the time between the rainfall event and the consequent flooding is short, which makes traditional flood warning systems, that rely on monitoring river levels, difficult or impossible to implement. In this case the use of flood precursors (rainfall thresholds) (Carpenter et al., 1999) implemented off-line and compared in real time with observed or predicted rainfall depths results in a practical alternative.

Main focus of this paper is, therefore, to describe a methodology for the implementation of an operational Flash Flood Guidance system for small catchments subjected to these kind of phenomena, based on the rainfall threshold approach.

In order to derive these flood precursors an Instantaneous Unit Hydrograph based lumped rainfall-runoff model with the SCS-CN routine for net rainfall was implemented (Brigandì, 2009; Brigandì and Aronica, 2008). This approach is chosen because of its simplicity and particularly because of the small number of parameters that need to be estimated. Rainfall thresholds are derived from the resolution of the "hydrologic inverse problem", which consists of deriving the total rainfall that will produce the critical discharge, given the current soil moisture conditions and the temporal evolution of the rain storm. When the critical discharge is defined, the code has to solve two phases: the first one performs the rainfall-runoff transformation through the SCS-CN technique (Mishra and Singh, 2003) whilst the second one carries out the convolution, that is not solvable in closed form, but through a Monte Carlo procedure of minimization of an objective function.

For the resolution of the hydrologic inverse problem it is also necessary to know the temporal evolution of the rain storm. In order to overcome the limitation due to the lack of sufficient records to produce statistically meaningfully results, synthetic events, generated using a Monte Carlo technique with characteristics in terms of shape, duration and rainfall amount derived by statistical analyses of the available historic records, were derived (Candela et al., 2014; Brigandì, 2009). When synthetic rainfall is generated, for each duration of rainfall, the code provides several pairs of discharge-height values. Among all the generated pairs of height-discharge, only the couples for which a fixed objective function is smaller than a set tolerance are considered.

Moreover, to take into account of the uncertainty related to the main parameters needed for the implementation of the code, an uncertainty analysis was carried out through the application of the GLUE (Generalised Likelihood Uncertainty Estimation) methodology (Beven and Bynley, 1992). The presented approach was applied to the Boscastle catchment (20 km²), in Cornwall, in the UK, where, on the 16th August 2004, an extreme rainfall event took place and up to 200 mm of rainfall...
fell in a period of approximately 5 hours. The peak discharge was estimated to be approximately 180 m$^3$/s and the return period of the rainfall of the order of 1000 to 2000 years (HR Wallingford, 2005). The results show the good performance of the system which would have allowed this extreme event to be forecasted and a flood warning to be issued.

![Fig 1: River Valency and the Village of Boscastle.](image)

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Derivation of rainfall thresholds for pluvial flood risk warning in urbanised areas

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Abstract

In the recent past throughout the Mediterranean area, many extreme events such as floods, debris flows and landslides occurred. Mediterranean ephemeral streams have specific features compared to other river systems; their basins are small and highly torrential and may generate flash-floods. Moreover, runoff generation in semiarid zones is the result of a lot of spatial and temporal complex processes related to hillslope and catchment scale. The complexity of the processes involved derives from great heterogeneity of rainfall inputs, surface and subsurface characteristics, and strong nonlinear dependency on antecedent wetness which controls the infiltration capacity of the soil surface and the connectivity of surface and subsurface runoff pathways.

Moreover, the rapid transformation processes of urban areas induced, as a consequence, the increase of catchment imperviousness and the derived increase of surface runoff generated during rainfall events. The natural drainage network is, often, insufficient to convey such discharges and it is gradually substituted by artificial systems having the function to convey the runoff coming from urban areas towards the closest receiving water body. However, flooding events in urban areas occur quite frequently as a consequence of rain events of lower intensity than the design one, even in case of correct network dimensioning. Usually, flood warning systems are based on on-line hydrological and/or hydraulic models in order to provide forecasts of water stages or discharges at critical river sections (Martina et al., 2006; Diakakis, 2012; Wu et al., 2015). This procedure is inappropriate for flash flood warning in urban areas or in catchments with a small area. Therefore, it would be helpful for the pluvial flooding model to be in accordance with the observed or forecasted rainfall if exceeding a critical value, namely, the rainfall threshold.

The use of a reliable flood forecasting model can play an important role in managing land and water resources. The purpose of this work is the development of an operational tool for pluvial flooding warning in an urban area based on off-line rainfall thresholds derived by coupling a rainfall–runoff modeling and an hydraulic routing. The critical conditions considered for issue flood warnings were not only based on the water stage, but also on the extension of the flooded area. Further, a risk assessment framework for quantifying the reliability of the rainfall thresholds has been included; rainfall thresholds used in pluvial flooding warning should be influenced by the uncertainties in the rainfall characteristics, including rainfall duration, depth and storm pattern. This risk assessment framework incorporates the correlated multivariate Monte Carlo simulation method (Candela et al., 2014), an hydraulic model for the simulation of rainfall excess propagation over surface urban drainage structures, i.e. streets and pathways, the FLURB-2D model (Aronica and Lanza, 2005). Thresholds rainfall are defined using the approach proposed by Wu et al (2015) particularly, this study designs a number of inundation criteria, and they are applied to analyze the change in the rainfall threshold due to various definitions of inundation. Starting from estimated water stages and flooded area from inundation simulation, carried out by the FLURB-2D hydrodynamic model, rainfall thresholds can be obtained according a specific inundation criterion, including, together, a critical water depth and a critical flooding area. Finally, the second phase concerns the imminence of a possible hydrological risk by comparing the time when cumulative rainfall and rainfall thresholds meet to each other. The developed procedure has been applied to...
the real case study of Mondello catchment in Palermo (Italy), and the analysis of the results allows the identification of some rainfall thresholds for flash flood warning. Actually, this tool could help to implement a precise system of civil protection in order to put in place all necessary emergency actions to reducing the loss of lives and damage to property.

Fig 1: Mondello catchment (Palermo) and study area (into red line).

References


Image-based rain sensing in an urban environment

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Abstract

The urban environment is particularly challenging for collecting accurate and robust high-resolution information on the spatial and temporal variability of precipitation (Berne et al., 2004). Operational networks of meteorological stations are generally sparse in urban areas. In addition, the rainfall information from weather radars is often available at a spatial resolution (~1 km²) that is too coarse for optimal urban water management. This calls for alternative sources of weather information for metropolitan areas.

We have devoted recent efforts to the design and development of novel strategies for rainfall data acquisition based on non-invasive and (prospectively) low cost measurement systems. In Allamano et al. (2015), we propose to retrieve quantitative measures of rainfall intensity by relying on the acquisition and analysis of images captured from professional DSLR cameras (SmartRAIN technique in the following). SmartRAIN is based on the fundamentals of camera optics and exploits the intensity changes due to drop passages in a picture. The main steps of the method include: i) drop detection, ii) blur effect removal, iii) estimation of drop velocities, iv) drop positioning in the control volume, and v) rain rate estimation. The method has been applied to real rain events with errors of the order of ±20%. In Figure 1 we show a schematic representation of the method for drop detection and positioning in the control volume.

Fig. 1: (a) example image with rain streaks, (b) schematic representation of drop positioning.

Images allow for non-invasive monitoring of extended areas and can be captured at high temporal resolution to provide insight on the continuous evolution of the physical phenomena. Hence the SmartRAIN technique is amenable to be exported to the urban environment for intensifying at-ground rain gauging by integrating webcam-equipped sites into the existing rain gauging networks.

In this paper we bridge the gap between the need of acquiring images via professional cameras (as described in Allamano et al. 2015) and the real possibility of exporting the technique to low-cost webcams. We apply the image processing algorithm to frames registered with a Raspberry camera module both in laboratory (i.e., controlled rain intensity) and field conditions. The resulting
images are characterized by lower resolutions and significant distortions with respect to professional camera pictures, and are acquired with fixed aperture, fixed focal length and rolling shutter. All these hardware limitations indeed exert relevant effects on the readability of the resulting images, and may affect the quality of the rainfall estimate. In this paper we demonstrate that a proper knowledge of the image acquisition hardware allows one to fully explain the artefacts and distortions due to the hardware. We demonstrate that, by correcting these effects before applying the image processing algorithm, quantitative rain intensity measures are obtainable with a good accuracy also with the Raspberry camera module.

Fig. 2: Measuring site located on a large roof terrace equipped with tipping bucket rain gauges and a Raspberry camera.

References

Metrological requirements for a laboratory rainfall simulator

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Abstract

The liquid precipitation at the ground level is measured by means of different techniques and technologies for areal and point-scale quantification of rainfall intensity RI (mm/h) and the resulting total precipitation amount h (mm). Point-scale precipitation gauges fall in two main categories: catching type gauges, which collect the liquid equivalent precipitation into a measuring bucket, and non-catching type gauges, where the collection of water is not required. Since the latter category of gauges employ a variety of developing measuring technologies, the implementation of appropriate calibration procedures has been included within the scope of the European Metrology Research Programme MeteoMet 2 (ENV58-REG3). This work reports about a study conducted by the WMO-CIMO Lead Centre “B. Castelli” on Precipitation Intensity (LC-PrIn) aimed at the design and preliminary testing of an advanced laboratory rainfall simulator capable of generating non-continuous water flows (droplets) with controlled RI and the drop size distribution. A real-world drops size distribution is approximated by simplifying the domain of droplets diameter d (mm) in three main categories of fixed size. The technical advantage derived from the availability of such device arises from its suitability to calibrate non-catching type gauges.

1. Introduction

In nature, the liquid precipitations have different micro- physic characteristics that mainly depends on the rainfall intensity (RI), the local climatology and also the chemical composition of the raindrops. Hydro-meteorological applications often characterize the time-space microstructure of precipitation event by means of the drops size distribution \( N(D) \) (m\(^3\)mm\(^{-1}\)), where \( D \) (mm) is the drop equivalent diameter. An example of \( N(D) \) measurements made by two different non-catching type instruments located in Florence (Italy) is provided by Caracciolo et al. (2008) and reported in Figure 1.

![Fig 1: Co-located DSD measurements made by an impact Joss-Waldvogel disdrometer (a) and a X-band radar disdrometer (b) in Florence (Caracciolo et al., 2008).](image-url)
Modern non-catching type gauges are generally able to provide such information about the internal structure of precipitation and to estimate the terminal velocity $v$ (m/s) and the deriving RI for a given sensing area. This kind of instruments can measure both liquid and solid precipitation using various measuring principles such as optical, piezo-electric and radar.

The recent WMO Field Intercomparison of Rain Intensity Gauges (Lanza and Vuerich, 2009) revealed noticeable error figures of the rainfall intensity measurements made by non-catching type instruments when compared to other commercial catching type gauges (Figure 2). During the campaign, reference RI values were provided by a selection of catching-type gauges whose performance had been validated in the laboratory. Such low performance are ascribed to the yet unsolved difficulties in establishing reliable relations between the rainfall rate and the physical variables measured by optical, acoustic or radar sensor indications.

Fig 2: Overall relative deviations (%) of the one-minute RI measurements made by co-located precipitation sensors during the latest WMO Field Intercomparison of Rain Intensity Gauges (Lanza and Vuerich, 2009). The right axis reports the sample size (n. of rainy minutes) and the red boxes highlight the performance of non-catching type gauges.

2. Methods

The Rainfall Simulator (RS) prototyped by the WMO-CIMO Lead Centre “B.Castelli” on Precipitation Intensity (LC-PrIn) is based on the use of independent hydraulic channels driven by volumetric pumping systems that are able to realise different flow rate values (Lanza et al., 2015). Each channel feeds a series of nozzles characterized by the same internal diameter and allows the drops generation of a known constant size.
The current version of the RS simplifies different drop size distributions reported on Figure 1 by classifying the drop diameter axis in three classes. This is achieved by adopting three hydraulic channels and as many groups of nozzles as synthetized in Figure 3.

The control of the drops distribution is performed by measuring the drops dispensing frequency of each nozzle with proximity Infra-Red (IR) light sensors and by adjusting the channel pump speed (i.e. the flow rate) accordingly. Figure 4 shows some details of the pressure head distribution chambers (panel a), the prototype drop dispensers grid (panel b) and the provisional RS tower (panel c). The final assembly of the RS tower is currently under development.

The next section outlines the preliminary results of the RS drop forming system tests necessary to establish the mathematical relationships between the channel flow rates, the drops frequency and
size. Several nozzle sizes are investigated in order to optimize the width of the simulated drop size classes with respect to the real-world rainfall distributions $N(D)$. The experiments have been conducted by weighing the water dispensed by a single nozzle connected to the pumping system which has been set at given flow rate values and by recording the drops frequency with a proximity IR sensor.

3. Evaluation of the simulator performance

Constant flow rates $Q$ (ml/min) tests highlighted steady drops dispensing frequency (Hz) from a single nozzle after an initial transient due to the hydraulic system warm-up (Figure 5). The time response of the pumping units has been previously estimated by means of dedicated laboratory tests reported by Colli et al. (2013). The repetition of single nozzle tests for different flow rates and different nozzles internal diameter $DI$ (mm) allowed the definition of the drop frequency/diameter $D$ (mm) curves reported on Figure 6. The tested set of $DI$ and $Q$ values allows covering a drop diameters range equal to $1.5 \text{ mm} < D < 3.5 \text{ mm}$. On the other hand, the drop size distributions measured in the field (Figure 1) has a wider $D$ range and particular relevance should be given to the $D < 1.5 \text{ mm}$ region since it’s associated to the higher $N(D)$ values. Dedicated testing are currently under progress at the LC-Prln laboratory in order to obtain smaller droplets by changing the superficial tension of the fluid and to reduce detachment time of the droplet from the nozzle.

Fig 5: Drop frequency (Hz) time series of a single nozzle dispensing under different constant flow rate $Q$ (ml/min) values (Lanza et al., 2015).
Fig 6: Scatter plot of the drop frequency (Hz) vs. drop diameter $D$ (mm) measured during constant flow rate tests of single nozzle (Lanza et al., 2015). The tests were repeated for four different nozzles internal diameter $DI$ (mm).

Figure 7 shows the results of preliminary drop frequency tests performed by varying the water mixture and imposing a constant flow rate and nozzle size $DI$. Relevant changes in the resulting drop diameters $D$ has been revealed by adding small fractions of alcohol and commercial surfactants to distilled water.

Further tests are currently under execution in order to check the performance of a series of nozzles operating in parallel and connected to the same pumping channel by means of a pressure head distribution chamber (showed in panels a and b of Figure 4).

Fig 7: Example of the drop frequency (Hz) time series measured for a single nozzle under constant flow rate $Q$ and varying the water mixture (Lanza et al., 2015). Different drop size $D$ (mm) values are reported on the plot.
4. Conclusions

The current Rainfall Simulator (RS) design is based on the approximation of realistic drop size distribution $N(D)$ by means different drop forming elements (nozzles) working in parallel and driven by separated water pumping channels. A real-time validation system still has to be included in the RS final assembly and dedicated tests will be performed. More work has to be done in order to generate droplets that fall with terminal velocity values that are comparable to the real precipitation.

The repeatability of the droplet size/frequency relationships has been demonstrated. A warming-up time must be accepted before starting the rainfall simulation, this is particularly true in case of small nozzles ($Dl<=0.303$ mm). It’s also necessary to expand the analysis to the simultaneous dispensing from a larger number of nozzles ($>>2$) in order to check the spatial distribution of the simulated drop size distribution for different gauge sensing areas.

The random position of rain drops over the disdrometers sensing area is here approximated by adopting a large number of operational nozzles. Future developments of this study will be aimed at the choice of optimal drop diameter classes that allow the simulation of realistic $N(D)$. In relation with this, more nozzle sizes and fluid mixture must be tested. In the current RS prototype, the drop size distribution is synthetized in three mean diameter classes.

The uncertainty associated with the generated rainfall intensity and drop size distribution values is currently under quantification by means of dedicated tests performed in a controlled environment.

Acknowledgement

This research is supported through funding from European Metrology Research Programme MeteoMet 2 (ENV58-REG3).

References

On extracting information from numerical weather prediction ensemble precipitation forecasts to anticipate urban runoff flow domains

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Abstract

Weather forecasts can provide valuable information to improve operational performance of urban drainage systems (UDS) and wastewater treatment plants (WWTPs). For example, radar-based rainfall nowcast are increasingly being used within real-time control (RTC) concepts. Numerical weather prediction (NWP) models can also contribute to forecast rainfall with the advantage of an increased lead-time. NWP models are already used in various fields from streamflow forecasting (Shrestha et al. 2013) to solar and wind energy prediction (Bacher et al. 2009).

Using uncertain information, such as NWP, to optimize storm- and wastewater systems in real time is generally challenging. Indeed, NWP is embedded with a significant uncertainty but such forecasts do however contain information that can contribute to optimization especially when utilizing multiple ensemble model runs. Therefore, we decided to create a method to extract information from NWP ensembles in order to distinguish the incoming flow domains rather than quantitatively predicting the flow values directly.

The method is elaborated around (i) a set of strategies for utilizing the information in the NWP ensemble, (ii) a model for predicting catchment outlet flow from NWP precipitation forecasts, and considering (iii) different sources of uncertainty (spatial, temporal) and (iv) forecast consistency. The strategies are designed with a view to obtaining more or less conservative predictions. The skill of each forecast strategy is evaluated using a threshold exceedance contingency table on the catchment outlet flow. Furthermore weights are assigned to each outcome of the contingency table to determine the expected benefit/damages of each strategy.

The urban scale in focus here requires precipitation data with fine spatial and temporal resolution, which is challenging for NWP models. Indeed, precipitation is one of the most difficult variables to forecast, due to it a large variability both in space and in time. In our case study we use the HIRLAM-DMI-S05 model, which has a horizontal resolution of 0.05° (approx. 5km) and hourly time steps (Feddersen 2009).

Figure 1 illustrates a conservative approach to cope with spatial uncertainty. The rainfall input to the runoff model is based on an area up-scaled beyond the physical catchment to include neighboring cells and differentiating convective and stratiform rains.
Figure 2 displays the runoff model output for a NWP and the high flow prediction for 7 different strategies that utilize the NWP ensemble information in different ways. The upper panel represents the modelled discharge at the catchment outlet considering the conservative up-scaled approach describe in Figure 1, which leads to very conservative estimates of flow threshold exceedances. The middle panel is based on the average precipitation over the catchment, which, as expected, provides more realistic flow forecasts. The last plot shows prediction of threshold exceedance for different strategies.

![Runoff model flow forecasts](image)

The strategies 1 to 4 are based on the middle panel and the strategy 5 to 7 on the upper panel. The strategies 5 and 7 are also considering the previous forecast. Such predictions can, for example, be used to disable a dry period optimization scheme (pumping strategy, WWTP inflow smoothing, energy consumption, etc.) when dealing with high flows has priority. The decision making to start the optimization is motivated by the prediction confidence resulting from the different strategies. The flow threshold and the strategies parametrization need to be adjusted to the prediction purpose.

References


Effects of different spatial and temporal rainfall data resolution on hydrological response in flat urban catchments

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Abstract

Flooding in urban areas is one of the main weather-related risk problems of the last decades. It is due to the fact that the population is growing and moving from the rural areas to the cities, which become more urbanized and densely populated. This phenomenon is combined with the climate changes of the last years, that present an increase of short but quite intense rainfall events. These conditions determine a fast and short-time response of the catchments, which increases the probability of flooding.

Previous researches have studied the sensitivity of different spatial and temporal resolutions on urban catchments, highlighting correlations between the rainfall resolution and the model scales (Bruni et al., 2015, Ochoa-Rodriguez et al., submitted). In particular Ochoa-Rodriguez et al.(submitted) considered the impact of different combinations of spatial and temporal resolutions on hydrological response in seven urban catchments, with the aim to identify critical resolutions. The study shows that the models are more sensitive to variations in temporal resolution than in spatial resolution and that there is a strong relation between the drainage area and the critical rainfall resolution: the effects of the different rainfall resolutions decrease with increased size of the subcatchment considered. The catchments investigated are located in areas with different geomorphological characteristics, and they present different extension, shape, slope, degree of impenetrability and drainage system.

In this study we focus on those catchments that do not have a relevant slope, and where the water that flows in system is mostly not moved by gravity. Instead, there are pumping stations and weirs that allow water to flow in different directions. Moreover, the drainage system is extremely looped, and the water can follow different patterns depending on the conditions of the system. The discharge in specific pipes is not enough to characterize the behaviour of the drainage system, because the flux can change direction and it presents an alternation of positive and negative peaks (Fig.1). The behaviour of these systems is difficult to understand and it is still poorly investigated. A statistical analysis is applied to try to better characterize the behaviour of the system, and the effects that different rainfall input resolutions can have on the hydrological response of the model.

Some districts of the city of Rotterdam (NL) are considered to investigate the behaviour of the drainage system in a flat urban area. Rotterdam is built in a polders area with ground levels below sea level. For this reason, during heavy rainfall, excess storm water needs to be pumped out to the river system or temporally stored.

To better understand the hydrological response of the catchment, high resolution rainfall data are required as input of the model. High resolution data are provided by the dual polarimetric X-band weather radar, located in Cabauw Experimental Site for Atmospheric Research (CESAR) of the Netherlands. The data are provided with different high spatial (from 100m up to 3000m) and temporal (from 1min to 10min) resolutions. Different combinations of spatial and temporal resolutions are considered to evaluate the sensitivity of the hydrological model to different input data. Storms
with different characteristics, such as intensity, duration and velocity, are selected for this study to understand how these parameters can influence the sensitivity of the model.

Results confirm the higher sensitivity of the hydrological response to the temporal resolution than to the spatial resolution presented in the previous studies (Ochoa-Rodriguez et al., submitted), and show that the characteristics of the storm have a strong influence on the output. Scenarios where rainfall events present lower average intensity and higher storm movement velocity tend to be more sensitive to the different spatial and temporal resolutions, presenting different outputs depending on the rainfall resolution used (Fig. 2).

Fig. 1: Discharge in a pipe that drains an area of 2ha, during a storm with a low rainfall intensity. The graph shows the variation of the direction of the flow represented by a positive and negative alternation of peaks.

Fig.2: Water depth in a manhole that drains an area of 2ha, during high intensity rainfall event (31.67 mm/h, left) and during a low intensity event (10.53 mm/h, right). The graphs show the response of the model to rainfall events measured with different combination of spatial and temporal resolution.

References


Beyond rainfall multipliers: modelling rainfall observation errors as stochastic processes improves runoff predictions

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Abstract

Rainfall is a major driver for natural and urban hydrological systems. Unfortunately, rainfall is also highly variable in space and time and existing monitoring methods, such as gauges and weather radars, often introduce large errors into observed rainfall intensities and amounts. As biased precipitation also leads to biased runoff predictions, it is very important for hydrological modelers and engineers to correct for bias in historical rainfall records, e.g. with "aerial correction coefficients" (ASCE 1969).

So far, two different approaches have been suggested in general to approach the dilemma that biased rainfall input also leads to biased parameter values (Andréassian et al. 2001). The first is to do “hydrology backwards” (Kirchner 2009; Leonhardt et al. 2014; Vrugt et al. 2008) and map observation uncertainty to rainfall observations only. Thus, areal rainfall information is directly computed from hydrological output observations under the assumption of zero observation error and a "true" rainfall runoff model. A second strategy is "total error analysis", which accepts the various sources of uncertainty, such as erroneous rainfall and land use data, model structure uncertainty, incomplete knowledge on model parameters and inaccurate level or flow measurements (Renard et al. 2011; Kuczera et al. 2006; Sikorska et al. 2012; Del Giudice et al. 2013). Specifically, the ultimate goal of a total error analysis is to mathematically formulate a likelihood function which realistically describes the involved errors, their distributions and, if needed, temporal behaviour. A realistic description of the errors then allows for sound parameter inference and reliable probabilistic predictions.

Regarding modelling rainfall uncertainty, a widely adopted approach for natural and urban catchments is to use additive or multiplicative errors, which are often applied to entire rain events (McMillan et al. 2011). At first sight, this seems to be an attractive approach because i) systematic errors in rainfall observations can be corrected, which leads to more robust and reliable runoff predictions, ii) the approach is virtually independent of scale and iii) computationally feasible. Unfortunately, the assumptions regarding the multiplicative rainfall errors are not always realistic. Two main limitations are that, i) runoff predictions cannot be corrected when no rainfall has been observed and ii) time-shifts between rainfall and runoff cannot be considered. Fundamentally, both limitations lead to biased parameter estimates, which is undesirable.

The objective of this study is therefore to improve statistical inference in rainfall-runoff modelling by moving beyond rainfall multipliers and investigate a more realistic representation of rainfall uncertainty. Specifically, we describe areal effective rainfall as a continuous Gauss-Markov process in a transformed space, which enables us to learn about and reduce the input and output uncertainties. Via Bayesian inference, we show how to infer probable rainfall input from available rainfall and flow observations given a rainfall-runoff model. The main advantages over existing error models is that...
we do not assume that the true precipitation, or pieces thereof, is proportional to the measured time series, which makes it possible to also deal with time-varying observation errors.

![Rainfall and Runoff Graph](image)

**Fig 1:** Top: Rainfall observations (dots) from the 7km-away rain gauge used to calibrate the rainfall-runoff model and estimated most probable areal rainfall input given the model and error assumptions. Bottom: Predicted rainfall runoff (grey lines) match the observations (dots). Runoff predictions based on traditional least-squares approaches or rainfall multipliers (not shown) cannot cope with the time-shift and will always show a peak around 18:30. NS is the Nash-Sutcliffe efficiency.

We demonstrate the usefulness of our approach on rainfall-runoff predictions in the 28.6 ha urban catchment of Adliswil (CH). We tested our approach predicting stormwater runoff based on rainfall data from the next Meteoswiss automatic monitoring station, which was 7km away and had lower time resolution and quantization. Our first results (Fig.1) indicate that the suggested error description can realistically estimate model input even in presence of heavily biased precipitation measurements. This leads to less biased parameter estimates and thus improves rainfall-runoff predictions.

Practically, this novel approach is most useful where rainfall uncertainty is the major influence factor. Although the estimated inputs is not independent of the applied model, it overcomes the major limitations of rainfall multipliers and thus enables both reliable output predictions and a better quantification of the error sources.

**References**


The impact of urbanisation, anthropogenic heat and aerosol loading on precipitation for four distinct climate regimes

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1. Introduction

The urban environment might affect precipitation variability in a number of ways: enhanced convergence due to an increased roughness, destabilization of the boundary layer due to the urban heat islands' (UHI) thermal perturbation, enhanced aerosol loading serving as cloud condensation nuclei, or bifurcation / divergence of precipitation systems by the urban canopy (Shepherd, 2005). To date, there is no conclusive answer to what mechanism dominates the urban-induced precipitation process or what the relative role, if any, of each mechanism is. To advance the understanding of how cities affect surface precipitation and to disentangle the role of various processes at play, 3D-real case and idealized modelling studies are needed (Han, et al., 2014).

2. Methods

2.1 Regional climate model COSMO-CLM

To address the above-mentioned questions, the default COSMO4.8-CLM4.19 version (hereafter CCLM) is extended with a number of new features. First, the default TERRA-ML scheme is replaced by TERRA-URB developed by Wouters et al. (2015). Secondly, the two-moment scheme by Seifert and Beheng (2006) is implemented, extended with the inclusion of hail. This scheme predicts mixing ratios and number concentrations of 6 hydrometeor species (cloud water, cloud ice, rain, snow, graupel and hail). The scheme parametrizes all relevant homogeneous and heterogeneous nucleation processes, including the activation of cloud condensation nuclei (CCN), making it useful for the investigation of aerosol effects on cloud and precipitation. Third, the impact of cities on aerosol loading is implemented via the Seifert et al. (2012) approach, adding a prognostic tracer which mimics the plume of high aerosol loading downwind of cities. This tracer is advected by the mean flow and experiences diffusion, similar to the hydrometeors. Within the microphysics scheme, the tracer value is then used to linearly interpolate between a background aerosol loading and the urban high CCN/IN (ice nuclei) loading. A tracer-value of zero indicates uncontaminated background loading, whereas a tracer-value of 1 indicates heavily polluted air. Since the Seifert and Beheng (2006) scheme has three different IN types (soot, organics and dust), our methodology greatly reduces the computational cost by imposing only one additional tracer to mimic the evolution of all CCN/IN, compared to a fully prognostic aerosol scheme.

2.2 Simulation characteristics

This extended model version is applied for Melbourne (Australia) for a four-month summer period (allowing one month spin-up), following three one-way nesting steps: 25 km, 2.8 km and 1 km, the latter using a 250x250x50 grid cell domain description (see Fig. 1). Model output is available on an hourly time interval, with surface precipitation available every 10 minutes. Lateral boundary conditions are provided by 6-hourly ECMWF Era Interim data (Dee et al., 2011). A total of 5 simulations are performed: four simulations were performed with urban land cover, each with a different combination of activate/inactive anthropogenic heat flux and urban aerosol loading. A fifth
'pristine' simulation consists of rural land cover without anthropogenic heat flux and background aerosol loading.

Fig 1: Overview of the 1 kilometer CCLM evaluation domain centered over the city of Melbourne. The corresponding urban land cover scales from 0 to 1 while the blue color refers to sea/inland lakes.

3. Results

Preliminary results of the analysis indicate that the urban surface and anthropogenic heat introduce an urban heat island (with a maximum of 8°C), an urban dry island due to the impervious surface and a decrease of 10m wind speeds above the urban areas due to an increased roughness. All scenarios indicate a decrease in total cloud cover fraction. This decrease is mainly caused by a decrease in low level cloud cover as a result of a drier urban surface (aerosols show a slight negative feedback). The aerosol scenarios result in an increase of cloud condensation nuclei (CCN) leading to higher total cloud number concentrations, more and smaller droplets, a reduced precipitation efficiency resulting in less low intensity precipitation. Medium level cloud cover shows an increase which is mainly driven by the increased aerosol loading. There is no clear change in the high cloud cover fraction. Finally, for precipitation, the modelled changes are less clear. Total precipitation over the full summer season does not change significantly between the simulation scenarios. Quantile plots indicate a reduction in low precipitation intensities, mainly caused by the urban fraction and only to a minor extend modulated by AHF and/or aerosols. In addition, aerosols slightly reduce the medium precipitation intensities while no change in extreme precipitation is observed.

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Torrential rains in the region of southern Moravia (Czech Republic) in the period 2005−2014

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Abstract

The paper is focused on the analysis of rainfall intensity data measured by tipping-bucket rain gauges at 11 meteorological stations located in the southern part of the Czech Republic. Study material includes 1-minute precipitation amounts in the period 2005−2014. Data were subjected to thorough quality control and incorrect values were removed from the processing. Corrected data were analyzed by Wussow’s method (Wussow, 1922) and the occurrence of various types of torrential rains was evaluated. Basic statistics of particular types of torrential events such as frequency or annual course were evaluated as well. As the time series are too short (10 years), it has no sense to analyze trend, but it is still possible to observe some changes in time. Moreover, the location of study sites enables the comparison between rural and urban environment. Besides the evaluation and statistical analysis of torrential events, the main goals of this work included also verification of the Wussow’s method and evaluation of its suitability in conditions of changing climate. This was achieved by computation of extreme percentiles from empirical values of rainfall intensities and their comparison with original thresholds for particular types of torrential events according to Wussow. Although Wussow’s classification was designed in the beginning of the 1920s, results show that it is still appropriate in the studied area, even in the conditions of changing climate.

1. Introduction

As the climate tends to be more extreme (e.g. IPCC, 2014), higher frequency of some extraordinary and dangerous weather phenomena is expected in the future. Among these phenomena are e.g. extremely high/low temperatures, thunderstorms, windstorms and torrential rains as well. In general, torrential rains are defined as very intense rains with relatively short duration and small affected area. Increasing extremity of precipitation regime in the study area was proven in the previous work of the author (Doleželová, 2014). It was found that annual rainfall in the study area shows slightly increasing trend while its trend is rather decreasing at the beginning of the vegetation season (April, May). Moreover, dry periods (defined as periods of at least 3 consecutive days with daily precipitation amount smaller than 1 mm) as well as wet periods (i.e. periods of at least 3 consecutive days with daily precipitation amount equal or higher than 5 mm) lengthen significantly. It means that precipitation tends to concentrate in time and precipitation regime tends to be more extreme. Relatively long periods without precipitation alternate with rainy periods that can even lead to flooding. Increasing extremity is manifested also by the occurrence of torrential rains that can have catastrophic impacts on many economic sectors like agriculture or infrastructure. In the Czech Hydrometeorological Institute (CHMI), torrential events are evaluated with the help of the Wussow’s classification that was designed at the beginning of the 20th century according to empirical data. Thus a question arises whether it corresponds to the reality even in the conditions of changing climate. To answer this question, statistical analysis of the whole dataset was carried out focusing especially on the estimation of some extreme percentiles.
2. Methods

Data comprising 1-minute precipitation amounts have been processed according to Wussow’s method (Wussow, 1922) which is used by CHMI as the official method for evaluation of torrential rains when informing the public or providing some kind of climate service. According to Wussow’s method we distinguish three classes of torrential rains or so called downpours: “downpour“, “heavy downpour“ and „catastrophic downpour“. Each of them is defined by the intervals of precipitation amounts for different durations of the rain (see Fig. 1). After the evaluation of torrential rains, basic statistical analysis including frequency of particular types of downpours in individual years and their annual course was performed. Percentage of precipitation amounts in days with torrential rain and their share in overall precipitation sum is determined as well. Maximum precipitation amounts for particular rain durations in individual torrential events are used for the estimation of percentiles that fit best the limit values of the three categories of downpours. Evaluation of torrential events was performed with the help of Proclim software (Štěpánek, 2015).

![Fig 1: Lower limits of precipitation amounts for given rain durations (1-120 min) to call the event “downpour” (D), “heavy downpour” (HD) or “catastrophic downpour” (CD) according to Wussow’s classification.](image)

3. Data

Study material includes 1-minute precipitation amounts from 11 meteorological stations belonging to the CHMI’s measuring network equipped with automatic tipping-bucket rain gauges. Measuring sites are located in the territory of CHMI’s regional office Brno (see Fig. 2). One site is purely urban (Brno-Zabovřesky station, BZAB) while the others represent rather rural environment. The study period is 2005–2014. The automation of Czech precipitation monitoring network started in the second half of the 1990s and so far 84 tipping-buckets have been installed in the Czech Republic. At the moment, 77 of them are working and their data are easily accessible via CHMI’s electronic database (in contrast to the data from previously used ombrographs). As rainfall intensity data are susceptible to measurement errors (especially in case of heavy rainstorms when rain gauge can be plugged by some objects), data quality was an important parameter taken into consideration when choosing study stations. Data of all of the 11 stations were carefully checked for errors (mainly with the help of radar data) and in case of incorrect function of the device the whole rainfall episode was removed from processing.
4. Results

In the studied area, torrential rains occur usually from May to October, rarely also in April and November. Total number of „downpours“ is higher compared to „heavy downpours“ while „catastrophic downpours“ are the less frequent. The highest number of events occurs in July regardless of the category (see Fig. 3). Temporal variability of the occurrence of torrential events is quite low. Figure 4 shows that annual number of „downpours“ at given meteorological station varies between 0 and 6 and mostly reaches values between 1 and 4. There are even several cases with no „downpour“ in particular year and meteorological station (e.g. BROD in 2005, BZAB in 2007 etc.). Annual number of „heavy downpours“ reaches values from 0 to 4, with the frequency of 1−2 being normal and 3−4 being rather rare. Cases with no „heavy downpour“ in particular year and location are more frequent compared to „downpours“. In the category of „catastrophic downpour“ common frequency varies between 0−1, more rarely reaches 2 or 3 events per station and year.

Fig 2: Location of study area and measuring sites used in this study.

Fig 3: Annual course of occurrence of particular categories of downpours at 11 meteorological stations in the period 2005–2014. (Total number of events for all meteorological stations and the whole studied period is depicted).
rainfall in urban and natural systems
10th international workshop on precipitation in urban areas

Fig 4: Overall number of „downpours“ at 11 meteorological stations in the period 2005–2014.

Average share of total precipitation amount in days with torrential rain in annual rainfall is 10 %. Share in particular years and meteorological stations varies between 0.0 % (more cases) and 24.4 % (HOLE in 2008). The highest portion of torrential rainfall was found in years 2008, 2012 and 2014 (for more details see Tab. 1). Warm seasons of these years were typical by frequent occurrence of synoptic situations favourable to convective phenomena.

Table 1: Share (%) of total precipitation amount in days with torrential rain (i.e. „downpour“, „heavy downpour“ and „catastrophic downpour“) in annual rainfall at 11 meteorological stations in the period 2005–2014.

<table>
<thead>
<tr>
<th>Year</th>
<th>HOLE</th>
<th>KROM</th>
<th>PROT</th>
<th>STME</th>
<th>STRZ</th>
<th>VIZO</th>
<th>BRD</th>
<th>BZAB</th>
<th>KMY</th>
<th>KUCH</th>
<th>VMEZ</th>
<th>AVG</th>
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<tbody>
<tr>
<td>2005</td>
<td>8.9</td>
<td>11.1</td>
<td>8.4</td>
<td>2.1</td>
<td>12.6</td>
<td>0.9</td>
<td>0.0</td>
<td>8.2</td>
<td>1.5</td>
<td>3.9</td>
<td>3.0</td>
<td>5.5</td>
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<tr>
<td>2006</td>
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<td>16.9</td>
<td>12.1</td>
<td>5.7</td>
<td>9.4</td>
<td>10.6</td>
<td>17.8</td>
<td>10.5</td>
<td>21.7</td>
<td>6.6</td>
<td>2.2</td>
<td>10.8</td>
</tr>
<tr>
<td>2007</td>
<td>13.7</td>
<td>17.4</td>
<td>10.4</td>
<td>13.9</td>
<td>18.1</td>
<td>16.2</td>
<td>5.3</td>
<td>0.0</td>
<td>7.9</td>
<td>2.5</td>
<td>5.7</td>
<td>10.1</td>
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<td>2008</td>
<td>24.4</td>
<td>14.4</td>
<td>15.7</td>
<td>18.8</td>
<td>22.8</td>
<td>21.3</td>
<td>4.0</td>
<td>13.3</td>
<td>4.9</td>
<td>14.9</td>
<td>7.1</td>
<td>14.7</td>
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<td>10.0</td>
<td>19.4</td>
<td>5.9</td>
<td>2.6</td>
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<td>6.4</td>
<td>16.3</td>
<td>10.7</td>
<td>8.9</td>
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<tr>
<td>2010</td>
<td>1.2</td>
<td>9.4</td>
<td>6.3</td>
<td>10.2</td>
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<td>6.7</td>
<td>7.7</td>
<td>17.1</td>
<td>0.0</td>
<td>4.4</td>
<td>8.9</td>
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<td>2011</td>
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<tr>
<td>2012</td>
<td>16.6</td>
<td>18.3</td>
<td>3.0</td>
<td>18.4</td>
<td>16.5</td>
<td>11.5</td>
<td>18.1</td>
<td>18.1</td>
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<td>2013</td>
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<tr>
<td>2014</td>
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<tr>
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<td>11.0</td>
<td>10.4</td>
<td>8.3</td>
<td>7.1</td>
<td>8.8</td>
<td>10.0</td>
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</table>

Regarding the distribution of empirical values, it was found that percentiles corresponding to lower limit for „downpour“ according to Wussow’s classification range from 95.0 to 98.0 with average value of 97th percentile. In case of „heavy downpour“ it ranges from 98.5 to 99.0 with average value of 98.9. In case of „catastrophic downpour“ lower limit lies between 99.25 and 99.90 percentile.
of empirical data with average value reaching 99.7. Limit values defined by these average percentiles fit the limits for particular types of downpours quite well (see Fig. 5 and 6).

Fig 5: Lower limits of precipitation amounts for given rain durations (1−120 min) for „downpour” (D), „heavy downpour” (HD) or „catastrophic downpour” (CD) according to Wussow (1922) and relevant percentiles of empirical data in the period 2005−2014 for the station Protivanov (PROT).

Fig 6: Same as in Figure 5 but for urban station Brno-Žabovřesky (BZAB).

5. Conclusions

The subject of presented study is analysis of rainfall intensity data from 11 CHMI's stations in the period 2005–2014. Thorough and time-consuming quality control that was done manually (with the help of radar data) has led to the establishment of reliable and quite vast database of 1-minute precipitation amounts. This database covers the longest period possible when particular stations overlap. The majority of torrential events occur in the period from May to September with maximum in July. Annual share of precipitation in days with torrential rain varies between 0 % (i.e. any torrential event in particular year) and 24 % of total annual rainfall in particular years. Average share per year is 10 %. Original Wussow’s limits for particular types of torrential events (i.e. D,HD,CD) correspond to 97.0th, 98.9th and 99.7th percentile of empirical values. These figures are quite high and thus we can assume that Wussow's classification is appropriate even in recent period of climate changes. Application on rainfall intensities measured in the time of method's creation (i.e. ombrographic data) and evaluation of corresponding percentiles should be the subject of further studies.
References


Employing the use of a dense monitoring network to quantify and characterize spatial variability of hydrologic and solute flux in urban forest fragments

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Abstract

The expansive impervious cover in urban areas often results in increased frequency of flash flooding and compromised quality of surface water resources (Smith et al., 2005). These negative hydrologic impacts of urbanization can be largely attributed to the fact that, in the absence of extensive green space, the natural mitigation of urban stormwater runoff via infiltration of precipitation into area soils and its interception by vegetative surfaces is significantly reduced. Much of the recent literature emphasizes that increasing total metropolitan canopy cover can serve as an effective solution to these water issues as urban forests perform an array of ecosystem services that yield significant attenuation of stormwater runoff (Kirnbauer et al., 2013). Where the literature is lacking, however, is in quantifying the hydrologic/chemical ecosystem services provided by individual forest fragments. As urban forest fragments are highly fragmented and variant in size, shape, structure, and surrounding land use, it is likely that they may exhibit heterogeneity in their respective partitioning of precipitation and cycling of solutes. Identifying how this differs on a per-site basis at both the local and regional scales will likely improve understanding and quantification of the hydrologic ecosystem functions and services of urban forests, specifically the potential for the capture of stormwater, subsequent attenuation of urban runoff through both increased infiltration and water loss via evapotranspiration, and betterment of surface water quality within metropolitan regions.

The current study attempts to investigate how the size, shape, structure, and spatial positioning of urban forest fragments affect hydrologic and solute flux in these remnant wooded ecosystems. To this end, hydrologic samples are collected from a dense array of throughfall and stemflow collectors within five forest fragments in the Wilmington, Delaware, USA metropolitan corridor (centrally located within the larger Megalopolis of the northeastern United States). The study consists of three urban (within Wilmington), one suburban, and one rural site (located approximately 35km west of the urban core). The purpose of the study is to determine the relationship between the hydrology and biogeochemistry of the selected study sites and their respective structural, exophysical, and spatial characteristics at three levels of analysis: (a) intra-plot, (b) intra-urban, and (c) intra-regional. At each of the experimental plots, study site design thus allows for the collection of hydrologic samples from twenty-five throughfall and seven stemflow collectors positioned along five transects that are oriented from forest edge to interior, with respect to the dominant direction of storm system movement in the study region (e.g., from southwest to northeast; see Figure 1). This setup allows for the identification of spatial variability of throughfall and stemflow, and subsequent transport and cycling of solutes, on a per-fragment basis within the city. Lastly, volumetric and hydrochemical throughfall and stemflow sample data from the rural, suburban, and one urban site are compared to identify how hydrologic, and specifically solute flux, vary along an urban-to-rural gradient. For each level of analysis (e.g., intra-plot, intra-urban, and intra-regional), nested ANOVA tests will be conducted in STATISTICA to determine the significance of the observed variability in the collected hydrologic and hydrochemical data, common factor analysis will be applied to identify the underlying factors that drive the observed variability, and multiple regression analysis will be employed to help quantify the strength of the relationship between the causal factors and the observed variability.
The collection of volumetric throughfall and stemflow samples are limited to rain events during which ≥ 7mm of rainfall occur. Hydrochemical samples are limited to four events per season and analysed using inductively coupled plasma optical emission spectrometry (ICP-OES) for concentrations of P, K, Ca, Mg, Mn, Zn, Cu, Fe, B, S, Al, NO₃, and NH₄. Results from the first quarter of throughfall and stemflow data collection (June-August 2015) will be presented.

Fig 1: Area and perimeter of each of the study sites. Asterisks denote sites within the city.

References


Setup of a radar event database for hydrologic applications: purpose and functions

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Abstract

A radar event database has been designed and implemented for hydrological purposes by some water boards of the land of North Rhine-Westphalia in Germany. The database contains in its first edition 13 years of radar data covering an area of approximately 20 000 km². The data are high quality adjusted radar data which have been produced offline. The purpose of the database is the facilitation of the use of radar data for hydrological end users. In particular, extreme events can be extracted from the database, analysed and compared to traditional station data as well as transferred to other locations for modelling extreme flow in hydrological models.

1. Introduction

Weather radar data have been collected for more than ten years in a homogeneous way with good data quality. Still, use of radar data is being hampered by missing tools to investigate the data for extreme events, interlink the traditional time series view with corresponding areal data displays and to make such data available to hydrological models in an easy to use and not too expensive way.

2. Data

In a joint project of ten water boards in North-Rhine Westfalia (NRW) and the German Weather Service (DWD) high quality radar data are produced and used for water management tasks (Treis, 2013). For these ten water boards, radar data based on the DX product of the DWD have been corrected and adjusted (Frerk et al., 2012) to yield high resolution precipitation estimates from November 2000 to October 2013. The data have a temporal resolution of 5 minutes, a spatial resolution of a one kilometre grid and cover an area of nearly 20000 km². They are available in an HDF5 Format.

3. Tasks

The water boards require an access to the highest events over the analysis area. Therefore, the following ideas were developed. They approach the following tasks

- data should be available in a central database
- for the amount of data the performance must be adequate
- preferably flexible and expandable with changes in database and methods
- data should be retrieved as time series for selected areas, selected duration intervals and selected thresholds (return periods)
- time series should be available for single pixels or pixel groups (i.e. connected pixels over 9 km², 25 km², etc.)
- selection criterion should also be the maximum number of highest values to be retrieved
- the corresponding radar data should be made available for the selected events for the purpose of visualisation.
A very simple sketch of the required tasks is contained in the concept for a user interface (figure 1) from the concept report, which was also used as tendering document.

![Event selector of the NRW water boards](image)

Fig 1: Concept overview of the functions for the event selector.

### 4. Solution

The data have been reprocessed by the SCOUT software, using the technology presented in Jasper-Tönnies & Jessen (2014) and will be fed into a data base. The setup of the data base retrieval functions must fulfil the described requirements. After the conceptual project phase being finished, a market analysis for different data base solutions was performed. The chosen solution is based on the HydroNET platform which is in use in many applications in the Netherlands and a few ones in Germany (e.g. Einfalt & Behnken, 2013).

The concept for the data base functions required a number of complex decisions to be designed. One of the important questions is when a selected event has to be considered to be independent from another one. Since in a first step, events are defined on a pixel time series, as it is traditionally done, conditions had to be set for independence from neighbours. This may lead to chained dependencies over numerous pixels in case of large thunderstorm cells. The consideration of areal rainfall for pixel groups is multiplying this complexity.

### 5. Applications

The radar event data base is intended to be used for a number of practical applications. The most important ones which were mentioned by the future users are:

- analysis of the highest observed events and comparison to local event statistics
- filling gaps of precipitation observation for local flash floods far away from rain gauges
- rainfall runoff simulation of extreme events based on the extracted time series
- shift of extreme events to other locations for emergency situation simulation
- overview of locations with highest or most frequent extreme events since 2000
- radar rainfall statistics and comparison to rain gauge statistics
- comparison of catchment areas rainfall characteristics
- usage of extracted time series for the validation of the dimensioning of water management structures.
It has to be expected that this list will grow longer when the users get more experience with the data and the possibilities of this tool. This effect has been observed as well by developing a tool for the analysis of heavy point rainfall (Krüger et al., 2015). With the background of observed increased frequency of occurrence of heavy rainfall with high potential for damages in urban areas, the water board Emschergenossenschaft focused on detailed investigations with regard to predefined selection criteria and threshold criteria have been developed. This software tool has been designed for the long-term monitoring network of continuous recording rain gauges. The first steps using this tool show that the demands of analysis possibilities increase steadily. The Wupperverband experienced the potential of radar data statistics and developed more ideas for research and applications within the first attempts (Scheibel et al., 2015). By growing experiences the field of applications will be discovered and enhanced. Therefore the tool is extremely important to enlarge this experience.

6. Outlook

The first version of the software setup of the radar event data base will be available in December 2015. Extensions for future versions are radar cell statistics which can be interrogated from the data base so that cell track directions can be analysed. This is an interesting and important feature for flood protection in the context of the European Directive on Flood Risk Management (Scheibel et al., 2012).

References

Flash flood warning for emergency management

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Abstract

Heavy rainfall events can cause severe damage on a local scale due to urban flash floods. The project RainAhead, funded by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety, was conceived to reduce potential risks caused by urban flash floods for the city of Luebeck. The project’s main objective was to develop a planning and warning tool to improve flood damage mitigation and the emergency service’s effectiveness. The project included an assessment of potential climate change impacts concerning heavy rainfall. The warning tool combined emergency service experiences, modelling results and the current weather situation and issued real-time warnings for urban quarters that would be subject to flooding. The warning system was implemented in May 2015 and has been evaluated since.

1. Introduction

The City of Luebeck had to deal with several heavy rainfall events in the past (e.g. 2001, 2002 and 2011). The project RainAhead (Integrated planning and warning tool for heavy rain in urban areas, www.rainahead.de) was designed to mitigate flood damage and reduce potential risks due to climate change in the City of Luebeck. The main objective was to identify locations prone to urban flash floods and to use this information for improvement of urban planning as well as flash flood emergency warning. Together with the project partners - hydro & meteo GmbH & Co. KG, Luebeck University of Applied Sciences and the Hanseatic City of Luebeck - further parties involved such as the fire brigade, the municipal service for waste and wastewater, urban planning and citizens were working on innovative, transparent and sustainable practices. RainAhead is funded by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (support code 03DAS014). The project has been started in June 2013 with a duration of three years.

2. Methodology

2.1. Theory

Within RainAhead a tool for urban planning and warning related to heavy rain events for local communities based on a vulnerability analysis is developed. The resulting map shows areas, objects, natural resources or dangerous goods susceptible to urban flooding. The warning tool combines those known vulnerable areas with short-term forecast precipitation information provided by weather radar.
Fig 1: The warning tool: basic design.

Additionally, a planning tool proposes measures for urban planning in order to mitigate flood damage. The decision-making process is accompanied by a multi-day workshop with different stakeholders. To reduce information overload and include opinions of all participants, a sensitivity model (sensitivity model by Prof. Vester®) is used to help analyse complex issues during the process (Ulrich, 2005). During the workshop, the question “How can negative impacts of heavy rain events be reduced in St. Lorenz Sued?” is discussed to get an overall picture of the current state and to develop the most appropriate measures for flood protection. The methodology is applied to two districts first. A detailed analysis is conducted in St. Lorenz Sued district and validated in the “University district” of Luebeck.

2.2. Pragmatic approach

An analysis of fire brigade operations of the Luebeck city fire brigade as function of rainfall amounts was conducted. For this, radar data between 2009 and 2014 were screened and compared to emergency operations with a water-related keyword. Overall, 174 emergency operations took place at different locations of the city during 22 rainfall events. In order to have a basic data volume, events with only one action in one area were skipped from the data base, resulting in 163 operations during 15 rainfall events. Of these, 137 operations took place during 3 events in 2008 and 2011. Those were taken as investigation data base.

Since the different locations within the city show a different response profile for rainfall, a spatially varying assessment of rainfall response was required to be developed for those areas with a sufficient data base at hand. For the remaining areas, a summary approach was carried out. As a result, a “typical duration” of 20 minutes was determined, and rainfall thresholds ranging between 13 mm and 18 mm for the investigated areas, representing return periods between 3.3 years and 10 years. The latter value corresponds well with a previous analysis (Einfalt et al., 2012), whereas the former value has to be used for an area which is known to be sensitive to heavy rainfall.

3. Implementation

3.1 Web-based radar information

The warning tool was implemented as an online web application. The application includes real-time radar measurements from the DWD Boostedt radar and radar-based precipitation nowcasting (short-term forecast over a period of one hour) (Tessendorf and Einfalt, 2011). Radar measure-
ments show the spatial distribution of precipitation and enable to track small-scale rain cells. The accuracy regarding space is important in the case of urban flash floods which are often caused by small-scale convective rain events (Einfalt et al., 2004).

The web application was implemented within the already existing internet portal HydroNET-SCOUT which has been developed for the project HydroCity (Einfalt and Lobbrecht, 2012). Here, rainfall and forecasts are visualised in picture and animation. Time series of measured values can be plotted (see Fig. 2) and downloaded for further modelling, e.g. in rainfall-runoff-models. The precipitation data from measurements and forecasts were combined with the fire brigade experience to create warnings for objects susceptible to flooding. The resulting warnings are available on a map within the web application and sent via email to the emergency services.

Fig 2: The HydroNET-SCOUT web application: detail with plotted precipitation time series.

3.2 Fire brigade warning

The results obtained from section 2.2 were used to setup district-wide warning thresholds within HydroNET-SCOUT (Behnken et al., 2013). For this, the city was divided into 10 districts, and a warning was issued if a pixel value was above the district’s threshold. Figure 3 shows the pixels over the city of Luebeck.

The warning is then sent to the fire service headquarter and used by the work dispatcher at the fire brigade. First priority is for staff scheduling in the emergency hotline centre. A lesson learnt from a flash flood in Muenster in 2014 (Heuer, 2014) is that the majority of emergency calls could not reach their destination at the first attempt due to a lack of telephone lines manned.
4. Post-event analysis

On 5 May 2015, a severe cold front approached Luebeck around 5.40 p.m. local time. Due to heavy rainfall and particularly severe gusts of wind peaking more than 100 km/h, around 250 emergency operations of the fire brigade were required. The cold front also produced four tornados among which was a F3 tornado ca. 100 km to the east of Luebeck.

The Luebeck fire brigade team leader was quoted to be surprised by the impact of the cold front, although its arrival was to be seen on radar already 45 minutes prior to the first rain drops. The rainfall measurement (approx. 10 mm in less than 15 minutes) was disturbed by wind effects for the gauges and by attenuation at the radar site for the radar measurement – so both measurements have to be considered underestimating the true rain amount.

A post-event data analysis showed that first automatic warnings could have been issued at 5.00 p.m. Following the post-event analysis of this damage-producing event, the warning system was established online on 7 May 2015.

5. Operational experience

In the course of summer 2015, overall 10 warnings were produced – none of them was during catastrophic rainfall. The analysis of the false alarms revealed that too high forecast values were produced due to
- an overestimation of growth effects of the observed rain cells.
- “hopping values”, i.e. the forecast time step of 5 minutes produced over estimations at peak points and underestimations between peaks due to the instantaneous character of radar images.

While the first effect was quickly eliminated in the SCOUT precipitation data software, the second one needs more fundamental software extensions and will be ready for the 2016 summer period. In the meantime, the warning thresholds were raised by approximately 30% to improve warning system reliability.
6. Summary and outlook

The project RainAhead is part of Luebeck’s initiative to adapt to climate change. Project experiences show that the attention of the municipal administration for the project is high. The project outcome is desired for practical use in municipal routine processes and could bridge the gap between urban planning and urban water management.

The warning system within the HydroNET-SCOUT implementation has proven to be operationally functional and reliable.

The forecast procedure will be extended to produce smooth forecasts from 2016 onwards. As the methodological approach is easily transferable to other communities, an implementation in other cities’ administration and emergency management is envisaged.

References


ISO 19926: the first series of international consensus standards on weather radar

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Abstract

The potential of the utilisation of radar measured precipitation data is multifaceted. A series of International Standards on weather radar is being elaborated, which deals in particular with aspects of measurement technology, instrument configuration, and quantitative precipitation estimation for water management, data quality assurance, shortest term forecast and water management requirements. With this, for the first time, a series of international consensus standards will be created, which embrace this subject in complete form and is in interdisciplinary agreement.

Weather radar system performance and operation

The first part of ISO 19926 will describe system performance of ground-based weather radar systems sounding the atmosphere using frequencies between 2 GHz and 10 GHz. These systems are suitable for area-wide detection of precipitation and other meteorological targets at different altitudes. This part of ISO 19926 will also describe ways to verify the different aspects of system performance including infrastructure. It will not describe weather radar technology and its applications. Weather radar systems can be used for applications like quantitative precipitation estimation (QPE), the classification of hydrometeors (e.g. hail), the estimation of wind speeds or the detection and surveillance of severe meteorological phenomena (e.g. microburst, tornado). Some of these applications have particular requirements for the positioning of the radar system or need specific measurement strategies. However, the procedures for calibration and maintenance described in this International Standard apply here as well. This part of ISO 19926 will address manufacturers and radar operators.

Quantitative precipitation estimation

The main application which will be standardized in the second part of ISO 19926 will be quantitative precipitation estimation (QPE). Area-wide detection of precipitation areas opens a series of important applications. One popular qualitative application is the real-time display of precipitation areas, and the distribution of these displays e.g. on various Internet portals accessible to the general public. Many professional users, such as weather services, water management or agriculture utilise the data obtained by radar networks, to detect the precipitation distribution. For this reason, the second part of ISO 19926 will cover not only measurement techniques per se but also the procedures used in the preparation of the data for various applications.

An important application of radar data in urban systems: water management

In water management, precipitation is the most sensitive input variable. The following tables show examples of radar data applications (online and offline) in water management (VDI 3786-20, 2014).
<table>
<thead>
<tr>
<th>Online application</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTC of sewer systems</td>
<td>In real-time control (RTC) of sewers, the use of free storage capacity in the sewage network can be optimised by controlling the runoff. A small gain of reaction time is already achieved through the radar precipitation measurement, since the precipitation is measured at an altitude and therefore before it reaches the ground and enters the sewage network. A further and sometimes significantly greater gain of reaction time can be achieved by nowcasting with the help of radar data (cell tracking).</td>
</tr>
<tr>
<td>Control of Sewage treatment plants</td>
<td>In rainy weather, increased inflow into the treatment plant may occur over several hours, necessitating a temporary increase in its capacity. This requires precipitation forecasting that predicts exceedance of critical thresholds well in advance. The necessary forecasting horizon depends on the type of procedures implemented at the treatment plant and the structure (flow times) in the sewage network. As in RTC of sewers, here too radar data can improve the quality and lead time of the required precipitation forecasting.</td>
</tr>
<tr>
<td>Flood warning services</td>
<td>Precipitation products and nowcasts can be used either as input variables for hydrological or sewage network models. Information about the exceedance of critical precipitation levels and the resulting runoffs, is beneficial for many services.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Offline application</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation climatology</td>
<td>Long-term accumulations (days, months, years) of radar precipitation measurements allow analysis of special regional features of the precipitation distribution, e.g. those due to orographic effects, urban impact, preferred storm paths and windward-leeward effects. On this basis, it is possible e.g. to optimise measurement station networks or identify high-risk regions (e.g. those having a high risk of heavy precipitation).</td>
</tr>
<tr>
<td>Event documentation and analysis</td>
<td>Radar data offer a better understanding of extreme and damaging precipitation events. They make it possible, for example, to establish whether a structure failed due to technical or operational defects, or whether the event exceeded the design limit. The consequences of inundated areas by water courses, too, can be classified more effectively in this way (with implications for questions of liability/insurance cover).</td>
</tr>
</tbody>
</table>

References

Partitioning sources of uncertainty in local climate change projections

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Abstract

Impact studies and practical applications demand for climate change predictions of meteorological forcing at local spatial scales and fine temporal resolutions. Concurrently, climate models are typically more reliable at the global and regional scales, but they may have significant biases at the scales of “human action”, e.g., few square kilometres and sub-daily scale. Therefore, there is a demand for advanced techniques that offer the capability of transferring predictions of climate models and relative uncertainty to scales commensurate with practical applications and for higher order statistics.

A stochastic downscaling technique that makes use of an hourly weather generator (AWE-GEN, Fatichi et al. 2011) and of a Bayesian methodology to weight realizations from different climate models is used to generate local scale meteorological time series of plausible “futures” (Tebaldí et al. 2005; Fatichi et al. 2013). We computed factors of change from realizations of 32 climate models used in the Coupled Model Intercomparison Project Phase 5 (CMIP5) and for different emission scenarios (RCP 4.5 and RCP 8.5). The approach simulates future climate projections for several meteorological variables (precipitation, air temperature, relative humidity, shortwave radiation) at three locations characterized by differing climate conditions, Zurich (Switzerland), Miami and San Francisco (USA), selected as representative examples.

The methodology allow us to partition three main sources of uncertainty: uncertainty due to climate models (model epistemic uncertainty), anthropogenic forcings (scenario uncertainty), and internal climate variability (stochastic uncertainty). The three types of uncertainty sources are considered as dependent, implicitly accounting for possible co-variances among the sources, conversely to previous studies (e.g., Hawkins and Sutton, 2011). For air temperature, the magnitude of the different uncertainty sources is comparable for mid-of-the-century projections, while scenario uncertainty dominates at large lead-times. The dominant source of uncertainty for changes in precipitation mean and extremes is internal climate variability, which is accounting for more than 80% of the total uncertainty also for end-of-the-century projections. For precipitation, the uncertainty due to historic climate variability is covering a large fraction of the total uncertainty for the projected future (Fig. 1). The relative magnitudes of the uncertainty sources are remarkably independent from the climate type for the three selected locations.

For precipitation statistics, there is a limited room for uncertainty reduction even for end-of-century projections because uncertainty is almost entirely due to internal climate variability. Conversely, projected changes in air temperature and other variables can be largely constrained, even at local scales, if more accurate emission scenarios can be delineated.
Fig 1: Changes in mean monthly precipitation ($\Delta Pr$ in mm) simulated with the weather generator for the period 2046-2065 with respect to the observational period for Zurich (upper row), San Francisco (middle row) and Miami (lower row). The observational period is 1981-2010 for Zurich and 1961-1990 for San Francisco and Miami. The coloured areas represent the 5th and 95th percentiles of the projections. Different uncertainty sources are presented: (a) total uncertainty; (b) climate model uncertainty; (c) stochastic uncertainty (internal variability); (d) emission scenario uncertainty; and (e) historic stochastic uncertainty. In (b) and (c), results for the two emission scenarios (RCP4.5 and RCP8.5) are presented separately.

References


Investigation of wet antenna attenuation dynamics of cellular microwave links

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Abstract

Use of microwave attenuation for path-integrated rain rate estimates attracted broader attention of scientific community in recent decade with extensive global growth of cellular microwave link (MWL) networks (Messer et al., 2006). Quantitative precipitation estimates from MWLs are, however, often biased by additional attenuation, so called wet antenna attenuation (WAA), caused by microwave scattering on wet radomes of antennas. Although, there have been several studies investigating this phenomenon (e.g. Leijnse et al., 2008) the dynamics of antenna radome wetting and its effect on WAA is still not well understood. This investigation therefore focuses on quantitative and qualitative description of WAA dynamics and presents initial results of dedicated experiment based on direct measurements of antenna wetting in our experimental catchment in Prague, Czech Republic.

The experimental layout consists of four commercial MWLs (25 GHz, 32 GHz and 2 x 38 GHz, MINI-LINK TN, Ericsson) operated by T-Mobile CZ. MWLs are polled each 15 seconds for their attenuation. Both antennas of MWLs are equipped by moisture probes TMS-3 (Tomst) which detect raindrops on the sensor surface (dt = 1 min). One distrometer (Thies Clima, dt = 1 min) is located at the main MWL node common for all four MWLs. It enables us to classify rainfalls and measure low rain rates. In addition rain rates are measured with dense network of six tipping bucket rain gauges (res. 0.1 mm/tip) placed at four locations in the catchment (Fencl et al., 2015). The analysis focuses mainly on light rain events where WAA dominates over path-integrated attenuation caused by raindrops. In addition, data form several experiments when antenna radomes were sprayed with simple sprinkler are analysed. The experimental period is from August 2014 until March 2015.

Fig. 1 Left: One of the antennas equipped by moisture probe TMS-3. Right: WAA Dynamics of 38 GHz antenna after spraying during dry weather with moderate wind heading towards antenna radome.
Our initial results show that both antenna wetting and drying dynamics is a complex process influenced not only by rain rate and length of period for which the antenna is exposed to rainfall but also by other environmental variables (wind, radiation). The analysis of light rainfalls show that WAA increases typically about 1 dB very quickly after beginning of rain event (often much earlier than any rainfall is detected by tipping bucket rain gauges) and stays at this level also for some period after the event. The length of this period depends probably on radiation and wind. Antenna spraying experiments however show that WAA responses very dynamically on radome wetting. WAA increases up to 4 - 6 dBs but within one minute after spraying decreases to one half or even quarter of the maximum value. This implies that WAA is partly caused by moist surface of antenna radome and partly by raindrops trickling down the radome. Whereas the „moist antenna attenuation“ has slow dynamics probably rather dependent on radiation and temperature, the “raindrop antenna attenuation” is very dynamic and depends strongly on exposition of antenna to the raindrops, i.e. probably not only on rain rate itself but also on wind direction and velocity.

Distinguishing between two states of antenna wetness (moist radome x radome with trickling raindrops) could improve recent WAA models which either assume WAA to be rain rate dependent or vice versa constant during the whole rain event or after some initial wetting period. The new model describing this behaviour could decrease bias in MWL rainfall estimates or/and improve MWL error models needed for efficient assimilation of MWLs with other traditional rain sensors. Our further research is focused on influence of other environmental variables (esp. wind) on WAA dynamics and relation between WAA and rain rate which is currently investigated on very short MWLs by which WAA dominates over path-integrated attenuation.

Acknowledgements

This work was supported by the project of Czech Science Foundation (GACR) No. 14-22978S and the project of Czech Technical University in Prague project No. SGS15/050/ OHK1/1T/11. We would like to thank T-Mobile Czech Republic a.s. for kindly providing us MWL data and being very helpful with development of the application for MWL polling. Special thanks belong to Pražské vodovody a kanalizace, a.s. who provided and carefully maintained the rain gauges. Last but not least we would like to thank Pražská Vodohospodářská společnost a.s. for providing us additional rainfall information from their RG network.

References

Dynamic bias correction of commercial microwave links

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Abstract

Urban storm water management requires rainfall data of high spatial and temporal resolution which are often not available (Schilling, 1991). Path-integrated rain rate information from cellular microwave links (MWLs) has potential to aid in this regard (Messer et al., 2006) as MWL network are very dense in urban areas and rain rate information can be at virtually no cost polled from each single MWL with sub minute temporal resolution. Unfortunately MWL rainfall is often significantly biased (Fencl et al., 2015). In this investigation we proposed method to dynamically correct MWL rain rates by remote rain gauges (RGs) with hourly temporal resolution, i.e. RGs often operated by national weather services. Our results show that although these RGs have insufficient resolution for most of the urban storm water management applications they can be conveniently used to calibrate MWL attenuation-rain rate model. Such calibrated model provides unbiased high-res quantitative precipitation estimates.

Methods

Commercial MWLs of cellular operators operate at frequencies where rain drops cause significant microwave attenuation. This attenuation can be related to rain rate using simple power law model. The other way around rain rates can be reconstructed from this attenuation and MWL can be used as a virtual RG:

\[ R = \alpha \cdot k^\beta \]  

(1)

where \( k \) [dB/km] represents MWL specific rain induced attenuation, \( \alpha \) and \( \beta \) are empirical parameters dependent on MWL frequency and polarization and drop size distribution (DSD). Specific attenuation \( k \) is usually determined as a difference between dry and wet weather specific path loss [dB/km]. In our case baseline for wet weather is estimated as a 99% quantile of antecedent dry weather specific attenuations. However, as additional attenuation caused by antenna wetting occurs during rainfall this simple baseline separation leads to significant bias. Therefore parameter \( a_w \) [dB/km] reflecting this bias should be subtracted from specific attenuation to correct the MWL rainfall:

\[ R = \alpha \cdot (k - a_w)^\beta \]  

(2)

The parameter \( a_w \) can be modelled by different wet antenna models (e.g. Leijnse et al., 2008), however these models are affected by significant uncertainty.

The proposed method treats \( \alpha \) and \( a_w \) as a calibration parameter and assumes \( \beta \) to be constant. It takes advantage of the fact that \( \beta \) is close to unity for frequencies most commonly used by cellular...
operators (20-40 GHz) and $a_w$ usually does not exceed few dB/km. Thus taking $β$ from literature (ITU, 2005) k-R model (2) can be treated as linear:

$$R ≈ α*(k' – a_w')$$

where $k' = kβ$ and $a_w' = a_wβ$. This is very convenient because linear model can be fitted using attenuation and rain rate data aggregated to arbitrary time step. We take advantage of a fact that spatial correlation of rain rates increases with time span over which they are integrated (e.g. Berne et al., 2004). Thus, using RG hourly data, i.e. data often available by national weather services, even rain rates from relatively far away RGs can be assumed as representative for MWL calibration. As the k-R model is nearly linear (3), fitted parameters used for original not aggregated MWL data do not introduce additional bias into rain rate estimates.

Both $α$ and $a_w'$ depend on rainfall type but also other environmental variables. Parameter $α$ is dependent on DSD but, especially by longer MWLs where rainfall can hit only part of its path, also on rainfall spatial variability. Parameter $a_w'$ depends besides of rain rates also on wind velocity and direction and other climatic factors influencing antenna wetting and drying (e.g. radiation, humidity, dew). In addition, $a_w$ can compensate bias introduced by baseline separation. As such both parameters $α$ and $a_w'$ vary in time. Dynamics of their changes can be captured to some extent by introducing dynamic calibration. Dynamic calibration is based on continuous fitting of k-R model using moving window of last wet weather consecutive hours. Optimal length of a window depends on a temporal aggregation of MWL and RG data and typical spatiotemporal patterns of rainfalls. Longer windows reduce errors introduced by optimization and quantization noise, however smooth out dynamics of parameter changes. In our investigation, where hourly RG data are used for MWL calibration, a window of three consecutive wet weather hours appears to be optimal.

Case study Prague-Letnany

We test the approach on five selected MWLs located in our experimental catchment Prague, Czech Republic (Fencl et al., 2013). The catchment has an area 2.3 km² and it is equipped by six tipping bucket RGs at four different locations (two of them are collocated). These RGs are used to calculate reference areal rain rates over the catchment’s area. MWLs are calibrated using rainfall from three remote tipping bucket RGs located between 2.5 and 3.5 km from the catchment (Fig. 1). These RGs provide hourly rain rates aggregates. MWLs were selected for the analysis based on multiple criteria. First of all MWL data availability was considered. Second, short MWLs were of special interest. On the one hand they cover very well catchment area, i.e. do not overlap its borders significantly, on the other hand they are usually more biased as wet antenna attenuation represents proportionally higher ratio of their total specific attenuation due to shorter path lengths along which rain drops attenuate their microwaves. Besides four short MWLs also one long was selected (Tab. 1) to investigate effect of path averaging on areal rain rate estimation.

<table>
<thead>
<tr>
<th>ID</th>
<th>Frequency [GHz]</th>
<th>Polarization</th>
<th>Length [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32</td>
<td>H</td>
<td>647</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>V</td>
<td>1024</td>
</tr>
<tr>
<td>3</td>
<td>32</td>
<td>V</td>
<td>611</td>
</tr>
<tr>
<td>4</td>
<td>38</td>
<td>H</td>
<td>1399</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>V</td>
<td>4533</td>
</tr>
</tbody>
</table>

Dynamically calibrated MWLs are compared against reference areal rain rates of one minute temporal resolution. Experimental period is between August and October 2014. All rainy hours are used for dynamic calibration (i.e. hours with $R > 0$ mm/h), however only events exceeding total heights 5 mm, i.e. events relevant for runoff generation, are included into performance evaluation.
Root mean square error (RMSE) is chosen as a performance statistics, as it reflects the ability to capture temporal dynamics of rainfalls.

Fig 1: Experimental catchment Prague-Letnany with experimental layout depicting MWLs evaluated (solid line) and MWLs excluded from the evaluation (dotted line), reference RGs (triangles) and remote RGs used for MWL calibration (rectangles).

Results and Discussion

Our results show that hourly data from remote RGs can significantly improve MWL areal rain rates of high temporal resolution. The calibrated MWLs are in general almost unbiased and capture very well areal rainfall dynamics. The most significant improvement appears by low rain rates where wet antenna attenuation dominates over the path rain drop attenuation (Fig. 2).

Fig 2: Rain rate from 32 GHz horizontally polarized MWL before (dotted line) and after (solid line) dynamic calibration.
The reduction in RMSE compared to k-R model with not calibrated parameters taken from ITU (ITU, 2005) is 19 to 67 % for single MWLs (Fig. 3). The highest reduction in RMSE (61 %, 63 %, 67 %) appears by MWL 1, 2 and 3, the lowest reduction (19 %) appears by MWL 5. The RMSE after calibration ranges for all single MWLs between 1.03 mm/h (MWL 3) and 1.46 (MWL 5). Mean MWL rain rate calculated from four short MWLs (MWL 5 was excluded as it overlaps catchment) has RMSE only 0.92 mm/h. To put the MWL errors into context we also compare rain rates measured by each single reference RG separately with areal reference rain rate, i.e. rain rate calculated from all RGs together. RMSE of single RGs ranges between 1.34 to 1.78 mm/h which is significantly higher than the one from MWLs.

Interestingly, MWLs with highest initial RMSE (MWL 1, 2, 3) experience after calibration the most significant improvement and have then the lowest RMSE also in absolute values. These are links which are least sensitive to path rain drop attenuation (short paths and/or low frequencies) but very well cover catchment area. In contrast, reduction of RMSE by MWL 5 which has the lowest initial RMSE is not so significant. This is probably because it overlaps catchment area and thus cannot capture properly local maxima and minima of rainfalls.

Although selected short MWLs cover very well catchment area their performance after calibration is surprisingly good, considering their rough quantization 1 dB and 1/3 dB for transmitted and received signal power, respectively. When estimating rain rates from path attenuation these quantizations correspond to approx. 6 and 2 mm/h, respectively. This may indicate, that antenna wetting (or other hidden factors influencing microwave attenuation) increases sensitivity of short MWLs to rainfall and can possibly contribute to MWL rainfall estimation.

Conclusions

MWLs can be conveniently corrected for a bias even by remote rain gauges with low temporal resolution, i.e. by rainfall information often available by national weather services. Corrected MWL rain rates correspond very well to reference rainfall measured in our experimental catchment and even significantly outperform rain rates measured by single RGs. Further research is currently focused on better understanding of dynamics of parameter changes and their causes and possible correction of MWLs using longer rain rate aggregates (e.g. day or longer). This will help to improve suggested method and formulate optimal strategy for MWL calibration when RGs are even more far away (tens of kilometres) than in our case or temporal resolution of RG data is even lower than one hour.
Acknowledgements

This work was supported by the project of Czech Science Foundation (GACR) No. 14-22978S and the project of the Czech Technical University in Prague project No. SGS15/050/OHK1/1T/11. We would like to thank T-Mobile Czech Republic a.s. for kindly providing us MWL data and being very helpful with development of the application for a MWL polling. Special thanks belong to Prazevodovody a kanalizace, a.s. who provided and carefully maintained the rain gauges. Last but not least we would like to thank to Prazska Vodohospodarska spolecnost a.s. for providing us additional rainfall information from their RG network.

References

Probabilistic and ensemble verification of the Short-Term Ensemble Prediction System in Belgium

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Abstract

The Short-Term Ensemble Prediction System was implemented in real-time at the Royal Meteorological Institute of Belgium (RMI) and is referred to as STEPS-BE (Foresti et al., 2015). STEPS is a probabilistic precipitation nowcasting system based on the extrapolation of weather radar images. The key idea behind STEPS is to represent the forecast uncertainty by perturbing a deterministic radar extrapolation nowcast with stochastic noise. The stochastic perturbations are designed to account for the unpredictable precipitation growth and decay processes (in moving coordinates) and to reproduce the spatial and temporal correlations of the forecast errors.

STEPS-BE provides 20 member ensemble precipitation nowcasts at 1 km and 5 min resolutions up to 2 hours lead time using as input the composite image of the 4 C-Band radars located at Wideumont (RMI), Zaventem (Belgocontrol), Jabbeke (RMI) and Avesnois (MétéoFrance). STEPS-BE also includes a couple of improvements to obtain smoother velocity fields and to generate stochastic rainfall within the boundaries of the advected radar composite.

Foresti and Seed (2015) performed a deterministic verification of STEPS nowcasts using 2 years of Australian weather radar data in the surroundings of Melbourne. Using the same dataset, Foresti and Seed (2014) studied the spatial heterogeneity, flow- and scale-dependence of the predictability of precipitation by STEPS. Both studies revealed a significant flow-dependence and spatial heterogeneity of the predictability of precipitation due to orographic forcing, but they did not analyze the reliability of probabilistic forecasts and spread of ensemble forecasts.

![Reliability diagram for the probabilistic forecast of exceeding 0.5 mm hr⁻¹ (left) and 5.0 mm hr⁻¹ (right). The small inset displays the sharpness diagram (Figure from Foresti et al., 2015).](image-url)
This contribution presents the probabilistic and ensemble verification of STEPS nowcasts in Belgium. The considered case study starts at 22:00 UTC on 19.07.2014 and ends at 06:30 UTC on 20.07.2014, for a total of 8h30 of rainfall. The accuracy of probabilistic forecasts is examined using reliability diagrams (see Fig 1). The grey area depicts probabilistic forecasts having a positive Brier Skill Score, i.e. that perform better than using the sample climatological frequency of the event as a forecast. Probabilistic forecasts of exceeding 0.5 mm hr\(^{-1}\) are reliable and exhibit predictability up to 120 min lead time (Fig 1, left). On the other hand, probabilistic forecasts of exceeding 5.0 mm hr\(^{-1}\) are only reliable up to 30 min lead time, which is simply due to the lower predictability of convective rainfall features. The probabilistic forecast of exceeding 5.0 mm hr\(^{-1}\) is also less sharp, which means that there are very few certain forecasts (see “Histogram” insert in the figure).

Fig 2 (left) shows the comparison of the error of the ensemble mean (RMSE) with the ensemble spread (standard deviation of ensemble members about the ensemble mean). The ensemble spread is lower than the error of the ensemble mean, which means that STEPS nowcasts are slightly under-dispersive and thus underestimate the forecast uncertainty. Fig 2 (right) illustrates the rank histogram of the 5 min lead time forecast, which is constructed by ranking the ensemble members from the lowest to the highest and evaluating the frequency distribution of the observations in each bin. Also the rank histograms denote a slight ensemble under-dispersion since a certain fraction of the observations falls outside of the lower and higher ensemble members. There are also relatively more observations that are above the highest ensemble members, which is probably due to the forecasts being less able to model the rainfall extremes.

The conclusions for this specific rainfall event are that:
- The probabilistic forecasts of exceeding 0.5 mm hr\(^{-1}\) are reliable up to 120 min lead time.
- The probabilistic forecasts of exceeding 5.0 mm hr\(^{-1}\) are reliable up to 30 min. As expected, convective rainfall features have less predictability than large areas of stratiform rain.
- The STEPS ensembles are slightly under-dispersive since the ensemble spread only represents ~80% of the forecast error.

Fig 2: Comparison of ensemble mean error and ensemble spread for various lead times (left). Rank histogram for a lead time of 5 minutes (right). Figure from Foresti et al. (2015).

References

Objective regional frequency analysis of extreme precipitation in Sicily, Italy

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Abstract

The extreme events have large impacts on society and are likely to increase under climate change. For design and management decisions, particularly around hydraulic infrastructures, accurate estimates of precipitation magnitudes are needed at different durations. In this paper, the regional frequency analysis has been implemented and applied to precipitation data recorded in Sicily, Italy. Annual maximum series for rainfall durations of 1, 3, 6, 12 and 24 h provided by about 130 rain gauges were used. The Regional Frequency Analysis (RFA) has been used to identify the homogeneous regions using Principal Component Analysis (PCA) followed by a clustering analysis, through k-means, aimed to identify regional groups. Two regional probability distributions have been used in order to derive the Depth-Duration Frequency (DDF) curves: lognormal distribution with three parameters (GNO) and generalized extreme value distribution (GEV). The regional parameters of these distributions were estimated using the L-moment ratios approach while the relative bias and relative RMSE have been calculated using a simulation study of regional L-moment algorithm for the assessment of the accuracy.

1. Introduction

The extreme precipitations show intensification in many regions and this is of key importance to society as a result of the large impact through flooding (Trenberth et al., 2003). For design and management decisions, particularly around hydraulic infrastructures, accurate estimates of precipitation at different durations are needed. Frequently the historical available rainfall series are unsuitable for this estimation process because of the gaps present in the period of registration, and then the regional frequency analysis is necessary. Regional rainfall frequency analysis (RFA) plays an important role for several civil infrastructure design and non-structural problems involving natural hazards associated with extreme rainfall events.

In previous works, it has been demonstrated that RFA provides more reliable estimates of return periods for extreme rainfall even in the case when the dataset is not very large (Hosking and Wallis, 1988). RFA is also able to resolve the problem of the evaluation of precipitation extremes at ungauged sites within the same region.

The aim of this work consists in the design and the application of the RFA procedure for the area of Sicily, Italy, based on the selection of suitable procedures which take into account the data availability and the meteorological features of the area. In previous works, related to the same area (Cannarozzo, et al. 1995; Lo Conti et al., 2007), the choice of the number and the extension of the homogeneous regions were made using hydrological criteria related principally on watersheds boundaries. In this work, we adopted an objective method to obtain the homogeneous regions that allow to consider several variables, linked to the extreme precipitation, in a robust mathematical framework.
2. Methods

Our analysis has been performed following the approach similar to that used by Jones et al. (2013). The first step of the methodology is the selection of the variables to include in the region identification. These variables directly influence the regional frequency analysis performances in terms of homogeneity. Variables adopted for this study are reported in Table 1.

Table 1: Variables used in rainfall region development.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z )</td>
<td>Station elevation</td>
</tr>
<tr>
<td>( AMR_d )</td>
<td>Annual maximum rainfall for different durations (mm)</td>
</tr>
<tr>
<td>( \theta_d )</td>
<td>Mean date of the events, represents a measure of the average time of occurrence of rainfall events.</td>
</tr>
<tr>
<td>( r_{m,d} )</td>
<td>Seasonality vector, provides a dimensionless measure of the spread of the data.</td>
</tr>
<tr>
<td>( nDry )</td>
<td>Number of days &lt; 1mm</td>
</tr>
<tr>
<td>( Rs/Rw )</td>
<td>Ratio between summer rainfall (April - September) and winter rainfall (October - May)</td>
</tr>
</tbody>
</table>

The Principal Component Analysis (PCA), whose primary purpose is to reduce the number of variables obtaining some “latent” variables which result uncorrelated (Wilks, 2011), was performed on the initial dataset. It is particularly useful when one needs a data reduction procedure that makes no assumptions concerning an underlying causal structure that is responsible for co-variation in the data. The principal components can be defined as a linear combination of optimally-weighted observed variables. Usually, only the first few components obtained are retained and interpreted. The PCA analysis has been applied to the selection of variables estimated for each station.

The successive cluster analysis was performed using the reduced number of significant synthetic variables retrieved from the PCA to which the normalized latitude and longitude of stations have been added to support the grouping of continuous regions. Operationally, the cluster analysis was performed using the \textit{k-means} clustering method (Hartigan and Wong, 1979). This method operates placing centroids of the initial clusters and reallocating group memberships on the basis of proximity to the cluster centroids. The algorithm is iterated until each data vector is closest to its group centroid and no further reallocations of memberships are made.

The main difficulty related to the \textit{k-means} method is that the number of clusters, \( k \), must be predefined. There are different ways to define the number of clusters if they are not known a priori. Nevertheless, these methods may provide different results. Therefore, it is useful to try \textit{k-means} with an initial range of values of clusters.

Once a set of physically plausible regions has been defined, it is necessary to assess their degree of homogeneity. Following the RFA approach proposed by Hosking and Wallis (2005), in this work three different tests were chosen: the discordancy measure \( D \) for each station, to examine possibly anomalous behaviour of individual stations, the \( HW \) (Hosking and Wallis, 1993) and the Anderson-Darling \( AD \) rank tests, (Stedinger et al., 1993) to assess homogeneity of the extreme rainfall regions obtained. Viglione et al. (2007) have compared the \( HW \) test and the \( AD \) test highlighting that, when the \textit{L-skewness} coefficient for the region under analysis is lower than 0.23, the Hosking and Wallis heterogeneity measure \( HW_1 \) can be considered the preferred method; if \textit{L-skewness} is greater than 0.23 the bootstrap Anderson-Darling test is preferable. In case of heterogeneity of a cluster, the possibility of combining it with another into a single region or that to subdivide it in two different clusters are evaluated.
The goodness of fit is evaluated for each homogenous region considering five parameter frequency distributions: generalized logistic (GLO), generalized extreme-value (GEV), lognormal (GNO), Pearson type III (PE3) and Generalized Pareto Distribution (GPA). After the choice of the frequency distributions, these were fitted to data from relative to sites in each homogeneous region. The distributions were fitted using the method of the L-moments (Hosking and Wallis, 2005) based on the dimensionless rescaled data $x'$. The quantiles relative to several return periods $T$ were obtained setting $F(x') = 1 - 1/T$. Finally, in order to evaluate the uncertainty and the reliability of the results obtained by statistical analysis, an assessment of the magnitude of uncertainty was carried out with a Monte Carlo simulation analysis.

3. Data

Sicily is the largest island in the Mediterranean Sea situated in the South of Italy with an area about 25,000 km$^2$. In order to apply the regional frequency analysis, this study used the extreme rainfall data published by the Servizio Osservatorio delle Acque. The rainfall data used in this research are the annual maxima rainfalls with durations equal to 1, 3, 6, 12 and 24 h and the daily time series. There is a total of 314 stations for sub-daily annual maxima data used for the analysis spanning the period 1928-2009 while for daily precipitation there are 382 stations spanning the period 1928-2009. However, some stations have many gaps due to non-operative periods and, for this reason, only those with at least 30 years of operation between the years 1972 and 2003 were selected, this being the period with maximum station operation. Thus, the observations for different durations comprise 124 stations, each with a minimum record length of 20 years.

4. Results

The Principal Components (PCs) evaluated separately for the different durations, were combined through an averaging operation because generally they showed similar score values among different durations. The residual percent variance method was used to select the principal components obtained from the analysis. It has been decided to retain the principal components which accounted for at least 5% of the total variance in the input dataset then only the five principal components were selected. Values of the score, for the first three principal components, highlight the responses of geography for the first component, while the second has shown a relation with the precipitation mean annual maxima and the greater value of the dry day; the third component is mainly related to the seasonality, with a particular influence in the east side where the events are short and intense. The five PCs obtained were used as input for the cluster analysis performed through the $k$-means.

Fig 1: Homogeneous regions obtained with the K-means.
As highlighted above, the cluster analysis was performed using the variables obtained from the PCA and, additionally, the latitude and longitude normalized of each station to support the grouping of continuous regions. In this study, the possible range of values of $k$ (i.e. number of clusters) was selected considering the minimum and maximum number of clusters used in previous work regarding the Sicily, i.e., from 3 to 8 (Cannarozzo et al., 1995; Lo Conti et al., 2007; Gabriele and Chiavalloti 2013). Therefore, this range was hence examined evaluating the results obtained through the method of the Silhouette value (Rousseeuw, 1987) which provided the most robust and optimal solution that relative to $k$ equal to 6.

At this point, the RFA tests described above are applied for the regions obtained. An analysis of the dependence of the L-moments values was achieved to confirm whether it was needed to consider a relation with the duration. The values of the regionally weighted L-moments were calculated for the different duration. The values of L-moments show clearly a behaviour of the L-moments of extreme rainfall for the duration of 1 hour different from that relative to the other durations (i.e. the latter results less variable). This behaviour could be due to the errors in the recorded data. Indeed, the uncertainty for the short duration is more evident because of the nature of the short extreme precipitations that could be due to particular meteorological conditions with different temporal and spatial extension compared with events of long duration. The distribution parameters are evaluated considering the mean value for each L-moment not including the values for the duration of 1h. When the test of homogeneity does not report a positive result for a region, the characteristics of sites that showed marked differences have been carefully examined, then these sites have been reassigned to other regions or deleted. In other cases, some clusters presented stations with discordant values although resulted homogeneous; in this case, stations were not deleted and they were used during the subsequent analysis.

On the basis of the homogeneous regions identified (Figure 1), the RFA was used to fit GNO and GEV distributions estimating the $x'$ quantiles (Figure 2) with the L-moments method.

![Fig 2: Growth curves for the different distributions, a) GNO and b) GEV.](image)

Finally, an assessment of the accuracy has been performed evaluating the BIAS and RMSE of quantiles estimated with fitted distributions with reference to those obtained from a Monte Carlo procedure reproducing the variability of data. Values of the relative BIAS resulted near zero or slightly negative for lower return periods. In particular, the GNO distribution reported a very low value. The RMSE values for the GNO and GEV distributions are very similar each other with an exception regarding the cluster 3, in particular in the extreme upper tail where $F \geq 0.99$ ($T \geq 100$ years). The cluster 3 has shown, for high return periods, a significant increase of the values of BIAS and RMSE, probably due to the small number of stations inside the region. The cluster 6, despite being identified as “possibly heterogeneous”, does not show RMSE values greater than the other clusters.
Since the values of the L-moment for the duration of 1h were not considered for the evaluation of the parameters of the distributions, the relative BIAS and RMSE for the GEV and GNO for the duration of 1h was evaluated comparing with the regional value achieved considering the real heterogeneity through the L-CV values for 1h and the regional growth curve previously obtained.

A comparison of BIAS and RMSE for the regional curve and for 1h duration are negligible, the greater difference is in the cluster 6 for both distributions. Finally, the regional growth curve obtained for durations lower than 3h shows acceptable performances.

5. Conclusions

This article presents a new set of regions for the RFA of precipitation in Sicily, obtained considering the matching between the at site characteristics with those relative to the extreme rainfall such as magnitude, the timing of events, seasonality and distribution between summer and winter events. The methodology adopted allows for a better and more robust regional frequency analysis, compared with traditional approaches. In previous works, the number of regions obtained with hydrological characteristic varied between three and eight. Through this new approach, homogeneous regions have been obtained with a cluster analysis, using new variables achieved by PCA. The best number of regions is equal to six, then similar to the number provided by previous works but with important spatial differences.

Quantiles have been obtained fitting two extreme different distributions, the GEV and the GNO. The precipitations for 1h duration showed a different behaviour due to particular kind of precipitation, usually convective precipitation with limited spatial extension. The GNO distribution has given result better than GEV, although both distributions have three parameters.

References


Implementation of a real-time warning and mapping system for natural hazards triggered by rainfall in mountainous and Mediterranean areas of Southeastern France

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Abstract

Due to its mountainous topography and its Mediterranean climate, the Provence-Alpes-Côte d'Azur (PACA) region in Southeastern France is particularly prone to flash floods, debris flows and mass movements (landslides and rockfalls). A mapping system for these rainfall-induced hazards has been tested by local and regional authorities and Government agencies since 2011 as part of the RHYTMME project. This system allows, thanks to radar rainfall estimation and rainfall-runoff modelling, the real-time warning and monitoring of flash floods wherever they may occur in the PACA territory. It is also intended to enable, during intense rainfall events, the localisation of the streams susceptible to generate debris flows and of the slopes the more likely to trigger landslides and/or rockfalls.

1. Introduction

Natural hazards occurring in mountainous areas (flash floods, debris flows, landslides, rockfalls) are largely dependent on rainfall. A good knowledge of these hazards and the ability to forecast them, therefore largely depend upon an accurate estimation of precipitations. In order to improve the risk management in the mountainous area of Southeastern France, Irstea and Météo-France have led the RHYTMME project with the support of the European Union, the Provence-Alpes-Côte d'Azur region and the French Ministry for ecology, sustainable development and energy (Westrelin et al., 2013). The goal of the project is to improve the ability to forecast and localize high-risk rainfall-induced hazards in the Provence-Alpes-Côte d'Azur administrative area. This goal is currently under achievement thanks to:

- the deployment of 3 X-band, dual-polarization radars in the Alpine region of southeast France, that allows to i) mitigate the coverage gaps of the French national radar network, mainly due to ground echoes and radar beam shielding by mountains, and ii) provide more accurate real-time quantitative precipitation estimates in this mountainous region;
- the implementation of a real-time warning and mapping system for rainfall induced natural hazards, fed by rainfall radar data and whose outputs are made available via the Internet to operators in charge of risk management (local and regional authorities, emergency and rescue services, road and rail networks managers, ...).

We describe here the achievements of the RHYTMME project regarding rainfall and related natural hazards warnings. The hazards warning system informs end-users on the imminence and the severity of hydro-meteorological events. The rainfall and flash flood hazards are real-time monitored while static information is currently given for debris flows, landslides and rockfall.

1 acronym for Hydrometeorological Risks in Mediterranean and Mountainous Areas, in French: Risques Hydrométéorologiques en Territoires Montagnards et Méditerranéens.
2. Flash flood warnings

To address the issue of rainfall and flash-flood warning, Météo-France and Irstea have developed the AIGA threshold warning system which compares real-time rainfall and runoff data with frequency estimates of rainfall and runoff (Lavabre and Gregoris 2006, Javelle et al. 2014). The real-time rainfall data are the radar rainfall accumulation information for different durations (1 hour, 2 hours, ... 72 hours) provided every 15 minutes by the radar network at the spatial resolution of 1 km². These data are compared to regionalized rainfall frequency estimates computed, in a previous research work, for the same durations and at the same 1 km² spatial resolution and for different return periods on the whole French territory (Neppel et al. 2014). Rainfall warnings are then provided on maps displaying the estimated return periods of the different radar rainfall accumulations for the ongoing event. The real-time runoff data are provided by a distributed conceptual hydrological model fed by the 1-hour radar rainfall grids and run every 15 minutes at a 1 km² resolution. It produces real-time peak discharge estimates along the river network which are compared to regionalized flood frequency estimates previously computed (Aubert et al. 2014). Runoff warnings are then provided on a river network map according to the estimated return period of the computed peak discharge. Figure 1 shows an example of the rainfall and runoff warnings emitted by the RHYTMME warning system, thanks to the AIGA method, for the 26/10/2012 storm event which occurred in the neighborhood of the city of Toulon. The main interest of the AIGA method, implemented in the RHYTMME warning system, is to be able to deliver to operational services rainfall warnings in any 1 km² of their area of interest and runoff warnings anywhere on the river network they monitor, even at ungauged locations.

Fig 1: AIGA warnings emitted at 16:00 the 26/10/2012 during a storm event in the neighborhood of Toulon city, southern France. (a) : Estimated return periods for the 1-hour radar rainfall. Estimated return period of rainfall:
- 2 years < T < 10 years
- 10 years < T < 50 years
- T > 50 years

(b) AIGA runoff warning for calculated peak discharge. Estimated return period of runoff:
- ~2 years < T < 10 years
- ~10 years < T < 50 years
- ~T > 50 years

3. Debris flow mapping

The RHYTMME warning and mapping system also provides a regional debris flow susceptibility map (Figure 2). This map has been produced thanks to geomatic and statistical methods integrating the two main predisposing factors to debris flow activity, which are the stream and catchment morphometry, and the sediment availability within the catchment. Within the triggering areas, a map of active erosion patches has been automatically produced based on the analysis of infrared orthophotos (IGN©) with remote sensing methods. A robust statistical model was also developed to predict the debris flow activity based on morphometric indicators to discriminate the bedload transport from the debris flow processes (Bertrand et al. 2013). The integration of these two factors (sediment availability and morphometric conditions) within source areas, allowed predicting the susceptibility to debris flow triggering. More downstream along the stream network, the susceptibility to debris flow propagation was computed for a given reach according to its own
probability of debris flow activity (its morphometric characteristics) and the susceptibility to debris flow activity of the reaches located upstream (recursive process). More details can be found in Bertrand (2014). This approach, developed by Irstea and applied in Southern Alps on each catchment smaller than 40 km², has been validated with field observations.

Fig 2: Map of susceptibility to debris-flow activity within the triggering areas.

The debris flow maps – susceptibility to debris flow activity within the triggering areas (figure 2) and susceptibility to debris flow propagation along the stream network – can be displayed in the RHYTMME warning system along with the real time maps of rainfall hazard in order to identify, during intense events, the areas the more likely to generate debris flows.

4. Landslides and rockfall mapping

Static landslides and rockfall hazards maps, produced by Cerema, are also available in the RHYTMME warning and mapping system. Cerema has developed a theoretical approach based on a geostatistical analysis of 1712 landslides events and 1567 rockfall events, and their related antecedent rainfall conditions, that have occurred in Southeastern France since 1900 (Batista et al. 2013). This approach is based on the subdivision of the Provence-Alpes-Côte d'Azur region into 13 areas showing a geotechnical homogeneity. In each of these areas, a statistical law calibrated on the observed data was established to assess the average number of hazards, and a simple law was established, relating this average number of hazards to different landslides and rockfall susceptibility factors, such as the slope, the exposure, the distance to the river network and the distance to geological faults. This regional approach enabled to assess the density of landslides and rockfall events in any point of the PACA area knowing the geotechnical area it belongs to and the values of the susceptibility factors in this point. It was then possible to draw maps displaying the susceptibility to landslides and rockfall based upon these densities of landslides and rockfall events (Figure 3).
Fig 3: Map of the susceptibility to landslides triggering, taking into account the number of observed events since 1900 in each homogeneous geotechnical area and susceptibility factors.

The landslides and rockfall maps can be displayed in the RHYTMME warning system along with the real time maps of rainfall hazard in order to identify, during intense events, the areas the more likely to generate landslides and/or rockfall.

5. Conclusions

The RHYTMME flood warning and mapping system has been successfully tested since 2011 by more than 80 local and regional authorities as well as Government agencies in charge of risk management. On the basis of this experiment, it will be fully implemented and made available to all local authorities of the PACA region by the end of 2016 (approximately 1000 user authorities). Current research work in the field of flood warning focus now on enhancing the current hazard warnings by producing flood risk warnings that will take into account the vulnerability of the exposed territories. Current work in the fields of debris flow, landslides and rockfall now focus on the determination of rainfall thresholds associated with debris flow, landslides and rockfalls triggering. For debris flow, this work is based on the compilation of data from several debris flow monitoring stations recently deployed in active torrents of the French Alps (Bel et al. 2014). The aim is to enable to deliver debris flow, landslides and rockfall warning based on the real time radar rainfall estimation.

References


Assessment of probabilistic areal reduction factors of precipitations for the whole French territory with gridded rainfall data

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Abstract

The purpose of our study was to develop and test a simple methodology to derive areal rainfall quantiles from point rainfall quantiles, via the concept of probabilistic areal reduction factor (ARF). This concept enables to estimate areal rainfall of a particular frequency and for a given duration from point rainfalls of the same frequency and duration. Assessing such ARF for the whole French territory is of particular interest since it should allow us to compute areal rainfall quantiles, and eventually watershed rainfall quantiles, by using already available grids of statistical point rainfall that are provided by a regionalized stochastic hourly point rainfall generator, the SHYREG method previously developed by Irstea and Météo-France for the French Ministry of ecology, sustainable development and energy (Arnaud et al., 2007).

1. Introduction

A stochastic hourly point rainfall generator was developed by Arnaud et al. (1999; 2007) to assess extreme rainfalls in France. Its ability to reproduce the different kinds of French climate (temperate climate for mainland France and tropical climate for the overseas French territory) and the regionalization of its parameters (Arnaud et al., 2008) enable to generate long time series of rainfall in each km² of the French territory. Being calibrated independently on numerous raingauges data, this method suffers from the limitation common to point-process rainfall generators stressed by Rodriguez-Iturbe et al. (1987) and Burlando et al. (1993): it can only reproduce point rainfall patterns and has no capacity to generate rainfall fields. Although it gives access to point rainfall quantiles everywhere in France, it can’t provide areal rainfall quantiles, the estimation of the latter being however needed for the construction of design rainfall or for the diagnostic of observed events.

One means of bridging this gap between local rainfall quantiles and areal rainfall quantiles is given by the probabilistic areal reduction factor of rainfall as defined by Omolayo (1993) who suggests that to obtain the probabilistic ARF for a duration D, the T-year areal rainfall $P_{area}$ over a region of size A should be divided by the $w_i$-weighted average T-year point rainfall $P_i$ of all gauges $i$ in the same region:

$$ARF(A,D,T) = \frac{P_{area}(A,D,T)}{\sum_{i=1}^{n} w_i P_i(D,T)}$$

Historically studied on dense network of raingauges, this factor has been computed here using rainfall fields instead of point rainfall data. This has led to a $w_i$ weight of 1 in equation 1, for the rainfall $P_i$ estimated in each pixel $i$ of the rainfall field.

We have computed the probabilistic ARF thanks to two sets of rainfall fields available on the whole mainland French territory. The originality of this study is the geographical domain covered: it is the first time so far that the ARF have been studied considering the whole French territory.
2. Data

Two sets of rainfall fields were gracefully provided by Météo-France, the French national weather service:
- a set of hourly rainfall fields from a 10-year reference database of Quantitative Precipitation Estimation (QPE) over France (Tabary et al., 2012),
- a set of daily rainfall fields resulting from a 53-year high-resolution atmospheric reanalysis over France with the SAFRAN-gauge-based analysis system (Vidal et al., 2010).

3. Method

We have built samples of maximal rainfalls for each cell location (the “point” rainfalls) and for different square areas centered on each cell location (the areal rainfalls) of these gridded data. To compute rainfall quantiles, we have fitted a Gumbel law, with the L-moment method, on each of these samples. Our sampling methodology and the data used have enabled us to assess the probabilistic ARF values in mainland France for:
- different square areas,
- different rainfall durations: sub-daily to 3-day rainfall,
- different return periods: from 2 to 100-year for the SAFRAN rainfall, from 2 to 20-year for the QPE rainfall,
- different time periods: whole year, “winter” period from December to May and “summer” period from June to November,
- different climatic areas taken from Choisnel et al. (1988) and shown in Figure 1: the oceanic, the semi-oceanic, the semi-continental, the Mediterranean and the Mountain climate areas.

![Fig 1: main climatic zones in mainland France, from Choisnel et al. (1988).](image)

4. Results

The daily and hourly ARF computed in this data-intensive study have shown four main trends:
- a sensitivity to the return period as can be seen on Figure 2 that shows how the median ARF values, computed over France for the daily and hourly rainfall durations respectively, evolve with the size of the computation area and the return period;
- a sensitivity to the rainfall duration as can be seen on Figure 3 that shows how the median ARF values, computed over France for the 1-day, 2-day and 3-day durations, evolve with the size of the computation area;
- a sensitivity to the season as shown by Figure 4 that displays how the median daily ARF values computed over France for the winter and summer periods, evolve with the size of the computation area;
- a sensitivity to the geographical location as can be seen on Figure 5 that shows how the median ARF values, computed for the daily and hourly rainfall durations respectively, evolve with the size and the geographical localization of the computation area.

Fig 2: evolution, for different return periods, of the French median daily ARF computed with the SAFRAN annual maximal rainfall (left) and of the French median hourly ARF computed with the QPE (right) annual maximal rainfall.

Fig 3: evolution of the 10-year French median ARF computed with the SAFRAN annual maximal rainfall for different durations.

Fig 4: evolution of the French median ARF computed with the SAFRAN annual maximal rainfall for different seasons and return periods.
Our results show that the ARF values decrease when the return period increases, i.e., when the severity of rainfall increases. This means that the less frequent an areal rainfall, the more it differs from the mean local rainfall quantiles of the same occurrence, computed on the same area. The ARF values also decrease when the rainfall duration decreases. This means that, for a given return period, the shorter the rainfall duration, the more an areal rainfall quantile differs from the mean local rainfall quantiles of the same occurrence, computed on the same area. We have then shown that the ARF values are smaller for the summer period than for the winter period and the summer values. This seasonal trend is in agreement with the typology of rainfall events occurring in mainland France: convective events of small spatial extent in late summer and autumn and more frontal events of wide extent in winter and spring, the former being associated with a high spatial variability of rainfall and thus leading to low values of ARF, the later with a low spatial variability and thus with high values of ARF. The geographical location of rainfall has also an impact on the values of the ARF. Regional trends can hence be observed with low daily ARF values in the Mediterranean climatic area and ARF values close to 1 for the climatic zones of Northern and Western France (oceanic to semi-continental climate). The low values of ARF in the Mediterranean climatic area reflect the high geographical variability of rainfall which characterizes this specific climate.

5. Conclusion

The results of this data-intensive study led for the first time on the whole French territory are in agreement with studies led abroad (e.g., Allen and DeGaetano 2005, Overeem et al. 2010) and confirm and widen the results of previous studies that were carried out in France on smaller areas and with fewer rainfall durations (e.g., Ramos et al., 2006, Neppel et al., 2003).

Having demonstrated the general trends of the probabilistic ARF of rainfall for the French mainland territory, we will be able to assess its mathematical laws. These laws will then enable us to compute areal rainfall quantiles using the grids of statistical point rainfall provided by the French regional stochastic hourly rainfall generator presented above, the SHYREG method.

References


Examples of the spatio-temporal variability of the precipitation field in the western Alps as seen by rain gauges, ground-based and spaceborne weather radars

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Abstract

This abstract presents a detailed example of the spatio-temporal variability of the precipitation field on the southern side of the Alps during the last autumn. Unfortunately, although the rain rate at the Lugano region was not extraordinary, a small-scale landslide occurred and hit an isolated house in the vicinity of the small village of Bombinasco.

The study of precipitation in regions with complex topography is still an open challenge: the practical use is obvious and broad, but so are the problems. Hydrologists need areal precipitation measurements. Although rain-gauge measurements may contain errors, the most difficult problem is their areal representativeness. Owing to the spatial variability of rainfall, it is obvious that point, in situ measurements lack representativeness even when the measurements themselves are reliable. Radar measurements may add the desired information on the areal distribution of precipitation. However, it is well known that radar observations suffer from several types of problems that make difficult to transform instantaneous, volumetric backscattering measurements made aloft to the corresponding surface rainfall intensity values. This is why in the recent years MeteoSwiss has been developing “CombiPrecip” (Sideris et al., 2012), which is a sophisticated gauge-adjustment application of the radar-only precipitation estimates (AQC). The main purpose of this application is to produce every 10 minutes two-dimensional, hourly-accumulated, gauge-adjusted, radar-derived precipitation maps that are as close as possible to the in situ reference values. CombiPrecip (CPC) has been built on the basis of cutting-edge techniques originated in the field of geostatistics. It uses co-kriging with external drift to merge spatiotemporal information from a relatively small number of rain-gauge point values with the precipitation field observed by the radar and produces an improved precipitation map (Sideris et al., 2014).

On the southern side of the western Alps, autumn is the season in which the largest daily rainfall amounts usually occur. This fact has long been known, as the presence of such “late summer” storms appeared already in works by the Roman author Plinius. In autumn the temperature over the Mediterranean Sea is still high, while cold air is already generated over the central-northern part of Europe. On the one hand, the thermal contrast facilitates the deepening of pressure low over the north-western part of the Mediterranean Sea; on the other hand, the warm air that arrives from the south, flowing over the Mediterranean, provides a steady source of moisture. The enforced rising of this warm-humid “meta-stable” air due to the Alpine barrier, causes extensive rainfall in space, time and total amount. One has the impression of being subject to a long storm, but, in reality, it is the continuous formation of stormy cells over the same places.

In November 2015, two precipitation events, which unfortunately led to casualties caused by landslides, hit the area surrounding Lugano, on the southern side of the Alps: both events can be investigated using MeteoSwiss data coming from the telemetered network of in situ measurements and observations aloft coming from the recently updated Doppler dual-polarization weather radar network. Interestingly, such data can be complemented with informative external ancillary data: on November 4-5, in situ measurements from a Canton Ticino rain gauge that happened to be only 1 km from the landslide are available! For the November 15-16 event, we have one rainy overpass of
the Global Precipitation Measuring (GPM) dual-wavelength spaceborne weather radar (while Grisons and Valtellina were observed at both 13.6 and 35.5 GHz, Ticino was under the umbrella of the Ku-band radar only). By way of example, in this abstract we provide a brief introduction to aspects of the first event (4-5 November; both events will be thoroughly described in the conference short paper).

The landslide occurred on November 6 around 17 UTC in the kilometric radar pixel with label “F”, with coordinates: East = 708.5 km; North = 96.5 km (CH1903, LV03); the terrain altitude is one kilometer below the lowest elevation of the Lema radar scan program. The Novaggio rain-gauge, which belongs to the Ticino state administration, is located at 625 m altitude, just one pixel to the right. The range from Monte Lema radar is just 4.1 km (Azimuth is 151°).

Figure 1 shows 23 hours of intense precipitation on November 6 as seen by the Novaggio gauge (blue), the radar only (green) and CPC (red), which is the aforementioned real-time geostatistical combination of the MeteoSwiss radar and gauge network. Notice that CPC does not include measurement from Novaggio nor any other data from partners' networks. According to such nearby rain gauge, the maximum, which is 6 mm in ten minutes, occurred at 15:20 UTC. According to CPC and AQC, the maximum occurred one hour later (same order of magnitude). Such amounts are certainly neither extraordinary nor rare for the Ticino region; nevertheless, after several rainy days, it was probably "the straw that broke the camel's back", hence causing the landslide that occurred around 17 UTC.

![Graph showing accumulated precipitation over time](image)

**Fig 1:** Estimates of total precipitation amounts in the radar pixel “F” where the landslide occurred according to Monte Lema radar (green line) and CombiPrecip (red line). The blue line shows in situ measurements from the Novaggio rain-gauge, which belongs to the Ticino state administration and is not included in the operation, real-time, radar-gauge merging tool (CombiPrecip).

**References**


Radar observations of 50 x 50 x 50 m³ volume defined drop by drop: a numerical experiment

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Abstract

Radars are the only device providing rainfall measurements in both space and time. The conversion between the observed radar quantities (reflectivity at both polarizations, differential phases...) and the rain rate in which hydro-meteorologists are interested still remains an open issue. In this paper we investigate the potential effect of constructive or destructive interference between the waves backscattered by each individual hydrometeors, through a numerical experiment: 50 x 50 x 50 m³ volume with all its drops is simulated along with its radar observations.

The findings on the rainfall field very small scales (mm to few tens of m) spatio-temporal structure of the HYDROP experiment (Lilley et al. 2006) and a recent analysis of 2D video disdrometer data in a Multifractal framework (Gires et al. 2015), are used to generate a distribution of drops' location in a 50 x 50 x 50 m³ volume. More precisely the Liquid Water Content (LWC) distribution is represented with the help a multiplicative cascade down to 0.5 m, below which it is considered as homogeneous. The cascade process is characterized by two Universal Multifractal parameters $C_1$ (mean intermittency) and $\alpha$ (multifractality). Within each 0.5 x 0.5 x 0.5 m³ patch, liquid water is distributed into drops according to a pre-defined Drop Size Distribution (DSD) and located randomly uniformly. Various realisations of the cascade process and the random distribution are tested. Such configuration is systematically compared with the one consisting of the same drops uniformly distributed over the whole volume. Finally the radar observation of the studied volume is simulated: the complex electric field backscattered by each drop is computed using a T-Matrix code (Leinonen, 2014) before summing all the contributions and estimating the square of the modulus which corresponds the measured radar intensity ($I_{\text{radar}}$). In this first step only a horizontally polarized wave is considered.

It appears that the distribution of intensities covers a wide range of possible values according to the realization and is well described by an exponential law, as mentioned in previous publications. It means that over various realizations, the probability of exceedance $P_r$ will follow $P_r \propto e^{-a I_{\text{radar}}}$. An illustration is displayed Fig. 1 (left). Because in the implemented model the scaling features stop at roughly 50 cm, i.e. at a scale much larger than the radar wave length (3-10 cm for weather radars), there are no significant differences between the case where drops are randomly located within the patches or within the whole volume. For a given level of average liquid water content, the Universal Multifractal parameters which are used to simulate the cascade process as well as the drop size distribution - currently considered as homogeneous within the volume for simplicity- have a strong influence on the retrieved distribution.

The temporal evolution of short periods (~ 1s) is simulated to mimic the average over various pulses performed by radars. See Fig. 1 (right) for an illustration. It appears that turbulent velocities and not only ballistic ones need to be taken into account to reproduce observations.
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UR15-25

Fig 1: (left) Illustration of the exponential law for the probability distribution of the simulated radar intensities ($Pr \propto e^{-a t_{\text{vert}}}$) for various UM parameters. Scaling model for drops' distribution in red and random homogeneous one in blue. (right) Temporal evolution of the simulated radar intensities over 0.5 s when considering vertical terminal fall velocity and random horizontal one (smaller than 1/3 of the vertical one).

Now that the 3D tool is available other tests should be carried out, especially changing the location of the studied volume in elevation, varying the DSD within the studied volume, testing the impact on other radar quantities ($Z_{dr}$, $K_{dp}$). It would also be relevant to compare the results with observations of radar kept with a fixed azimuth and elevation during few seconds. This will be done with the new dual polarisation X-band which has recently been installed on the Ecole des Ponts ParisTech campus.

Authors acknowledge the financial support of the Interreg IV NEW RainGain project (www.raingain.eu) and the chair “hydrology for resilient cities” endowed by Véolia.

References

Improving the precipitation accumulation analysis for the benefit of hydrological and environmental forecast and management applications

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Abstract

Different methods on how to better estimate the precipitation accumulation fields have been investigated. A method combining radar data with precipitation gauge data, using the Regression and Barnes techniques (e.g. RandB-method), proved to increase the quality when calculating the precipitation accumulation amount. During summer 2015 a new method using lightning data (converted to artificial reflectivity profiles) has been investigated and show encouraging results. Additionally, the impact of different time sample interval (hours – days), to adjust the gauge-radar bias correction in RandB-method, is on-going work. The most recent results, from all the above mentioned assimilation techniques, will be presented at the UrbanRain conference 2015.

1. Introduction

To improve the precipitation analysis as much as currently possible, the Finnish Meteorological Institute (FMI) is developing methods that enable estimation of accumulated precipitation in a spatially precise and timely accurate manner, by upgrading the usage of weather radar, lightning observations and rain gauge information in novel ways. This will lead to better possibilities in estimating extreme rainfall events and the accumulated precipitation for the benefit of water energy resources (hydropower), flooding, catchment-areas, drainage, sewer-system etc.

In many cases the accumulated precipitation values are based on pure radar analysis. Radar echoes are related to rainfall rate and thereafter transformed into accumulation values. However, such conversions are based on general empirical relations, which are not suitable for all meteorological cases (e.g. depending on precipitation type). Other examples of uncertainty factors affecting radar reflectivity are electronic mis-calibration, beam blocking, attenuation and overhanging precipitation (Saltikoff et al., 2010).

2. Methods

FMI operates The Local Analysis and Prediction System (LAPS; Albers et al., 1996 and Koskinen et al., 2011), which integrates the latest observations together with the most recent forecast, to obtain a now-casting analysis at high spatial resolution (3 km). Such a high-resolution thus extends its potential use for hydrological/environmental authorities, since it better copes with water catchment scales.

FMI has already proven that there is a benefit of assimilating various sources of data to better estimate the precipitation accumulation, e.g. by combining radar and gauge data using RandB-method within LAPS (Gregow et. al., 2013). The correction through the use of gauges is done by combining two different methods in sequence: 1) a linear regression correction and 2) the Barnes bias correction. The correction methods between radar-gauge pairs has to be carefully interpreted, taking into account different weather phenomena (e.g. frontal vs. convective precipitation) and errors in radar and gauge measurements. Results from the operationally running FMI LAPS-RandB model are shown in table 1 and Fig. 2.
2.1. Use of lightning data

The on-going work hypothesis is to improve the accumulation estimation by the use of lightning data assimilation (LDA). The LDA source code has been distributed by Vaisala and FMI has thereafter implemented it into the FMI LAPS operational suite, with certain modifications. The LDA method strives to find a relationship between the lightning intensity (i.e. amount of flashes) and the reflectivity profiles, retrieved from radar data. First, the amount of strikes are collected for each LAPS gridbox, with horizontal resolution of 3*3 km, and for a time interval of 5 minutes. Simultaneously, the LDA code collects the corresponding radar reflectivity profile for the gridboxes and same time interval (see Fig. 1; top panel). In the second phase, the strikes are categorized (bins of exponential division: 2^n...2^n+1) and corresponding radar reflectivity profiles are divided into same categories. The collected radar profiles, for each category, are averaged so that there is one reflectivity profile representing each strike category (see Fig. 1; lower panel).

With this method, the lightning generated reflectivity profiles are distributed to LAPS gridpoints and the data is thereafter spread to the surrounding gridpoints via Gaussian distribution. The new lightning-reflectivity information is merged with existing radar reflectivity field, this, in order to fill in areas where no radar information exists or in areas of low radar quality. The result is a gridded precipitation accumulation field with high resolution in space, influenced by both radar and lightning information. As the next step, gauge observations will be assimilated together with the radar-lightning generated field, i.e. via RandB-method, in order to correct the final precipitation accumulation field generated in near real time (e.g. within 30 minutes). FMI has been validating the LDA impact on precipitation accumulation during years 2014-2015.

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Fig 1: Description of the new LDA-method, correlating lightning with radar reflectivity profiles.
2.2. Use of longer time series

The RandB-method (see Gregow et. al., 2013) use gauge observations from the recent 1 hour only. Such dataset can suffer from few observations and can therefore, naturally, effect to the quality and robustness of the Regression and Barnes methods used in the corrections. As a further investigation we have therefore used a selection of longer time periods, e.g. the previous 6, 12, 24 hours and 7 days of data, in order to build up a larger set of the G/R pairs. The periods are chosen so that the situational weather occurring, is more and more losing its importance and a more long-term statistical correlation between gauges and radar is becoming more dominant (e.g. after 7 days). The longer time interval, the less information is from the precipitating situation occurring at actual analysis time (i.e. frontal or convective weather pattern) and the dataset is getting more “smoothened” (i.e. extremes disappear).

3. Data

In this work, the LAPS system is used as the platform where we will build and develop the new assimilation methods using datasets from:

1. Nine (and from autumn 2015 ten) C-band Doppler radars, which give reasonable coverage for most of Finland. Measurements are made in bins that are 500 meter long and 1° wide, up to 250 km in range from each radar.
2. Almost 450 surface precipitation observations within Finland. FMI manages 77 stations (weighting gauges) and the Finnish Transport Agency (FTA) runs 370 road-weather stations (optical sensor measurements).
3. The Lightning Location System (LLS) of the Finnish Meteorological Institute (FMI), which is part of the Nordic Lightning Information System (NORDLIS). The system detects primarily ground-to-ground strokes in the low-frequency (LF) domain. In future, satellite based lightning measurements will become available through EUMETSAT.

4. Results

The performance of the FMI LAPS RandB-method has been verified against surface gauge observations of precipitation accumulation during period: April to October, 2011. The observations have been divided into two subsets: dependent and independent, where the dependent are used within the Rand-method, while the independent observations are not used in the corrections. The results are shown both as statistical verification (see table 1) and as density plots (see Fig. 2) for independent and dependent datasets, respectively.

Tab 1: Statistical verification results for the independent stations datasets.

<table>
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<tr>
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<th>LAPS-radar</th>
<th>RandB</th>
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<tr>
<td>Number of observations</td>
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</tr>
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<td>STDEV(R/G)</td>
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<td>0.91</td>
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<td>CORR</td>
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Fig 2: Density plots of analyzed precipitation accumulation (y-axis) against observed rain-gauge values (x-axis) for the dependent stations: LAPS-radar, in left panel, and LAPS-RandB, in right panel. The continuous line is a linear fit to the dataset and the dashed line represents the perfect 1:1 fit in the plots.

The results from validating the lightning data assimilation (LDA) method and different time sample intervals are being processed and will be presented at UrbanRain conference, year 2015.

5. Conclusions

The operational LAPS-RandB model running at FMI does give an improved precipitation accumulation result, compared to using only radar data. The newest verification results will presented at the UrbanRain conference, together with validation outcome of the LDA-method's performance from summer period year 2015. Additionally, the impact of using different time sample interval has been investigated and the results will, as well, be presented at the UrbanRain conference and later, included as article in HESS-Special Issue in Rainfall & Urban Hydrology.

References

Modelling tropical cyclone rain

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Abstract

Tropical cyclones (TC) can cause torrential rain, and the strongest observed rainfall events on timescales from several hours to several days all result from land-falling tropical cyclones. As tropical storm Allison (2001) illustrated, tropical cyclone rain can cause damage of several billions of US dollars when hitting major urban centres even if the storm does not reach hurricane strength. Risk Management Solutions Ltd. (RMS) has developed a TC-Rain Model which is based on a combination of observations, experience and physical parameterizations. Based on an event set of TC tracks it allows the calculation of several hundred thousand TC-rain footprints which can then be used for the estimation of flood levels and their return periods via a complex dynamical hydrological model.

The TC-Rain Model takes a number of physical mechanisms into account, including (a) the effect of surface roughness change at land-fall, (b) orographic rain enhancement, (c) drift of rain due to strong horizontal winds, (d) asymmetry, (e) outer rain bands, (f) extratropical transition, (g) predecessor rain events (PRE), and (h) the dependence on sea surface temperature. It is calibrated for the US using about 350 landfalling tropical cyclones from 1948 to 2007 and for Japan using 57 typhoons from 1998 to 2008. The model is not designed as a forecasting tool, but rather a tool for risk assessment. Nevertheless using the model to make forecasts can provide a useful test, and this was tried for the very active 2008 US hurricane season.

Since the RMS TC-Rain Model is generic and physically based it can be and is applied to other regions of the world with only minor changes to meet local and regional conditions. Furthermore since it is based on physics it also allows for sensitivity analyses such as estimating the impact of climate change (via sea surface temperature rise or changes in storm intensity or frequency) on tropical cyclone rain.

References

Spatial distribution of the short-term precipitation in the highest part of the Carpathians

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Abstract

Mountains give birth to most large river systems on the Earth. Due to large variability of natural conditions, harsh climate and topography, small or none human population, hydrological studies in mountain catchments have to rely often only on extrapolation of the key data such as precipitation or air temperature. Altitude gradients are helpful in mountain catchments to obtain catchment precipitation or spatial distribution of air temperature as the main input data to hydrological (rainfall-runoff) models or water balance studies. While they may provide correct catchment values of seasonal or annual precipitation, their deployment in extrapolation of the short-term rainfall (e.g. daily of hourly) may be biased. The knowledge on spatial variability of daily or shorter time step rainfall is mountains remains limited.

Our previous work showed that although the territory of Slovakia is well covered by the standard meteorological network, the problems due to inadequate precipitation data often arise when the hydrological cycle in small mountain catchments (areas approximately 20-40 km\textsuperscript{2}) is studied. Therefore, an extended network of rain gauges was installed in a research mountain catchment to obtain better information on:
- spatial and temporal distribution of rainfall in the warm period of the year (June to September)
- frequency of rainfall events covering only part of the catchment which cause runoff response at catchment’s outlet
- comparison of rainfall characteristics in the mountain and foothill parts of the catchment
The obtained knowledge should help in better understanding of hydrological processes in the mountains.

Fig 1: Spatial distribution of rain gauges in the Jalovecký creek catchment; the gauge located outside the catchment at 570 m a.s.l. is not shown.

The study was conducted in the Jalovecký creek catchment (the Western Tatra Mountains, northern Slovakia). Catchment area is 22.2 km\textsuperscript{2}, mean altitude is 1500 m a.s.l. (820 to 2178 m a.s.l.), mean slope is 30°. Thirteen to fifteen rain gauges (three of them weighting, other tipping bucket) were installed at altitudes 570 m a.s.l. (this site is located in the foothill part of the catchment) to 1900 m a.s.l. in the warm periods of the years 2013-2015 (Fig. 1). 10-minutes,
hourly, daily, monthly and seasonal precipitation (rainfall) data from June to September were processed. Measured seasons represented contrasting rainfall conditions. Summers 2013 and 2015 were drier, summer 2014 was wetter than the average. The evaluation focused on spatial differences of precipitation measured with time resolutions 10-minutes, 1 hour and 1 day.

Altitude explained only about 60% of precipitation variability even for seasonal totals, i.e. total rainfall between June and September. Position of individual rain gauges (windward slopes, shaded valleys, forest) was especially important in the wetter year 2014. Precipitation-altitude relationships were less scattered in drier years 2013 and 2015. Similar conclusions can be drawn for monthly data.

Daily precipitation at different altitudes does not exhibit a clear altitudinal dependence (Fig. 2). Altitude gradient was a good descriptor of daily precipitation (i.e. correlation coefficient between altitude and daily precipitation at least 0.6) for only about one quarter of rainy days. Days with higher daily precipitation had higher altitude gradients, but only up to approximately 6 mm. Wetter days did not exhibit clear relationship between the mean daily precipitation and altitude. Daily mean precipitation in the mountains was higher than in the foothill part of the catchment, but the variance of the values around the mean was bigger as well. Also the number of rainy days was higher in the mountains, but the difference was very small in drier years.

When it was raining, precipitation occurred almost always at all locations. Rainfall events which hit only part of the catchment and caused runoff response at catchment’s outlet were not observed. Decreasing temporal resolution of precipitation measurement resulted in the decrease in the differences in median values of precipitation in the mountains. Patterns of hourly precipitation at different altitudes were similar to those of daily precipitation. Patterns of the 10-minutes rainfalls (minimum and lower quartiles) reflected measurement resolution of the tipping buckets (0.2 mm) and weighting gauges (0.01 mm). The patterns at this temporal resolution slightly differed for the wet and dry years.

Precipitation maxima did not exhibit clear altitude gradients (Fig. 3). Maximum daily precipitation in the wet summer 2014 was similar to the dry summers 2013 and 2015.
The monitoring provided a lot of data on precipitation in the mountains at different temporal resolution. Although it rains more and more often in the mountains, the differences in the number of rainy days are not big in the drier years. It means that hydrological drought in the foothill part of the catchment cannot be improved by precipitation in the mountains at this spatial scale. Runoff response is at the outlet of the mountain catchment is almost exclusively caused by rainfalls which occur at all altitudes.

Fig 3: Maximum rainfall between June and September 2013-2015 at different altitudes; the mountain part of the catchment is above 800 m a.s.l., forest grows approximately up to 1400 m a.s.l.

Acknowledgement

This work was supported by the grant of Slovak Ministry of Education, Science, Research and Sport VEGA 2/0055/15.
Detecting predictor variables and their influence on changes in regional rainfall patterns in South Australia

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Abstract

Daily rainfall records from seven stations in South Australia (SA) with record lengths from 50 to 137 years are investigated for evidence of changes in the statistical distribution of rainfall patterns. In addition, the annual time series are analysed for three stations for which records exceed 100 years. There is no evidence of any trend in the mean or standard deviation. Analysis of changing patterns in rainfall is based on an assumed underlying stochastic process, which is too restrictive for environmental time series. An alternative to analyse the data and detect changes is to apply the methods of multivariate statistical quality control. The results shown in Figure 1 (a&b) indicate that the underlying process is not in statistical control. In addition there is no clear systematic pattern in the rainfall anomalies and no convincing evidence for suggestion of trend. Therefore randomization procedures were applied to resample the rainfall pattern in order to further investigate the changing rainfall patterns.

Fig 1: Multivariate statistical quality control with action line (red line): a) annual mean rainfall; and b) annual maximum rainfall in SA.

A factor analysis provided some evidence of a change in the spatial structure of extremes. The variability of a factor that represented the difference between rainfall patterns in SA increased in the second half of the time series period relative to the first half. There is also some evidence that the mean of this factor increased in absolute magnitude. We have linked rainfall anomalies and to the influence of climatic indices such as the Southern Oscillation Index (SOI) and the Indian Ocean Dipole (IOD), and we have found evidence of an association between the SOI and IOD and rainfall patterns in South Australia. This finding is consistent with previous studies (Cai et al., 2011; Kamruzzaman et al., 2013). To verify the prediction model, this study will apply the Holt-winter algorithm process and copula model for year ahead forecasts of rainfall in SA.
References


Does climate change have an impact on Swiss urban drainage infrastructures?

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Abstract

Precipitation extremes are particularly relevant when analyzing rainfall/runoff processes in urban drainage systems, and in the light of a changing climate various attempts are being made to predict future extremes based on climate modelling. However, results remain highly uncertain so far. In this study we aim to quantify the potential impact of climate change on rainfall extremes considering inherent natural precipitation variability. Ultimately, this information can be integrated in early design adaption strategies for drainage networks in order to minimize adverse socio-economic impact of urban flooding.

Despite a growing knowledge base regarding climate modelling, the spatial and temporal scales of these global and regional climate model (GCM/RCM) outputs are too coarse and cannot be used directly for predictions of small scale hydrological processes. We tackle this issue by applying a stochastic rainfall simulator coupled with a simple statistical downscaling technique. For climate change scenarios we generate realizations of daily precipitation with the Neyman-Scott Rectangular Pulse model (NSRM), the parameters of which are driven from adjusted observed precipitation statistics by multiplicative factors of changes (Kilsby et al. 2007; Fatichi et al. 2011; Egger & Maurer 2015). The Multiplicative Random Cascade model (MRC) (Rupp et al. 2009) is then used to disaggregate daily precipitation down to 10-min resolution. This nested modelling approach was developed and tested by Paschalis et al. (2014).

Before assessing the climate change impact, we verify the performance of the stochastic model against recorded data for 22 meteorological stations of MeteoSwiss (Federal Office of Meteorology and Climatology), which evenly cover the diverse hydrological regions of Switzerland. Monitoring data from 1981-2010 with a sampling resolution of 10 min are considered the baseline for the current climate. The capability of the model was tested to reproduce observed statistics for three durations: long (1 day), medium (1 hour) and short (10 min) precipitation. Further, two MRC models with different parameterization of the cascade generator were compared (MRC A and B) to better understand how model performance is affected by model complexity.

Projected future climate, i.e. daily precipitation is derived from ten different realizations of GCM/RCMs from the ENSEMBLES project (van der Linden & Mitchell 2009), based on the A1B emission scenario of IPCC. The output predictions are resolved into 25 km grid cells and a daily scale covering the period from 1950 to 2100. The impact of climate change is investigated explicitly for two future periods: near (2035-2064) and far future (2070-2099). The application of the stochastic rainfall simulator to generate future precipitation includes the following steps: First, the multiplicative factors of change derived from multi-model GCM/RCMs outputs are applied to the observed statistics. Second, the parameters of the NSRM are re-calibrated based on the modified statistics. Third, MRC disaggregates daily rainfall data to 10 min temporal resolution.

A representative example of the model output for extremes is given in Figure 1. Here the current (solid line) and near future (dashed line) annual maxima precipitation as function of return period at three different durations for Basel, Switzerland, are shown. The simulated values are given as average
Predictions of extreme precipitation at 10 min resolution indicate that climate change effects cannot be distinguished from current climate variability and are dominated by high levels of uncertainty. (2) Projecting future precipitation is highly uncertain for convective events which are heavily localized in time and space (results will be shown in the full paper).

As the evaluation of the stochastic model reveals a deficiency of the modelling system to represent convective precipitation we suggest addressing the following issues in further research: (a) improving the MRC model to better capture extreme convective events that are the main trigger of urban flooding, and (b) improving the downscaling technique to include other possible effects of a warmer climate on precipitation extremes, e.g. relations to air temperature.

Fig 1: Annual precipitation maxima for different return period and at three different durations 1 day, 1 hour and 10 min, respectively. The figures illustrate observed data in the period of 1981-2010 (markers) and simulations of current climate with NS+MRC model B (solid colored line) and ten realization of near future 2035-2064 (dashed grey lines), with the 90% confidence intervals.

References

Long-term impact of urbanization and subsequent densification on the water balance in Vancouver, Canada

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Abstract

The objective of this study is to analyze the effects of changes in land use and land cover on the water balance of two suburban areas (Sunset and Oakridge) in Vancouver, Canada for the period 1920 to 2010. In 1920’s forested area was clear cut in order to start developing the area, which by 2010 had been built to a modern-day high-density suburban area. To do this Surface Urban Energy and Water Balance Scheme (SUEWS, Järvi et al. 2011) that previously has been found to perform well when evaluated against observed turbulent fluxes and water balance components is used. Numerous measurements undertaken in this region are used to assess aspects of model performance.

The required meteorological forcing variables for SUEWS (solar radiation, air temperature, precipitation, wind speed, air pressure and relative humidity) are obtained from the WATCH forcing data WFD (1920–1978, Weedon et al. 2011) and WFDEI (1979–2010, Weedon et al. 2014). These datasets have been derived from ERA-40 and ERA-Interim reanalysis products via sequential interpolation to half-degree resolution with 3 to 6 hour temporal resolution. This will be interpolated to the model time step of one hour. The WATCH forcing data has two precipitation datasets using different bias corrections. These datasets are corrected by using Climatic Research Unit's CRU TS2.1 (WFD) and CRU TS3.101 (WFDEI) and Global Precipitation Climatology Centre's GPCCv4 (WFD) and GPCCv5 (WFDEI). In this study we used the GPCC corrected precipitation dataset because of better correlation between the two datasets (WFD and WFDEI). To take the coarse resolution of WFD and WFDEI into account, daily precipitation sums are downsampled to match the daily statistics of local observations using methods similar to those described in Räty et al. (2014). In addition, the surface information includes the changing plan area fractions of built and pervious surfaces, building and tree heights and population density. Changes in surface cover in the study neighbourhoods have been analyzed and digitized from historical aerial photographs and maps.

Based on the SUEWS results, long-term changes in the surface runoff and drainage are evaluated. Analysis of model results allows assessment of the impact of changes in land cover, people’s behaviour and meteorological conditions. Thus, the results could support urban planning and environmental management decisions.

References


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Effects of long term radar rainfall time series on the results of urban drainage models

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Abstract

The performance assessment of urban drainage systems (UDS) based on historic rainfall time series observed by rain gauges is an established practice within the design and proof of existing systems. However, when using point information in urban drainage models it is believed that the rainfall is uniformly distributed in space in the catchment. This assumption is in error since the rainfall is highly variable in space and time. Especially convective rainfall events which are most important for design and performance of urban drainage systems are characterized by strong structured rain cells which lead to inhomogeneous distributed rainfall. A remedy to account for distributed rainfall is the use of a network of rain gauges located in the catchments. A further option is the use of high resolution radar data.

Schilling (1991) and Berne et al. (2004) provide recommendations on the temporal and spatial resolution of rainfall measurements required for urban hydrological applications. Ochoa-Rodriguez et al. (2015) analysed nine storm events observed by polarimetric radar with different spatial and temporal resolutions and investigated the results on the hydraulic performance of different catchments between 300 to 800 ha size. These different studies conclude that the impact of data resolution decreases with increasing catchment size and that the temporal resolution of rainfall inputs affects modelling results more strongly than variations in spatial resolution. The preferred temporal resolution should be less than five minutes, ideal-typically one minute.

However, so far there is no comprehensive analysis on the effects of long term high resolution radar rainfall data on the results of urban drainage models used to assess the performance of UDS. For design and performance assessment two general criteria have to be addressed:

- Hydraulic performance: the design is focused on extreme storm events with return periods T between 1 < T < 10 years and even higher for urban flood modelling. Hydraulic performance analysis requires rainfall runoff simulation with hydrodynamic models. Objective criterion is the frequency of surcharges per manhole.
- Quantification of discharges / combined sewer overflows (CSO): all rainfall events causing discharges are relevant. In Germany this is the case for frequent storm events with at least 4 mm rainfall. Hence, continuous rainfall time series are simulated with lumped hydrologic models to seize the impact of discharges on receiving waters. Objective criteria are the number and duration of discharges as well as discharged volumes.

To quantify the effects of rainfall variability on the results of urban drainage modelling radar time series are used to analyse the effects for the sewer system of the city of Freiburg (Fig.1). The system comprises 794 km with 19 overflows and a connected area of 4,910 ha. The sewer system is implemented in the hydrodynamic model HYSTEM EXTRAN for hydraulic performance analysis and for discharge analysis the hydrologic model KOSIM is applied. Both models are calibrated. The hydraulic performance is analysed for 42 extreme storm events of the period 01/2002 – 12/2014 which have been identified using partial time series analysis of a central gauge located in the city centre of Freiburg (Fig 1. green circle). For discharge modelling 63 relevant storm events of a one year continuous time series in 2014 are selected.
C-band radar data are provided by the German Weather Service for the radar Feldberg located 20 km south east of the city centre of Freiburg (Fig. 1) as continuous time series for the period 01/2002 – 12/2014. The DX product contains radar reflectivity data (single pol) in polar coordinates with a spatial resolution of 360 radar beams and a radial range of 128 km with gate length of 1 km. The time resolution is \( dt = 5 \) minutes. For direct use of radar data in urban drainage models the data have to be carefully corrected since C-band radar rainfall estimates underestimate the “true” rainfall as measured by gauges at magnitudes of 40 to 70 %. The applied radar correction methodology accounts for clutter, wet-radome attenuation, rain induced radar signal attenuation (Krämer and Verworn, 2009) and R-Z conversion depending on storm type (stratiform / convective). Validation with rain gauges shows that radar data are corrected quite well within ±25% agreement limits. For use in the hydraulic models radar rainfall data are transformed into Cartesian gridded data. Data are processed with different grid length of 500, 1.000 and 2.000 metres to analyse the effect of spatial resolution. Since the original time resolution of the radar observations is \( dt = 5 \) minutes the resolution is increased to \( dt = 1 \) minute by extrapolation of storm structures. Extrapolation and analysis of relevant storm characteristics (storm movement, change in intensity) are performed using the HYRATRAC model (Schellart et al. 2014).

The radar rainfall time series are compared with homogeneous gauge rainfall to quantify the effect of rainfall variability on the results of urban drainage models. The analysis of different spatial and temporal resolutions is performed to quantify the uncertainty and the error when inappropriate rainfall information is used for design of sewer systems and dimension of sewers.

The analysis is part of the Research Project SYNOPSE “Synthetic Rainfall Times Series for Optimal Planning and Operation of Urban Drainage Systems” founded by the German Ministry of Education and Research.

References

Analysis and assessment of different operational quantitative radar rainfall products for flood forecast and management in the River basins Emscher and Lippe

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Abstract

A radar data correction methodology which accounts for wet-radome attenuation, attenuation of the radar signal and different approaches to allocate R-Z relations to corrected radar reflectivity fields is presented. The methodology aims to provide corrected radar rainfall data for operational flood forecasting and management systems for the river basins of Emscher and Lippe in real time. The results for a multitude of rainfall events of different types are validated with a dense network of 69 rain gauges. It is demonstrated that the radar data are effectively corrected.

1. Introduction

Rainfall estimates from weather radars are a key input to hydrological applications and incorporate a high potential for water management and flood forecasting. But the use of radar rainfall data in hydrological models requires a high level of accuracy and reliability. In addition radar data have to be processed in real time. From a quantitative point of view single polarized C-band radar rainfall measurements are affected by physical effects such as wet-radome attenuation, rain induced radar signal attenuation and conversion of radar reflectivity into the target figure rain intensity by R-Z relations (Villarini and Krajewski, 2010). In consequence, not corrected C-band radar rainfall may underestimate the "true" rainfall at magnitudes up to 40 %. One widely spread method to overcome the problem of radar rainfall underestimation is the adjustment of radar rainfall by means of a network work of rain gauges. The central disadvantages of adjustment techniques are the dependency of the quality and performance on the density of the gauge network and the storm characteristics. In addition, adjustment techniques require integration intervals of radar and gauges observations over several time steps to derive robust adjustments factors. Hence, the use and benefit of adjustment techniques in catchments with a dynamic rainfall runoff response is limited. The alternative is the correction of the physical effects on radar measurements (Krämer and Verworn, 2009). The proposed correction methodology based on single polarized radar data accounts for the following physical influences:

1. Clutter
2. Wet-radome attenuation
3. Rainfall induced attenuation of radar signal
4. R-Z conversion.

To validate the radar data correction methodology and to estimate the performance for the operational flood forecasting and management of the river catchments Emscher and Lippe a multitude of rainfall events of different types has to be analysed. Different approaches to account for events specific allocation of R-Z relations are investigated and are assessed by a dense network of rain gauges.

2. Methods

Wet-radome attenuation correction: The correction is based on a time step wise analysis of the reflectivity structures in the data over the radar location. Radar data are interpolated for the first
gates to minimize clutter influences from the radar nearfield. A correction factor is calculated using radome attenuation loss measurements by Manz (2001) and Kuuri & Huskonen (2008).

**Attenuation correction of the radar signal:** The correction is based on the Hitschfeld and Bordan (HB) algorithm. In contrast to the use of constant attenuation coefficients (Harrison et al. 2009), variable coefficients within predefined bounds are applied to correct each radar ray for attenuation to avoid the instability of the HB-algorithm. The bounds have been derived from reference measurements by a 30 km microwave link parallel to a C-Band radar (Krämer and Verworn, 2009).

**R-Z relation:** The common approach to derive rainfall from radar reflectivity is the use of a constant R-Z relation of the form \( R = a \times Z^b \), where \( a \) and \( b \) are coefficients which are derived from drops size distribution (DSD) measurements by disdrometers. A widely used R-Z relation is \( a = 0.0364 \) and \( b = 0.625 \) (Marshall and Palmer, 1948). These coefficients fit quite well in a climatological sense and are uniformly applied to the entire radar reflectivity PPI (Fig 1. left). In contrast to the use of a climatological R-Z relation the R-Z coefficients can be derived event specific when DSD data are available.

A more sophisticated approach is proposed by Steiner et al (1994). Regions of convective and stratiform rainfall in the radar data are defined by texture analysis of the reflectivity structures. This approach is applied. Standard R-Z relations for different types of rainfall are allocated to the reflectivity structures depending on their size and the maximum reflectivity found within the structures. R-Z coefficients and parameters used are given in Tab. 1. An inhomogenous and a homogenous allocation method can be distinguished (Fig.1, middle and right).

A pragmatic approach for small catchments is the application of a quadratic regression on measured \( R \) and \( Z \) values. The advantage lies in the fact that the R-Z relation is always bound to physical sensible data when a maximum and a minimum value are fixed (Fig. 2). A moving window of 30 minutes can be introduced to account for intra event variability of rainfall processes.

Table 1: R-Z coefficients and parameters to determine regions of different types of rainfall.

<table>
<thead>
<tr>
<th>Linear factor ( a )</th>
<th>Exponent ( b )</th>
<th>Threshold [dBZ]</th>
<th>Structure size [km²]</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0442</td>
<td>0.640</td>
<td>≥ -2.7</td>
<td>≥ 64</td>
<td>light rainfall</td>
</tr>
<tr>
<td>0.0364</td>
<td>0.625</td>
<td>≥ 30</td>
<td>≥ 32</td>
<td>rainfall stratiform</td>
</tr>
<tr>
<td>0.0136</td>
<td>0.714</td>
<td>≥ 50</td>
<td>≥ 16</td>
<td>rainfall convective</td>
</tr>
</tbody>
</table>

Fig 1: Different approaches to allocate R-Z relations to radar reflectivity structures, left: uniform, entire PPI, middle: inhomogenous within single structure, right: homogenous within single structure.
Fig 2: Quadratic regression of the R-Z relation using fixed minimum and maximum values

3. Data

C-band radar data are provided by the German Weather Service (DWD) as uncorrected radar raw data after signal processing in polar coordinates for horizontal reflectivity $Z_h$ in 5 minute resolution (DX-format, gate length: 1 km, azimuth: 1°). 69 rain gauges within the Emscher and Lippe catchments recording at 1 minute resolution are operated by the water boards EG/LV. They serve as reference for assessment and validation of the radar correction algorithms (Fig. 3). Event specific R-Z relations are derived from laser optical drop size distribution measurements for three locations provided by the DWD. From the period Mai 2012 to July 2014, 21 rainfall events have been selected for the performance analysis of the different correction approaches. The selected events comprise different types of rainfall, continuous stratiform winter events as well as intense convective storm events during summer times.

Fig 3: Catchments of the rivers Emscher and Lippe and rainfall observing network.

4. Results

The performance of the correction algorithms is assessed by comparing radar results for event rainfall accumulations with the 69 gauge observations. Different quality criteria are used for assessment:

1. Slope of regression of the radar - gauge comparisons as a measure of the systematic error (bias). With respect to the use of radar rainfall data as input to hydrological models a zero bias is the main important target figure
2. (±) 10% / 25% agreement limits as measure of uncertainty (scatter)
3. Mean absolute error as a measure of accuracy

The radar-gauge comparisons are based on polar raster data for the central raster element corresponding to the gauge location. In order to account for different sources of uncertainty in the results (e.g. wind drift effects) the surrounding raster elements of the central element have been analysed as well. Fig. 4 shows some detailed results for July 28\textsuperscript{th} 2014, left time series for uncorrected and corrected radar reflectivity and radar rainfall are given (for the event see also Pfister et al., 2015). The right diagram shows a scatter plot for uncorrected, corrected for the central and the surrounding radar rainfall matrix elements of the 69 radar-gauge comparisons.

The box plots in the following Fig. 5 summarize the results for the 21 rainfall events for the radome attenuation correction, the rainfall induced signal attenuation correction and the different methods to allocate the R-Z relation in the radar data.

Fig 4: July 28\textsuperscript{th}, 2014; left: time series of uncorrected / corrected radar and gauge observation; right: radar-gauge scatter plot for 69 event accumulations for radar raw data, corrected radar data and analysis of surrounding raster elements.
It can be found that:

- Uncorrected radar data underestimate the rainfall at the magnitude of 30 – 40%.
- The radome and the radar signal attenuation correction algorithms significantly reduce the underestimating bias.
- The event specific R-Z relation outperforms all other R-Z approaches.
- The homogenous R-Z approach is the best operational approach. In average more than 50% of the radar – gauge comparisons are found within the ± 25% agreement limits of gauge rainfall. The homogenous approach performs at a magnitude of 10% better than the commonly used Marshall and Palmer R-Z relation.
- The consideration of the surrounding radar raster elements points to strong effects of uncertainty in the radar - gauge comparisons. Especially the results for the event specific R-Z relation are markedly improved compared with the other R-Z approaches.

5. Conclusions and outlook

1. The radar data correction scheme which accounts for the physical effects on radar rainfall measurements such as radome attenuation, radar signal attenuation and event specific R-Z relation is able to correct radar rainfall in real time (within less than five minutes after radar observation).
2. Due to the largely reduced underestimating bias in the corrected radar rainfall data it is expected that the data can be directly used as input for hydrological models in order to generate reliable flow predictions.
3. It can be concluded that the remaining uncertainty as revealed by the radar – gauge comparisons is less than the error which is made by areal extrapolation of rain gauge (point) observations.
4. In contrast to gauge adjustment techniques the attenuation correction approach is able to perform local, areal differentiated corrections of the radar reflectivity field which is finer than the adjustments derived from radar – gauge comparisons.
5. The results demonstrate that there is a distinct benefit of measuring drop size distributions by distrometers and using event specific R-Z relations for quantitative rainfall estimates.
6. Rainfall runoff simulations are performed and compared with flow observations to analyse systematic differences in resulting flows depending on this rainfall information.
7. The next step will be the online implementation of this radar data adjustment in the flood early warning system of Emschergenossenschaft and Lippeverband.

References

GRASS GIS module for processing of rainfall data from cellular networks

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Abstract

Although path-integrated rainfall measurements by microwave attenuation was suggested already by Olsen, et al., (1978) it has attracted broader scientific interest already in recent decade with extensive worldwide development of cellular backhaul networks often composed of microwave links (MWL). MWL rainfall measurements are especially interesting for storm water management applications which require rainfall information of high spatial and temporal resolution often in real-time. The paper presents solution specifically developed for efficient MWL data processing. It is based on geographic information system (GIS) linked to PostgreSQL database. Described approach allows represents framework for processing and handling data within widespread free and open source geographic information system GRASS GIS (Landa, Neteler, et al., 2012) and take advantage of a comprehensive geospatial analytical package.

Developed software package wx.mwprecip provides tools for transferring and processing raw data from a database to GRASS GIS enhanced by a suite of analytics procedures. In addition tools for selecting vector objects in GRASS GIS were developed and their interaction with wx.mwprecip package was provided. The package enables user to set model for microwave attenuation transformation to quantitative precipitation estimates. Specifically, several methods to identify baseline are provided. Moreover data from rain gauges or high resolution radar data can be imported for further comparison studies. Geospatial rainfall data are aggregated into user defined time step to enable to create space time dataset. This enables to use advanced tools to handle and analyze vector and raster space time dataset within GRASS GIS Temporal framework.
Described applications is currently used in on-going research in city of Prague, Czech Republic, where attenuation data from hundreds of microwave links are collected in high (seconds) temporal resolution (Fencl, et al., 2015). It is efficient solution for fast data processing, their visualization and animation.

Fig 3: Schema describing solution of data processing.
Acknowledgements

This work was supported by the project of Czech Science Foundation (GACR) No. 14-22978S and the project of the Czech Technical University in Prague project No. SGS15/050/0HK1/1T/11. We would like to thank T-Mobile Czech Republic a.s. for kindly providing us MWL data and being very helpful with development of the application for a MWL polling. Special thanks belong to Pražské vodovody a kanalizace, a.s. who provided and carefully maintained the rain gauges. Last but not least we would like to thank Pražska Vodohospodarska spolecnost a.s. for providing us additional rainfall information from their RG network.

References

Modeling daily rainfall conditional on large-scale atmospheric forcing: assessing rainfall statistics based on climate model results

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Abstract

Due to its intermittent and highly variable character, and the modeling parameterizations used, precipitation is one of the least well reproduced hydrologic variables by both Global Climate Models (GCMs) and Regional Climate Models (RCMs). This is especially the case at a regional level (where hydrologic risks are assessed) and at small temporal scales (e.g. daily) used to run hydrologic models.

To improve the level skill of GCMs and RCMs in reproducing the statistics of rainfall at a basin level and at hydrologically relevant temporal scales, two types of statistical approaches have been suggested. One is the use of distribution mapping (i.e. quantile-quantile, Q-Q, plots) to statistically correct climate model rainfall outputs based on historical series of precipitation. The other is the use of stochastic models of rainfall to conditionally simulate precipitation series, based on large-scale atmospheric predictors produced by climate models (e.g. geopotential height, relative vorticity, divergence, surface pressure). The latter approach, usually referred to as statistical rainfall downscaling, aims at reproducing the statistical character of rainfall, while accounting for the effects of large-scale atmospheric circulation (and, therefore, climate forcing) on rainfall statistics.

While promising, statistical rainfall downscaling has not attracted much attention in recent years, since the suggested approaches involved complex (i.e. subjective or computationally intense) identification procedures of the local weather, in addition to demonstrating limited success in reproducing several statistical features of rainfall, such as seasonal variations, the distributions of dry and wet spell lengths, the distribution of the mean rainfall intensity inside wet periods, and the distribution of rainfall extremes.

In an effort to remedy those shortcomings, Langousis and Kaleri (2014) developed a statistical framework for simulation of daily rainfall intensities conditional on upper air indices. Here, we test the developed downscaling scheme using atmospheric data from the ERA-Interim archive (http://www.ecmwf.int/research/era/do/get/index) and daily rainfall measurements from western Greece, and find that it accurately reproduces several statistical properties of actual rainfall records, at both annual and seasonal levels, including: wet day fractions, the alternation of wet and dry intervals, the distributions of dry and wet spell lengths, the distribution of rainfall intensities in wet days, the distribution of yearly rainfall maxima, dependencies of rainfall statistics on the observation scale, and long-term climatic features of rainfall. This is done solely by conditioning rainfall simulation on a vector of atmospheric predictors, properly selected to reflect the relative influence of upper-air variables on ground-level rainfall statistics.

In a follow up application study (Langousis et al., 2016), we assess the relative effectiveness of: a) the developed statistical downscaling scheme, and b) quantile-quantile (Q-Q) correction of climate model rainfall products (i.e. an approach commonly used in climate change impact studies) in reproducing the statistical structure of rainfall, as well as rainfall extremes, at a regional level, based on climate model results. This is done for an intermediate-sized catchment in Italy, i.e. the Flumen-
dosa catchment, using climate model rainfall and atmospheric data from the ENSEMBLES project (http://ensembleseu.metoffice.com). In doing so, we split the historical rainfall record of mean areal precipitation (MAP) in 15-year calibration and 45-year validation periods, and compare the historical rainfall statistics to those obtained from: a) Q-Q corrected climate model rainfall products, and b) synthetic rainfall series generated by the suggested downscaling scheme. To our knowledge, this is the first time that a detailed statistical comparison of climate model rainfall, statistically downscaled precipitation, and catchment averaged MAP is performed at a daily resolution.

The obtained results are promising, since the proposed downscaling scheme is more accurate and robust in reproducing a number of historical rainfall statistics, independent of the climate model used and the length of the calibration period. This is particularly the case for the yearly rainfall maxima, where direct statistical correction of climate model rainfall outputs shows increased sensitivity to the length of the calibration period and the climate model used. The robustness of the suggested downscaling scheme in modeling rainfall extremes at a daily resolution, is a notable feature that can effectively be used to assess hydrologic risk at a regional level under changing climatic conditions.

References


iFFRM Kluang: dynamic calibration of radar rainfall data for flood forecasting in Malaysia

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Abstract

The Malaysian Meteorological Department (MMD) currently operates two Integrated Radar Network in Peninsular Malaysia and Sabah/Sarawak. The Peninsular Malaysia network consists of six (6) S-band weather radars located in Butterworth, Subang, Kuantan, Kluang, Alor Setar and Kota Baru. All the radars and the Real-time Display System are linked to the Data Collection Center (DCC) Workstation located at Malaysian Meteorological Department Head Quarters in Petaling Jaya. The radar site at Kluang is the focus of this project. The figure below highlights the location and the 300-km coverage of the Kluang radar (the red circle marker and line), as well as the Muar river basin (blue outline).

A methodology has been developed to conduct dynamic Z-R calibration (i.e. \( Z = aR^b \), where \( Z \) is the radar reflectivity, \( R \) is the rain rate, and \( a \) and \( b \) are variables to be calibrated in this work) using the coincidental rain gauge data in real time. The proposed methodology includes two parts. The first part was to implement a fast ‘least-square’ algorithm to derive the ‘best’ \( a \) and \( b \) variables based upon the coincidental ground rain gauge records. The second part is to dynamically carry out the calibration using a moving-window (in time) approach.

The proposed least-square algorithm aims to minimize the MSE (mean squared error) between co-located radar and rain gauge data at rain gauge locations. Because the rain gauge data are in one-hour time interval, the calibration was therefore conducted based upon one-hour interval. The 10-
min radar rainfall rates were then further aggregated into 1-hour resolution to be comparable with the 1-hour raingauge data. By substituting different a and b variables, the best Z-R relationship can be obtained. However, this could be very time-consuming to exhaust all possible pairs of a and b, so Brent’s numerical method (Brent, 1973) was employed in this report to conduct fast estimation.

In addition to the least square algorithm, a moving-window approach was also employed to take into account the temporal dynamics of rainfall. The idea is to carry out the Z-R calibration at each time step using current and previous data within a given time horizon. A number of different widths of the moving window were tested; these included 18-/24-/30-/36-/42-/48-hour widths (see Fig 2). After taking into account the balance between rainfall dynamics and numerical stability, a 24-hour time horizon has been chosen to carry out the dynamic Z-R calibration.

The proposed methodology has been incorporated into a tool to process MMD S-band radar data and to provide radar QPEs in real time for the hydrological modelling over the Muar river basin area.

![Z-R calibration analysis: 23-29 Nov 2012](Fig 2: Comparisons of RD estimates derived from dynamic Z-R calibration with different widths of moving windows.)

References

A landslide warning concept for Switzerland based on daily rainfall thresholds

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Abstract

Natural hazards such as floods (89%), debris flows (4%), landslides (6%) and rockfall (1%, data available only since 2002) have caused approximately 800 Million Euros damage in Switzerland in the years between 1972 and 2014 (Hilker et al., 2009). Long-duration rainfall was recognized as the first and most frequent cause behind most of these events, followed by thunderstorms.

This paper focuses only on landslides because they potentially affect a much greater surface area of the country and, being very complex from the process point of view, are much more difficult to predict than floods. Many different approaches have been taken to better understand the link between precipitation and landslides such as building intensity-duration threshold curves (Guzzetti et al., 2008), analyzing many different predisposing and triggering factors for small areas (Van Ruette et al., 2011), or considering a limited time frame when many events occurred (Nicolet et al., 2013).

Herein the entire country is considered and two unique precipitation and landslide databases, each of which covers more than 40 years, are combined to assess the predictive power of a simple model based on daily precipitation. More specifically the rainfall threshold was determined both for the entire country and separately for regions defined based on parameters considered to be important for landslide susceptibility such as lithology, erodibility, slope and vegetation cover. Mean daily precipitation (MDP) for the 1972-2012 period was used to represent general climatology.

Based on the results, an elementary landslide warning concept can be obtained that, given the daily rainfall forecast, can be used to identify whether a landslide could occur and provide the associated prediction error.

From the WSL database the landslides with known location and date, 2272 events in total, were extracted. The 2x2 km gridded dataset RhiresD from Meteoswiss was used and daily precipitation was used to define events (one event is defined as consecutive days with rainfall >1mm). An event was considered landslide-triggering if at least one landslide occurred during or the day following the event. For each event the following variables were computed: duration (days), maximum daily intensity (mm/day), mean daily intensity during the event (mm/day) and cumulative precipitation for the entire event (mm). For each of these variables a simple threshold model was assumed and the best threshold value was found utilizing statistics such as specificity, sensitivity, AUC and the True Skill Statistic (e.g. Begueria, 2006; Van Ruette et al., 2011), which optimizes the correct positive (landslide) and negative (non-landslide) predictions. The same analysis was repeated for variables standardized by the MDP of the respective cell. For the analysis only precipitation cells in which at least one landslide occurred within the entire time period were used. Consequently, areas where landslides cannot occur or are not reported were not considered and the results only apply to areas susceptible to landsliding.

Precipitation variables leading to a higher TSS (>0.60) were found to be total event rainfall (threshold 44mm) and daily rainfall (25mm/day) that both had sensitivity (correct landslide prediction) and specificity (correct non-landslide prediction) above 0.75. The map shown in Fig.1 is an example of how these results can be used to assess landslide susceptibility related to precipitation. In this case the maximum daily intensity divided by the MDP of the specific cell was considered for each
event leading to a threshold of 6.7. This threshold was then multiplied by the MDP of each precipitation cell in Switzerland to obtain the respective maximum daily intensity threshold for each cell, as shown in the Figure. The good performance (TSS>0.6) obtained for the analysis that considered MDP, which leads to higher thresholds for cells with higher MDP, suggests the existence of a landscape-scale balance between climate, erosion and soil formation. Higher rainfall is required to generate landslides in steep wet areas where the vulnerable hillslopes have already been stripped of soil.

Among the different classification parameters used to divide the country into regions (with the analysis then repeated for each region), the parameter that led to relatively large differences in the thresholds between areas was land surface erodibility based on the geotechnical classification from Kuehni and Pfiffner (2001), with areas with higher erodibility having a lower threshold.

Fig 1: The maximum intensity threshold for each precipitation cell in the MeteoSwiss gridded data based on the R/MDP (maximum daily intensity threshold over Mean Daily Precipitation) threshold. The red dots represent the landslides with known location from the WSL database (N=2272).

References

Combining single polarization X-band radar and ground devices for hydrological applications

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Abstract

Recently, the Department of Civil, Environmental, Aerospace Engineering, and Materials (DICAM) of the University of Palermo (Italy) has installed several devices for the monitoring of precipitation for the urban area of Palermo. These devices include a single polarization X-band weather radar, a rain gauge network spread over the urban area, and a laboratory site where advanced precipitation devices (an optical disdrometer, a weight rain gauge, and a weather station) are available.

Given the ensemble of measurements retrieved by sensors, a set of models for the combination of data has been developed in order to exploit their joint usage. The disdrometer information have been exploited for the calibration of both the radar equation and the Z-R relation. The availability of rain gauges data is considered for the implementation of a correction procedure that is aimed to the improvement of congruence between ground rain references measurements, and the radar estimates. The application framework has been evaluated with reference to their specific potential suitability for both hydrological and meteorological applications.

The analyses have been carried out with reference to long measurement series for calibration models, and considering some specific events for the validation of results. A one year-long measurement record retrieved from the disdrometer has been analyzed for the characterization of the temporal variability of the Z-R relation and the determination of the best setting strategy. The study confirms the opportunity of coupling the radar system with auxiliary instruments that significantly contribute to the quality of final estimates. The contribution of the sensor blending is particular worthy for hydrological rainfall, while for meteorological applications a trade-off between calibration/correction procedures and the readiness of data has to be considered.

1. Introduction

Advanced tools for the monitoring of weather comprise not only the new satellite resources available from the international community, as the advanced GPM (Global Precipitation Measurement) system, and estimates provided by physically based analysis, i.e., GCM and LAM models. Indeed, an important role in the analysis of weather events is still supplied by the monitoring local networks distributed in many areas. Such systems are nowadays supported by new technologies and tools available with moderate costs. The X-band weather radar represents one of the most interesting area of exploration of monitoring methods particularly referred to the effects on the territory. Such a condition is supported by the spreading of X-band radar devices made available by several producer companies.

While the most appropriate applications potentially supported by a X-band weather radar are those related to the monitoring of precipitation dynamics, elaborations can be even considered for quantitative and hydrological applications. Such a possibility implies the analysis of the uncertainty related to radar estimates and the corresponding efforts to reduce them (see Villarini and Krajewski, 2009, for an exhaustive description of single band radar uncertainties). Among the most
effective actions for improving the estimates retrieved from radar measurements, the combination of radar data with other instruments should be pursued when possible.

This paper describes the precipitation monitoring system designed and installed by the Department of Civil Engineering, Environmental, Aerospace, of Materials (DICAM), of the University of Palermo, in the urban area of Palermo, Italy. The main instrument of the system is a single polarization X-band weather radar. Other instruments are given by a rain gauge network, an optical disdrometer, a weight rain gauge and a weather station. A procedure for the blending of data from different sensors has been synthesized within a procedural scheme where only the radar, the rain gauge network and the disdrometer are considered. Possibilities offered by single blending procedures are evaluated with reference to two different application fields, that are meteorological and hydrological applications respectively. The first is mainly devoted to the derivation of dynamic features of precipitation events, while the second involves the goodness of the quantitative estimates.

The paper is organized as follows: in the first section the monitoring system is presented along with each single sensor; then procedures for the elaboration of data and their links are reported in the second section; in the third section results from validation analyses are discussed. Finally, some final remarks are presented.

2. Study area and sensors

The monitoring area is represented in Figure 1 and covers a rather wide territory (i.e., ~500 Km²) within the dense urban area of Palermo (Italy) with a population of ~ 700,000 people.

![Fig 1: Precipitation monitoring system for the urban area of Palermo.](image)

The radar is the X-Band mini Weather Radar developed and produced by EnviSens Technologies (Allegretti et al., 2012). This device is a non-Doppler, single polarization radar, operating just the PPI (plan position indicator) scanning mode. The maximum range of the instrument is set to 30 km and it has been installed in the eastern mountains overlooking the urban area of Palermo (Sicily, 38°02'N-13°27'E). The radar is able to produce an image map each minute with a spatial resolution of 60 m, which is transmitted, via GPRS, to a central server, where it is opportunoely processed and published on the web.
The laser-optic disdrometer is an OTT Parsivel2 multifunctional device; it measures the size and the fall velocity of precipitation drops based on the interaction between such particles with a horizontal laser beam transmitted and received by specific units. The rain gauge network was designed for monitoring the city of Palermo and its realization was in progress during this study.

Even though the complete network include a set of 18 rain gauges distributed within the radar observed area, for the analysis period considered in this study a reduced number of rain gauges were continuously operative because of some maintenance operations; for this reason only data retrieved from five working stations have been considered in the module where rain gauge data are involved.

3. Data processing for the blending of sensors measurements

Based on the availability of sensors, the following three procedures were developed:
- calibration of the radar equation;
- calibration of the Z-R relation;
- correction of radar precipitation fields based on rain gauges measurements.

A scheme representing data sources, procedures, and their connections is reported in Figure 2.

The calibration of the radar equation is performed optimizing the unique parameter of this equation (related to device losses and mean atmospheric conditions) in order to obtain radar reflectivity estimates constrained to those provided by the disdrometer. The Z-R relation is calibrated for the disdrometer site considering both the reflectivity and the precipitation rate derived from the physical relationships linking them to the DSD (drop size distribution) measured by the disdrometer. Finally, the radar precipitation estimates can be constrained to ground measurements by means of a rain gauge network correction procedure. Such an analysis is presented here in preliminary form as the limited number of rain gauges available during the study did not allow for the derivation of a more robust procedure. The method presented correspond to the algorithm proposed by Koistinen and Puhakka (1981).

Fig 2: Scheme of the ensemble of application for the blending of precipitation measurement data.
4. Results

Procedures previously introduced, have been applied to observation obtained during the period September 2013 – September 2014. Figure 3 reports the illustrations of such applications. The radar equation calibration was applied to the radar and disdrometer measurements relative to the period February 2014 – March 2014. The optimization was carried out considering the RMSE between the reference radar reflectivity provided by disdrometer and that estimated transforming radar measurements into radar reflectivity by means of the radar equation where a constant term, indicated as “const.” in Figure 3 (a), has been considered ranging within a known range of values (i.e., the expected const. value). The optimum value obtained (96.4 dBZ) resulted significantly different from the default value suggested by producers (91.4 dBZ).

Fig 3: Results obtained by the application of elaboration procedures. (a) Radar equation calibration; (b) Z-R relation calibration; (c) Rain gauge network correction.
The Z-R relation calibration reported in Figure 3 (b) is relative to a single event (occurred on October 6th 2013). The left panel shows the event dynamic while the right panel displays the calibration surface where the “A” and “b” parameters of the Z-R relation are optimized, in terms of RMSE, comparing the reference disdrometer rain rate with that obtained transforming the disdrometer reflectivity, i.e., using the Z-R relation. Again, value obtained for parameters, resulted quite different from the reference values that can be assumed for the Z-R relation from the literature, e.g., A=200 and b=1.6 (Marshall and Palmer, 1948). This analysis was repeated for a selection of relevant events observed during one year (i.e., September 1st 2013 – September 1st 2014). Representative average values were estimated in terms of median values from this analysis equal to A=279.5, b=1.71. Results shown a great variability of both parameters, leading to two strategies for the selection of Z-R parameters. These can be calibrated for the single event, as shown in the example reported, when estimates are needed for post-event analyses. For the “online” retrieving of rain estimates, that is, the direct transformation of radar measurements to rain rate during the observation of events, long-term mean values reported above can be adopted.

Figure 3 (c) reports the results obtained from the execution of the rain gauge network correction. As indicated above, the algorithm adopted is that presented by Koistinen and Puhakka (1981). It is based on the characterization of ratios between rain gauge values and corresponding radar pixel estimates. Given the limited number of stations temporally available, this analysis has been reported just to complete the framework proposed while a full validation is to refer to future developments of both the rain gauge network and the proper algorithm design.

5. Conclusions

The availability of a local weather radar, allowed by the spreading of the X-band technologies for low-cost applications, provides relevant insights to both the meteorological monitoring applications and those requiring reliable quantitative precipitation estimates. Such a possibility has been explored by means of other supporting sensors that enable the blending of sensors data in order to reduce errors and uncertainties of radar estimates. The paper presented the monitoring framework developed at the DICAM, University of Palermo (Italy). Three procedures for the refining of the transformation of radar measurements into precipitation information have been presented. These procedures are based on the exploitation of the disdrometer and the rain gauge network measurements. Depending on the activity of interest, roughly grouped as meteorological and hydrological applications, the ensemble of procedures can be fitted in order to meet the requirements either in terms of speed for the retrieving of information about the hydrometeor dynamics or in terms of reliability of quantitative estimates.

Future developments of the system are related to the consolidation of the rain gauge network, the development and validation of a proper rain gauge network correction procedure, and the validation of the system for heavy events occurring in the observed area.

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The potential of using social media for precipitation and flood assessment

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Abstract

It is a virtual truism that high-resolution weather and precipitation data from national or regional weather services are sparse. This is why weather services have been tapping into the potential of so-called “weather spotters” or “storm spotters” since several decades. Two very successful examples from the U.S. are i) the “Skywarn®” volunteer program of the U.S. National Weather Service, which started in the 1970s, where about 290,000 trained weather spotters currently report on severe weather to the National Weather Service (Skywarn 2015) and ii) the Community Collaborative Rain, Hail and Snow (CoCoRaHS) network. CoCoRaHS is a targeted non-profit, community-based network which the goal is to measure and map precipitation (rain, hail and snow) (COCORAHS 2015). Such weather spotting initiatives appear to be very successful. For example CoCoRaHS claims that their data are “used by a wide variety of organizations and individuals. The National Weather Service, other meteorologists, hydrologists, emergency managers, city utilities (water supply, water conservation, storm water), insurance adjusters, USDA, engineers, mosquito control, ranchers and farmers, outdoor & recreation interests, teachers, students, and neighbors in the community are just some examples of those who visit our Web site and use our data.”

In this contribution, we investigate in how far weather spotting can be augmented by reports from non-volunteers on internet services typically labelled as “social media”. As suggested by Hyvärinen and Saltikoff (2010), the rationale behind this is two-fold. First, a large number of imprecise observations, e.g. on rainfall or flood extent, are probably more informative than sparse very precise observations. Second, there are probably two to three orders of magnitude more social media users than weather spotters (Statista 2015).

In this study we would like to demonstrate the potential of social media harvesting to improve available information on precipitation and its impact, e.g. through flooding and discuss it with the urban rainfall community. Early works in this regard have been reported using the API of Flickr, a photo-sharing service, and Twitter. Hyväriinen and Saltikoff (2010) analyzed Flickr information for hail and recommend to further look into social media, especially Twitter as data sources. In comparison to photo-sharing services, Twitter has two advantages: i) a large amount of information is shared in ii) almost real-time. For example, Demirbas et al. (2010) created a spatio-temporal rainfall map with information from the crowd, and Moffit (2015) found a close correlation between observed rainfall intensities in Las Vegas and tweets related to precipitation. In contrast, Cox and Plale (2011) failed to improve reports of localized weather types based on Twitter, e.g. detecting that precipitation is hail or snow rather than liquid.

Also, monitoring the extend of floods has been reported (Fuchs et al. 2013; Herfort and De Albuquerque 2014) and there are a few current projects focused on mining social media to estimate flood extent, e.g. “Intelligent Synthesis and Real-time Response using Massive Streaming of Heterogeneous Data” (INSIGHT-ICT) and the FLOODTAGS project. This later project aims to enrich of Twitter data with a Digital Elevation Model for real-time flood extent mapping, calibrating and validating global flood models and prioritization of tags using text mining.
At the UrbanRain2015 workshop, we would like to discuss our results from using the Flickr image-sharing service to investigate the possibility to derive precipitation and flood-related quantitative information from people-centric observations.

Figure 1, left, shows preliminary results of the number of images available on Flickr regarding the occurrence of flooding, in three different languages. The right plot suggests a very interesting correlation of related Flickr posts to the magnitude of economic damage caused by flooding in Switzerland.

In the future, we will investigate the potential of social media for individual regions, e.g. where traditional sensors are missing, and how to best augment traditional weather observations with these information. Although we find that information from social media is non-authoritative and transient, we agree with Hyvärinen and Saltikoff (2010) that it might compare quiet favourably, given the inadequate spatial sampling of most traditional measuring devices, e.g. hail pans. When people even suggest to use cars for quantitative precipitation monitoring (Rabiei et al. 2013), using social media to augment and complement existing data seems to be worth trying.

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Sub-daily extreme precipitation under current and future climate conditions from high resolution RCMs

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Abstract

The increase in extreme precipitation is likely to be one of the most significant impacts of climate change in cities, where short duration extreme precipitation is one of the main causes for severe floods. Hence, reliable information on changes in sub-daily extreme precipitation is needed for the design of robust adaptation strategies.

Some recent studies point towards the fact that the representation of sub-daily extreme precipitation by climate models increases with increasing spatial resolution (Kendon et. al., 2014). This study explores extreme precipitation over Denmark generated by the same regional climate model (RCM) HIRHAM-ECEARTH at different spatial and temporal resolutions. The temporal resolutions 1, 3, 6, 12, 24, and 48 h and the spatial resolutions 8, 11, 25 and 50 km are investigated. For the period 1991 to 2010, the performance of the RCMs is evaluated against two observational datasets: a network of high-resolution rain gauges operated by the Water Pollution Committee of the Society of Danish Engineers and the Danish Meteorological Institute (DMI), usually referred to as the SVK dataset, and the gridded observational dataset Climate Grid Denmark (CGD).

The performance and changes projected in the spatial pattern and the area average Intensity-Duration-Frequency (IDF) curves for 2, 10, and 100 years return periods are evaluated over Denmark. The Partial Duration Series (PDS) methodology is used to extract extreme value series. A threshold corresponding to an average of three annual exceedances is applied. The Generalized Pareto Distribution (GPD) is fitted to the extreme value series using the L-moment approach. In accordance with the approach of Madsen et. al. (2002), we assume a constant regional shape parameter in the GPD over Denmark.

The results show that the RCMs at lower spatial resolution (25 and 50 km) perform similarly to the RCMs at higher spatial resolution (8 and 11 km) at low temporal resolutions, but worse at higher temporal resolutions (see Figure 1). At daily resolution the mean extreme event and shape parameter of the GPD reveals that all the RCMs perform similarly. At hourly resolution the representation of the mean extreme event increases for increasing spatial resolution of the RCMs. In addition, the physical parameterisation of the RCM leads, in general, to more skewed extreme value distributions than the observational dataset for hourly extreme precipitation. This leads to an over-estimation of hourly extreme precipitation by the RCMs at 8 and 11 km, which are the models in the so-called grey zone. The biases in the spatial pattern of extreme precipitation change across temporal and spatial resolution.
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Fig 1: IDF for the 10 years event. Area Reduction Factors (ARF) have been applied to the RCMs to "downscale" the T-year event to point estimates. The shaded area shows the spectrum covered by all the bootstrapping samples from the SVK stations. All the results represent the area average intensity over Denmark.

The changes projected by the RCMs for the period 2081 to 2100 compared to the period 1991 to 2010 depend on the spatial and temporal resolution. The RCMs disagree on the magnitude and spatial pattern of the changes. However, there is agreement on higher changes for higher temporal and spatial resolution (see Figure 2).

Fig 2: Area averaged changes for the 10 years event estimated from the RCMs for different temporal resolutions.

Overall, the results from this study show that the biases of the RCMs increase and the projected changes decrease for decreasing spatial resolution of the RCMs. This highlights the importance of the spatial resolution of the RCMs and points towards the need for high spatial and temporal resolution RCMs to obtain reliable information on changes in sub-daily extreme precipitation.

References


Precipitation analyses based on all multiple sources

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Abstract

This article describes a method for analyzing precipitation rates on a high temporal resolution by taking into account several types of observational data and if necessary, also model data. This includes common and special station observations (precipitation sum, number of tips, present weather state) as well as radar, satellite, lightning and modelled numerical weather prediction data.

All sources are defined either on point locations or on grids with different grid sizes (from 1km for radar to 16km for model data), additionally, the temporal frequency of all sources differs and ranges from 5 min (some radar sources) over 10 min (some station observations), 15 min (satellite data) up to 1 hour (model data, station observations). The result of the here described analysis consists of gridded precipitation sums with spatial resolutions between 1 and 4 km and with temporal resolution of 10, 30 or 60 minutes, depending on the availability of the input data.

The core of the analysis method is based on VERA (Vienna Enhanced Resolution Analysis), a method, for analyzing irregularly distributed point data to a regular grid by taking into account optionally additional and apriori defined or observed patterns. The VERA algorithm separates meteorological fields into an unexplained and into one or more explained components. Each explained component is expressed as a weighted Fingerprint (pattern) whereas the weighting factor is allowed to vary spatially. The unexplained component as well as the weighting factors are considered to be as smooth as possible but allowing the field values to fit point observations as close as possible. This information is formulated as a const function with has to be minimized resulting in a system of linear equations. The solution consists of the analysis values and weighting factors for the Fingerprints. A prominent candidate for a Fingerprint is of course radar data which works fine as long as only one radar source is used. Multiple radar sources may have very sharp transitions, overlaps and gaps which avoids one to split the precipitation field into several explained parts with smooth weighting factors. In order to handle this problem, not the radar precipitation itself is analyzed, but the ratio of precipitation based on radar and station observations.

For regions without or with a very sparse station observation network and without radar coverage, precipitation deduced from satellite (multi sensor precipitation estimate) is taken into account. Additionally, hourly forecasts from local numerical weather prediction models are used and temporally downscaled to 10 minute time intervals using a one dimensional VERA approach with an additional constraint for conserving 1 hourly precipitation sums. Figure 1 (left) shows the result of an analyzed 10 minute precipitation sum for Central Europe based on radar (multiple overlapping domains) and model data as well as station observations from rain gauges. In spite of these different sources concerning spatial and temporal resolutions, no edges or discontinuities can be detected. The right image illustrates that (weighted) radar data dominates the whole analysis but there are regions where radar beams are shielded by mountains. In these regions the analysis is identical to the background field which is only calculated from point observations. The southern part of the considered domain is not covered by radar, furthermore, the station observation network is quite sparse which results in the acceptance of the temporally downscaled model field as best estimation.
In some regions, precipitation is not measured by using rain gauges but there are still human based observations which are encoded as significant weather state addressing precipitation type and intensity. In such cases it is at least possible to use a representative estimation for precipitation rate which is sufficient for some purposes such as selecting the proper weather symbol on a weather portal.

In addition to a qualitative precipitation analysis for a single point in time, consistent temporal transitions are required for precipitation patterns. This is self-evident for decluttered radar data but not necessarily for precipitation analyses based on station observations. To overcome this problem, a 3D version of VERA (considering time as third dimension) will be applied to station observations.

In practice, all observations exhibit different delay times. As a result, the analysis of the most recent observations is located 15 to 20 minutes in the past. This problem is solved by applying a short range forecast (correlation approach) based on the two most recent precipitation analyses.

![Fig 1: (left) Analyzed 10 minute precipitation sum for 15th May 2015, 07:00-07:10 taking into account radar, station (gauges) and model data. (right): Components of analysis for same time interval. The green component is the contribution of radar precipitation, red component corresponds to the background field based on station data and the blue component is based on model precipitation.](image)

References

Underestimation of DDF values obtained from paper pluviograms

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Abstract

Extreme rainfall triggers many hazards in river basins (e.g., floods, landslides, mud-rock-debris flows) with particularly heavy impacts in cities and urbanized areas (e.g., urban flooding, storm/sewer drainage overflows). In Chile, persistent and ubiquitous urban flooding problems led us to question the official depth-duration-frequency (DDF) estimates used in drainage design in the country (Soto, 2004). In a preliminary analysis for the city of Concepción, we found severe underestimation of short duration rainfall, increasing with return period but decreasing with duration (Soto and Meier, 2013). After considering all possible alternative explanations, we hypothesised that the strong negative bias is caused by two simplifying procedures that were applied when estimating the DDF values from the original weekly paper charts (pluviograms – Meier et al., 2013, 2015).

Firstly, because of the low resolution of such charts, rainfall maxima for the different durations (1, 2, 4, 6, 8, etc. hours) were extracted using fixed (“clock”) time intervals of 1 hour, instead of continuous time. In other words, rainfall was first totalized over clock hours (e.g., from 8:00 to 9:00, 9:00 to 10:00, etc.), before examining the record in the search for extremes. In this way, for example, when seeking the annual maximum for a 2-hr duration, only totals aggregated every 2 hours (e.g., from 8:00 to 10:00, or from 9:00 to 11:00, or 10:00 to 12:00, etc.) were compared, instead of sliding a 2-hr long time-window along the continuous rainfall signal, until hitting the “true” 2-hr maximum. It is clear that such a procedure can only result in biased maxima that are always equal or smaller than the actual extreme values, an effect that is well known in the literature and in engineering practice (see, for example, Young and McEnroe, 2003). It should be noted that a similar problem still happens currently, as most meteorological services report rainfall data aggregated over 10 to 30 min fixed-time periods.

Secondly, in order to save time in an otherwise arduous process, only a subsample of all the storms was considered when extracting the maxima from the pluviograms. In this way, instead of having to consider, say, 60 different events per year, on average, when searching for the extremes for each duration, only the 4 or 5 largest annual storms (ranked by total storm depth) were scrutinized. On geophysical grounds, this approach should also add a negative bias, increasing for shorter durations, as shorter, “smaller” events (in the sense of total depth), are discarded; in effect, these could very well contain extreme intensities over short periods, notwithstanding their lower integrated rain depth. In central Chile, for example, where mostly stratiform rainfall occurs, cold fronts tend to be more intense than warm fronts, but last less and have lower total storm depths. In the present digital era, there is absolutely no need for this procedure, but it certainly helped save a lot of time when searching for maxima in tens of thousands of daily paper rain charts; this is why it was used in different countries. This bias might introduce a problem that has not been recognized yet in the literature, as far as we are aware: older IDF (or DDF) values, obtained from pluviograms with this procedure cannot be directly compared to recent, digitally-derived ones.

Our goal in this work is to assess the effects of these two simplifying procedures in a consistent manner, across many stations, to better understand the biases they might cause. To do so, we use
the records from 52 stations of the SwissMet network, with the same instrument and gauging protocols. The data cover the same concurrent, continuous 32-year-long (1982-2013) period, consisting of accumulated rainfall over 10 min-long aggregation periods.

We first obtain the “correct” DDF values at each station, for rainfall durations of 1, 2, 3, 4, and 5 h, considering the original 10-min data and all storms in the record. Then, to simulate the effects of the two simplifying procedures described above, we generate three sets of alternative DDF values, first by aggregating the original 10-min data over increasing fixed (“clock”) time windows (20, 30, and 60 min), then by extracting the rainfall maxima from only the four largest storms for every year in the record (instead of looking at all of the data for the year), and finally by doing both things at the same time. In order to avoid estimation problems, we only work with frequent, 1 to 5 year return periods, and obtain our DDF values directly, from ranked partial duration series. We then compare the “correct” DDF values with those obtained by (i) aggregating temporally over fixed time, (ii) considering only a subset of storms, and (iii) using both simplifying procedures concurrently.

The results are quite surprising: Two commonly-accepted practices, the aggregation of rainfall data over even “reasonably short” periods and not considering all events when searching for the maxima, can cause a large underestimation of design precipitation, which is highly dependent on location. Aggregating over 1-hr fixed time, causes a mean bias of -10.4% (averaging over the 52 locations) in the 1-hr duration rainfall, for average return intervals (ARIs) between 1 and 5 yr, but the underestimation can be as high as -22.6% at some stations, for ARI = 5 yr. Even though it is already known that sampling the variability in rainfall intensity over fixed time intervals reduces the observability of true high rainfall intensities (e.g. Young and McEnroe, 2003), the effect has been rarely quantified explicitly, particularly as a function of ARI and duration. In this study, we also find that there is a large variability between stations that still needs to be quantified.

In turn, searching for the maxima within only the four largest storms per year (instead of considering the whole record), introduces a mean bias of -35.5%, across all locations, for ARI = 1 yr, which monotonically decreases to -14.9% for ARI = 5 yr. The maximum underestimation due to this effect can be as large as 57%. The combination of both procedures (i.e., as was done in Chile: aggregating data over fixed 1-h intervals and simultaneously considering only the four largest storms when extracting the maxima) results in mean biases of -24.9%, -12.9%, -7.4%, -5.0% and -3.3%, for durations of 1, 2, 3, 4, and 5 h, respectively, for ARI = 5 yr. These severe negative biases in DDF values correspond to averages over 52 Swiss locations (Fig 1). At individual stations though, the underestimation can be up to 5.1 times as high as the average, depending on rainfall duration, for T=5 yr. Finally, one should consider that the original data used in these analyses are not continuous but were already aggregated over 10-min periods, so that the actual biases should be even higher than what we report herein.

We conclude that: (i) both simplifying procedures can produce large negative biases, (ii) even though it is known that sampling rainfall over fixed time intervals introduces such negative biases, the large variability of this effect across locations has seemingly not been appreciated up to now, and (iii) when looking at long-term behaviour of rainfall extremes, comparing older, chart-derived DDF values, with newer, digitally-derived ones, it is necessary to understand whether the older values were obtained considering only a subsample of all storms: if it is the case, such values will definitely not be directly comparable to more recent ones.
Fig 1: Mean bias in hourly annual rainfall maxima (+/- 1 st.dev.) for average return intervals R=2 and R=5 yrs computed from 52 SwissMetNet stations with 10-min data, accounting for the time sampling effect (aggregating the 10-min data over 1-h fixed periods), the storm count effect and both effects combined (left). Mean bias as a function of rainfall duration D for R=5 yrs return period (right).

References


Temporal rainfall disaggregation using a multiplicative cascade model for spatial application in urban hydrology

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Abstract

For urban hydrology rainfall time series with a high temporal resolution are crucial. Observed time series of this kind are very short in most cases, so they cannot be used. On the contrary, time series with lower temporal resolution (daily measurements) exists for much longer periods. The objective is to derive time series with a long duration and a high resolution by disaggregating time series of the non-recording stations with information of time series of the recording stations.

The multiplicative random cascade model is a well-known disaggregation model for daily time series. For urban hydrology it can be assumed, that a day consists of only 1280 minutes in total as starting point for the disaggregation process (e.g. Molnar & Burlando, 2005). Three new variants for the cascade model have been analyzed, which are functional without this assumption. These methods are extensions of the uniform splitting approach with a branching number \( b=3 \) in the first disaggregation step of the cascade model, introduced by Müller and Haberlandt (2015). For all further disaggregation steps \( b=2 \) is applied, so that temporal resolutions of e.g. 15, 7.5 or 3.75 minutes are achieved.

Fig. 1: Average event characteristics of observed versus disaggregated time series for 24 stations in Lower Saxony, Germany.
The existing 1280 minutes approach (called method A) is outperformed by the so-called method B2 regarding time series characteristics like wet and dry spell duration, average intensity, fraction of dry intervals (Fig. 1) and extreme value representation (Fig. 2). To achieve a final resolution of 5 minutes, in B2 a linear interpolation of the 7.5 minutes time steps is carried out.

![Fig. 2: Rainfall extreme values (partial duration series, 5 minutes) for station Uelzen (time period July 2003 – December 2012).](image)

However, in both approaches rainfall time series of different stations are disaggregated without consideration of surrounding stations. This yields in unrealistic spatial patterns of rainfall. We apply a simulated annealing algorithm that has been used successfully for hourly values before (Müller and Haberlandt, 2015). Relative diurnal cycles of the disaggregated time series are resampled to reproduce the spatial dependence of rainfall. To describe spatial dependence we use bivariate characteristics like probability of occurrence, continuity ratio and coefficient of correlation. Investigation area is an artificial combined-sewer system with three rain gauges. We show that the algorithm has the capability to improve spatial dependence. Without spatial dependence, manholes and combined sewer overflow volumes are strongly underestimated. However, after the implementation results are comparable to those from the observations (see Fig. 3).

![Fig. 3: Manholes (upper part) and combined sewer overflow volume (lower part) resulting from extreme values with a return period of 4.4 years at the master station (30 minutes duration, ‘res’ indicates the resampled analogues for each variant).](image)

**References**


Precipitation intensity during heavy rains in various altitudes

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Abstract

The main factor influencing runoff during flash floods is the precipitation intensity. Estimated return levels of precipitation intensities are utilized when evaluating design discharges. Nevertheless, because precipitation can be distributed very unequally during heavy rains, the hydrological response can be significantly influenced by the temporal rainfall distribution. We develop an algorithm which enables to classify precipitation events with respect to the course of precipitation intensity. The aim of the study is to analyze differences among topographically heterogeneous sites with respect to the proportion of precipitation event types.

The methodology consists of several steps (Figure 1): (i) determination of precipitation episodes within time series: maxima of the precipitation total $P_t$ for the moving time window $t$ (purple columns in Figure 1a); (ii) separation of the main precipitation $P_m$ (maximum $P_{t/2}$) from the side precipitation $P_s = P_t - P_m$ (dark and light blue in Figure 1b, respectively) and evaluation of $P_m$ by the ratio $x = P_m / P_t$; (iii) accumulation of the external half of side precipitation ($P_s/2$) starting both from the beginning and the end (light green in Figure 1c) and determination of the relative duration of the internal side precipitation $P_{is}$ (another 50% of $P_s$, dark green in Figure 1c) according to $y = t_{is} / t_s$; (iv) determination of the duration of the antecedent part of $P_{is}$ (the duration is labeled $z$). The sequence is then repeated considering only $P_m$ of the previous time window (Figure 1d).

![Fig 1: Diagrams demonstrating the methodology of precipitation intensity analysis (x-axis represents time, y-axis precipitation intensity).](image_url)

The methodology was applied to adjusted radar-derived precipitation estimates from the Czech Republic 2002-2011 (Sokol, 2003). We presented results from four 1x1 km pixels with different topography where following rain gauges are located: Semčice (234 m.a.s.l., lowland), Kopisty (240 m.a.s.l. but in the vicinity of mountains), Milešovka (833 m.a.s.l., isolated cone), and Churáňov (1118 m.a.s.l., Šumava mountains).
Preliminary results regarding only precipitation concentration are depicted in Figure 2. The diagrams represent 10 maximum 24-h (top), 6-h (middle), and 1-h (bottom) precipitation totals in the four studied pixels. Curves represent individual precipitation episodes, characterized by the ratio $P_t / P_6$ for $t = 1, 1.5, 2, 3, 6,$ and 12 hours. Curves of steady (~stratiform) and torrential (~convective) rains are oriented diagonally and horizontally, respectively. We can state that maxima of 24-h totals belong to both types in lowlands while steady rains significantly prevail in mountains. Whereas torrential rains are typical for 1-h maxima, such maxima can also occur during steady rains in mountains.

It can be concluded that the study proved significant differences in precipitation intensities between lowlands and mountains but also between daily and sub-daily totals. The mere comparison between 12-h precipitation total and maximum 1-h precipitation intensity (Figure 3) enables to distinguish two main types of events: (a) torrential rains when more than 50% of the 12-h total is concentrated within only one hour (typically in lowlands); (b) steady rains when maximum 1-h precipitation intensity is less than 25% of the 12-h precipitation total (typically in mountains). A more sensitive classification will consider not only the main but also the weaker phase of a precipitation episode. The role of the other parameters $y$ and $z$ seems to be most significant in case of transitive episodes between the two main types.

Fig 2: Temporal analysis of 10 maximum 24-h (top), 6-h (middle), and 1-h (bottom) precipitation totals from the period 2002-2011 in four studied pixels.
Fig 3: Maximum 1-h precipitation intensities during 12-h precipitation totals in four studied pixels. The lower is their ratio, the more steady was the precipitation.

**Acknowledgments**

The research was supported by the grant QJ1520265 of the Czech Ministry of Agriculture, using data provided by the Czech Hydrometeorological Institute.

**References**

Validation of long term synthetic precipitation time series for sewer systems

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Abstract

In urban hydrology models are necessary for the dimensioning of sewer systems as well as for waste water treatment. The target of dimensioning sewer systems is to prevent flooding, which means large flow volumes and thus, extreme precipitation events are the decisive parameters. The objective of waste water treatment is to achieve good quality of water bodies. In practice the focus is rather on integrated discharge amounts than on specific quality parameters. However, initiated by the Water Framework Directive more and more attention will be drawn to quality parameters in future.

For modelling quality parameters in sewer systems not only extreme events are important, but also medium and smaller events and their temporal structure need to be regarded. Therefore, continuous long term precipitation time series of a high temporal resolution are necessary as input data. Unfortunately, such time series are very often not available or of an insufficient data quality. A solution is the generation of synthetic precipitation time series (Bárdossy, 1998).

The validation of synthetic precipitation time series with only statistical parameters is a challenging task. One option is the use of event based statistics. However, these statistics imply the definition of events which is on the one hand not straightforward and on the other hand may depend on the application setup. Another widely used validation is analyzing global statistics, like for example the autocorrelation function. Unfortunately these statistics are not sufficient in order to validate the time series for polluting load models.

![Figure 1: Deviation of synthetic time series and measured time series in the overflow duration for different storm water tanks.](image)

The approach shown here is an indirect validation method using a simplified sewer network with different storm water tanks introduced by Drechsel (1991). It will be demonstrated that analyzing different overflow characteristics of different storm water tanks help to understand and to validate the temporal structure of precipitation time series. Additionally, it will be highlighted that a validation with just one overflow characteristic (e.g. overflow volume), or just one storm water tank does not allow a general statement about the applicability of the precipitation time series on different problems. Figure 1 shows an example of the large bandwidth of deviations of synthetic and measured
time series in the overflow duration depending on the storm water tank configurations if the same input data is applied.

References


Towards a high resolution stochastic rainfall generator for urban applications

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Abstract

Traditionally, urban hydrological applications rely on spatially-uniform rainfall estimates derived from point measurements. However, several studies indicated that the performance of urban runoff and drainage simulations may largely depend upon the spatial and temporal variability of the rainfall input and that, therefore, rainfall input at high spatial and temporal resolutions is required. Historical data with such resolutions are, however, short in time. For this reason, long-term synthetic rainfall data generated by a stochastic model, accurately representing the real spatial-temporal rainfall properties, would be very beneficial. Such generated data is not constrained by the length of available historical data, hence would provide a better basis for urban-scale applications, such as urban pluvial flood risk analysis and urban drainage design. For this purpose, the early stages towards a development of a stochastic spatial-temporal rainfall generator for urban hydrological applications are presented in this work. The spatial stochastic generator for small spatial scales presented by Willems (2001) is employed as the starting point.

The core of Willems’ generator is a conceptual rain storm model that aims to characterise rain storms with a number of physically-meaningful features (e.g. storm direction and velocity, rain cell extent, peak intensity and so on), and then to describe the statistical properties of each of them with a specific probability distribution. Based upon this, design rainfall with spatial variability can be simulated by firstly sampling a number of rain cell clusters over a ‘simulation area’, and then by moving the overall simulation area across the ‘catchment’ area with a given speed and direction. However, three main aspects where the model could be potentially improved were identified:

- The parameters of Willems’ model were primarily calibrated based upon point rain gauge data, which could be insufficient to capture the real structure of rain storms and cells.
- The rain cells were conceptualised using bi-variate Gaussian model, which might oversimplify the real structures of small-scale rain cells and consequently smooth off the rain cell peaks.
- The temporal variability of the rain field was due to merely (stationary) field advection, so the temporal evolution of the field itself was not taken into account in Willems’ model. This will lead to the ‘unrealistic’ isotropy in the spatial and temporal scaling behaviours of simulated storms (Seed et al. 1999).

To start tackling these deficiencies, the following strategies have been implemented:

- High-resolution radar images (provided by the Royal Meteorological Institute of Belgium) were used to better capture the spatial and temporal characteristics of rainfall fields. However, the use of radar images made the storm cell identification and tracking more challenging, in particular for small-scale rainfall details. To cope with this, two main algorithms were developed. First, a multi-threshold identification algorithm based upon the hierarchical threshold segmentation (HTS) method (Peak and Tag, 1994) was created. With this technique, adjacent storm cell clusters at small scales could be better identified and isolated. Secondly, an enhanced version of the TITAN algorithm (Dixon et al., 1993) by means of integrating optical flow techniques, was also developed. The performance of the enhanced TITAN tracking algorithm was evaluated by the ROC (Receiver Operating Curve) analysis (Fig. 1).
Fig 1: ROC plots for different threshold levels and catchment extents. The lower curve shows TITAN performance. Multi-threshold method inclusion improves the performance while optical flow integration gives the best results (Upper curve).

- A multi-layer conceptual model based upon the superposition of different rainfall entities (including high intensity peaks, rainfall cells, and small and large storm scales areas) was adopted. By making use of the improved TITAN algorithm, the rainfall fields were built by overlapping high intensity peaks within rain cells, which, in turn, were embedded in small mesoscales areas (Fig 2). Rain cells were still modelled using a bivariate Gaussian model. Small mesoscales areas were fitted as ellipses with constant intensity.

Fig 2: The original radar rainfall image (left) and the conceptualised rainfall image (right).

Results show that the integration of optical flow with a multi-threshold identification method considerably improved the performance of the original TITAN method. Furthermore, the conceptual model shows great potential to mimic the spatial distribution of rainfall intensities in convective rainfall fields. Therefore, the methods presented in this work enable better capturing the behaviour of small-scale and high-intensity storm cells, and suggest a great potential to provide added values to the implementation of Willems’ rainfall generator.

References


Intercomparison of rainfall measurements from three different types of weather radars covering the same urban area

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Abstract

Accurate and reliable rainfall measurements are vital for the daily work of urban drainage designers and managers, concerning operation, planning and maintenance of the system. Historically, rain gauges have provided these valuable data. Recently, distributed high quality rainfall measurements from weather radars are becoming more accessible. Small weather radars, especially developed for urban drainage applications are being installed in order to support design, analysis and nowcasting. These weather radars have obvious benefits in relation to urban drainage applications, as the weather radar provides high resolution, real time observations of precipitation throughout the city. Dependent of the radar type, its configuration and location relative to the city, it is capable of providing rainfall observations in temporal and spatial scales matching the fine scales and fast response to rainfall, typical for urban catchments (Berne and Krajewski, 2013; Einfalt et al. 2004).

Fig 1: The experimental test-site for weather radar measurements.

Different types of weather radars are in operation today ranging from meteorological C- and S-band weather radars with long range to small X-band weather radars with high resolution in both time and space. Dependent on the application, the radar types have different advantages. Meteorological weather radars cover large areas, and are capable of detecting the precipitation before it reaches the city. The long range radars therefore have a now-casting potential, which, for the short-range X-band radars is limited. The strength of the short-range radars is that it can be dedicated to urban drainage applications. It can be located near the city with optimal conditions for the radar measurement. The close vicinity to the area of interest gives the possibility of a higher
spatial resolution. Moreover, the smaller X-band weather radars can be operated with frequent scanning, leading to a higher temporal resolution as well. The combination of high spatial and temporal resolution makes X-bands radars the preferred choice for urban drainage applications.

The presented work is based on weather radar observations over city of Aalborg, Denmark. The study area is an experimental test-site for rainfall observations, and facilitate unique possibilities for comparison and analysis of weather radar measurements. A meteorological C-band radar and two different types of X-band radars cover the study area. A map of the site is illustrated in figure 1. The C-band radar, which is located approximately 45 km north of the city, is a Doppler radar and is part of the Danish national network of weather radars operated by the Danish Meteorological Institute (DMI). The two X-band radars are of different brands and are based on significantly different technology. The Eldes WR-10x radar is a non-polarimetric weather radar without Doppler, whereas the FURUNO WR-2100 is a dual-polarimetric, Doppler X-band radar. Aalborg University operates both X-band radars for the purpose of research within urban hydrology. Key specifications of the radar systems are presented in table 1.

Table 1: Key specifications and configurations of the three radar systems evaluated in the study.

<table>
<thead>
<tr>
<th>Radar specifications</th>
<th>C-band</th>
<th>WR-2100 X-band</th>
<th>WR-10x</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>Max 240 km, QPE 120 km</td>
<td>50 km</td>
<td>36 km</td>
</tr>
<tr>
<td>Range resolution</td>
<td>500 m</td>
<td>100 m</td>
<td>150 m</td>
</tr>
<tr>
<td>Horizontal beam width</td>
<td>1°</td>
<td>2.7°</td>
<td>3°</td>
</tr>
<tr>
<td>Vertical beam width</td>
<td>1°</td>
<td>2.7°</td>
<td>3°</td>
</tr>
<tr>
<td>Scanning interval</td>
<td>10 min</td>
<td>1 min</td>
<td>5 min</td>
</tr>
</tbody>
</table>

In the weather radar test area a network of eight tipping bucket rain gauges are installed. Moreover, the site is equipped with three laser disdrometers, which also is used as ground observations in the experimental setup. The disdrometers measures the drop size and velocity distributions of the precipitation by mean of laser, which facilitates direct measurements of the relation between the radar reflectivity and rainfall intensity at surface level.

The advantage of this study site is that the overall performance of the three radar systems are compared under the exact same atmospheric conditions, as the radars measures the same rainfall events over the area. The purpose is to study the impact of the temporal and spatial scale difference between the radar systems on their rainfall estimates. Based on rain gauges and disdrometers the overall QPE-performance is quantified for the three radars and based on specific events, the benefits of using high resolution X-band radars is evaluated.

References

Comparing precipitation patterns at three urban catchments in Helsinki (Finland) using high-resolution rain gauge and radar measurements

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Abstract

Urban catchments are characterised by intensive land use leading to high proportions of impervious surfaces and, consequently, rapid response to rainfall events, high surface runoff, and often poor water quality. A Finnish Academy project URCA (Quality and Quantity of Runoff Water in Relation to Land Use in Urbanized Catchments), an interdisciplinary project between Aalto University and the University of Helsinki, studies the links between precipitation, runoff, stormwater transport, and land use in urbanized areas. In this work the focus is on studying the spatio-temporal aspects of precipitation in the urbanized study catchments.

High temporal resolution rainfall data have been collected at three urban catchments in Helsinki (Fig. 1) for the snow-free periods of 2014 and 2015 using fully automatic 0.2 mm tipping bucket rain gauges with one minute temporal resolution. Additionally stormwater runoff has been measured at the sites with one minute resolution. The catchments are located in close vicinity to each other, residing inside a radius of six kilometres, thus enabling comparisons of the spatial properties of rainfall in the region. University of Helsinki operates a dual-polarization C-band weather radar in Kumpula, Helsinki (Fig. 1), also located inside the six-kilometre radius, for which data are available at 2.5 min temporal and 250 m spatial resolution. In addition, University of Helsinki has a tipping bucket rain gauge located in Kumpula. Furthermore, the Finnish Meteorological Institute (FMI) has rain gauges located in Kumpula, only a few hundred meters away from the University measurement station.

This research takes advantage of the collected precipitation data in the three study catchments and in Kumpula to gain insight on the similarities and differences observed in the recorded precipitation amounts among different sites at varying temporal scales. The FMI rain gauge data from Kumpula is used as a reference data against which the automatic observations from the study catchments are compared in order to validate the observations. The high-resolution radar data is used as a further measure to validate the catchment observations especially in regard to convective summer showers that may have only occurred over an individual ground observation site. Differences in the occurrence, timing and volume of rainfall are studied for all available observation sites. Also, applicability of the radar data as a catchment rainfall estimate is studied by comparing the radar observations over the study catchments to the ground observations.

In addition to comparing the precipitation patterns between the observation sites, the rainfall analysis serves for identifying intensive storm events to be used as an input for subsequent urban runoff modelling, where the impact of differences in the distribution of urban surfaces on runoff will be explored.
Fig 1: Study catchments in Helsinki, Finland. Locations of rain gauges are indicated by purple circles. The red diamond depicts the location of the C-band weather radar (and additional rain gauges) in Kumpula.
Abstract

The WMO project Solid Precipitation Intercomparison Experiment (Nitu 2013), WMO SPICE, will conclude its field tests in 2015. Formally started in the fall 2012, the field measurements will report on the performance of currently available technologies for the point measurement of precipitation and snow on ground. The results will be based on the data from experiments conducted over two winter seasons on 20 field sites located in 15 countries, on both earth hemispheres (see Figure 1).

Fig 1: Field measurement sites involved in the WMO/CIMO SPICE project.

With about 30 different instrument models, the broad range of climates among the SPICE sites enables a unique opportunity for testing similar technologies in different conditions. From the first preliminary results it appears that equivalent technology types may lead to different responses, in different climate regimes.

The example of Figure 2 shows results that illustrate these early findings. The catch ratio data for one winter season for the same instrument model (weighing gauge) tested on three different sites show different trends which may be attributed to the differences in the climatic conditions of the three sites.
Fig 2: Catch efficiencies of an instrument under test (weighing gauge) against the reference, as a function of wind speed for the same instrument located at three different sites. Catch ratio is defined as the ratio between the precipitation accumulations (amount) reported by the instrument under test and the field reference, for the same reporting interval. These results reflect the 30 minute precipitation accumulation.

The presentation will display some of these early results, based on the comprehensive and coordinated dataset derived from the overall field measurement.

Following SPICE, the entire dataset is meant to be available for further data mining. The SPICE Members invite therefore the whole community to take advantage of such an opportunity in order to reinforce our understanding of the best approach to get a good precipitation measurement and to assess the value of such results linked with other research precipitation fields.

References

Probabilistic urban inundation nowcasting

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Abstract

A probabilistic model has been set up and evaluated for the nowcasting (short-term forecasting) of urban inundations. It consists of the following components:

- A rainfall nowcasting model based on the Short Term Ensemble Prediction System (STEPS), originally co-developed by the UK Met Office and Australian Bureau of Meteorology, but further customised for urban applications in Belgium (denoted STEPS-BE). It provides high-resolution (1 km / 5 min) rainfall nowcast ensembles with a 2-hour lead time.
- A hydraulic model that consists of the 1D sewer network and an innovative ‘nested’ 2D surface model to model 2D urban surface inundations at high resolution. The surface components are categorised into three groups and each group is modelled using triangular meshes at different resolutions; these include streets (3.75 – 15 m²), high flood hazard areas (12.5 – 50 m²) and low flood hazard areas (75 – 300 m²).
- Functions describing urban flood damage and social consequences in relation to inundation depth. These functions were empirically derived based on questionnaires to people in the region that were recently affected by sewer floods.
- Statistical post-processing methods in order to produce probabilistic urban flood risk maps: spatial maps representing the probability of flooding.

The method has been implemented and tested for the villages Oostakker and Sint-Amandsberg, which are part of the larger city of Gent, Belgium. After each of the different above-mentioned components were evaluated, they were combined and tested for five recent historical flood events. The rainfall nowcasting, hydraulic sewer and 2D inundation modelling and socio-economical flood risk results each could be partly evaluated: the rainfall nowcasting results based on radar data and two rain gauges; the hydraulic sewer model results based on water level and discharge data at pumping stations; the 2D inundation modelling results based on limited data on some recent flood locations and inundation depths; the results for the socio-economical flood consequences of the most extreme events based on claims in the database of the national disaster agency. Different methods for visualisation of the probabilistic inundation results are proposed and tested.

Acknowledgement

These are results of the interdisciplinary research project PLURISK on “Forecasting and management of extreme rainfall induced risks in the urban environment” for the Belgian Science Policy Office (Belspo).
Evaluation of radar-rain gauge merging methods for urban hydrological applications: relative performance and impact of gauge density

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Abstract

Rainfall estimates of very high accuracy and resolution are required for urban hydrological applications, given the high impermeability, small size and fast response which characterise urban catchments. Traditionally, urban drainage modelling applications have relied mainly upon rain gauge data as input, given that these sensors provide relatively accurate point rainfall estimates near the ground. However, they cannot capture the spatial variability of rainfall, which has a significant impact on the urban hydrological system and thus on the modelling of urban runoff. With the advent of weather radars, radar quantitative precipitation estimates (QPEs) with higher temporal and spatial resolution have become increasingly available and have started to be used operationally for urban storm-water modelling. Nonetheless, the insufficient accuracy of radar QPEs, arising from the indirect measurement of rainfall -often significantly high above ground-, has proven problematic and has hindered its widespread practical use (Schellart et al., 2012). In order to improve the accuracy of radar rainfall estimates while preserving their spatial description of rainfall fields, it is possible to dynamically adjust them based on rain gauge measurements. Gauge-based adjustment of radar QPEs, also referred to as radar-rain gauge combination or merging, has been an active topic of research over the last few decades and has proven effective to improve the accuracy of radar QPEs, thus improving their applicability for hydrological applications. However, most gauge-based adjustment methods have been tested and applied at large spatial and temporal scales -of the order of thousands of square kilometres and at temporal resolutions ≥ 1 h- (e.g. (Goudenhoofdt & Delobbe, 2009)), and their suitability for small-scale urban hydrology is seldom explored.

In this work we evaluate the performance of several radar-rain gauge merging techniques of various degrees of complexity at urban scales. The techniques under investigation were selected on the grounds of their widespread use and/or their relative performance against other existing techniques, as reported in previous studies (Goudenhoofdt & Delobbe, 2009; Wang et al., 2013; Jewell & Gaussiat, 2015). The tested techniques include the simple mean field bias (MFB) correction, the Kriging with external drift (KED), and the more advanced Bayesian (BAY) merging (Todini, 2001) and singularity-sensitive Bayesian (SIN) merging (Wang et al., 2015). The study area is a sub-catchment of Birmingham (drainage area ~ 67 km²), UK, for which Met Office C-band radar QPEs (at 1 km / 5 min resolution), as well as records from 20 rain gauges (at 2 min resolution) and 41 flow gauges (at 2 min resolution) over a 6 month period are available. The relative performance of the different merging methods is first assessed on an event basis through comparison against rain gauge records and through hydrological verification (Figure 1). Moreover, the effect of rain gauge density on the performance of the merging methods is investigated. For this purpose, a simple approach of removing gauges from an initially dense network of rain gauges was applied; the selected approach ensures realistic configuration of rain gauge networks of different densities. The initial conclusions of this study are the following:

- All adjustment methods improve the applicability of the original radar and rain gauge QPEs estimates to urban hydrological applications (Figure 1); however, the degree of improvement varies for each method.
In general, MFB is insufficient for satisfactorily correcting the errors in radar QPEs (Figure 1 (a, b)) and this is evident in the associated hydraulic outputs, which fail to properly reproduce peak depths and flows. This suggests that more dynamic and spatially-varying adjustment methods are required for urban hydrological applications.

At high rain gauge densities (~1 rain gauge every 3 km²), KED, BAY and SIN rainfall estimates show very good quantitative performance, both in terms of comparison against rain gauge records and in terms of their ability to reproduce observed urban runoff (Fig. 1). The SIN QPEs perform particularly well at reproducing peak rainfall intensities and associated depths & flows.

At low rain gauge densities (~1 rain gauge per 16 km²) KED, which is one of the most popular methods (Goudenhoofdt & Delobbe, 2009; Jewell & Gaussiat, 2015), performs poorly, and the advantage of the BAY and in particular the SIN method becomes more evident (Fig. 2).

Fig 1: Quantitative performance of different merged QPEs – Storm 1: (a) Areal average total rainfall accumulations; (b) Areal average rain gauge vs. radar/merged QPEs instantaneous rain rates; (c) Observed vs. simulated flows.

Fig 2: Impact of rain gauge density on the rain gauge interpolated (BK: block-kriging) and radar-rain gauge merged QPEs.

References


Sensitivity of urban drainage models to the spatial-temporal resolution of rainfall inputs: a multi-storm, multi-catchment investigation

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Abstract

Urban hydrological applications require high resolution precipitation and catchment information in order to well represent the spatial variability, fast runoff processes and short response times of urban catchments (Berne et al., 2004). Although fast progress has been made over the last few decades in high resolution measurement of rainfall at urban scales, including increasing use of weather radars, recent studies suggest that the resolution of the currently available rainfall estimates (typically 1 x 1 km² in space and 5 min in time) may still be too coarse to meet the stringent requirements of urban hydrology (Gires et al., 2012). What is more, current evidence is still insufficient to provide a concrete answer regarding the added value of higher resolution rainfall estimates and actual rainfall input resolution requirements for urban hydrological applications. With the aim of providing further evidence in this regard, a collaborative study was conducted which investigated the impact of rainfall input resolutions on the outputs of the operational urban drainage models of four urban catchments in the UK and Belgium (Figure 1).

Fig 1: Boundary and sewer layout of the pilot urban catchments.

Nine storm events measured by a dual polarimetric X-band weather radar, located in the Cabauw Experimental Site for Atmospheric Research (CESAR) of the Netherlands, were selected for analysis. Based on the original radar estimates, at 100 m and 1 min resolutions, 15 different combinations of coarser spatial and temporal resolutions, up to 3000 m and 10 min, were generated. Coarser spatial resolutions were generated by averaging in space, whereas coarser temporal resolutions were generated through two different strategies: (1) by sampling radar images at the desired temporal resolution, thus replicating radar scanning strategies; (2) by averaging in time. The
resulting rainfall estimates were applied as input to the operational semi-distributed models of the urban catchments, all of which have similar size (between 5 and 8 km²), but different morphological, hydrological and hydraulic characteristics (Figure 1). When doing so, methodologies for standardising model outputs and making results comparable were implemented. Hydrodynamic response behaviour was summarised using dimensionless performance statistics and was analysed in the light of drainage area and critical spatial temporal resolutions computed for each of the storm events. The main features observed in the results are the following (Figure 2):

- The impact of rainfall input resolution decreases rapidly as catchment drainage area increases.
- In general, the coarsening of temporal resolution of rainfall inputs affects hydrodynamic model results more strongly than the coarsening of spatial resolution. This is particularly the case when coarser temporal resolution rainfall estimates are generated through sampling of radar images; however, in the case of averaging in time, temporal resolution still shows a dominant effect over spatial resolution.
- There is a strong interaction between the spatial and temporal resolution of rainfall input estimates and in order to avoid losing relevant information from the rainfall fields, the two resolutions must be in agreement with each other.
- For the storms, models and drainage areas under consideration, temporal resolutions below 5 min appear to be required for urban hydrological applications, whereas spatial resolutions of the order of 1 km appear to be sufficient.

Based on these results, initial models to quantify the impact of rainfall input resolution as a function of catchment size and spatial-temporal characteristics of storms are proposed and discussed.

Fig 2: Logarithmic functions fitted to performance statistics of hydraulic outputs (relative error in maximum flow peak, coefficient of determination ($R^2$) and regression coefficient ($\beta$)) as a function of drainage area size, for different space-time resolution combinations. Line type denotes different temporal resolutions (1 min = solid; 3 min = dash-dot; 5 min = dashed; 10 min = dotted) and colour range denotes different spatial resolutions (100 m = green; 500 m = blue; 1000 m = purple; 3000 m = orange).
References


Analysis of the drainage inlets efficiency, variability and vulnerability of the urban system

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Abstract

Pluvial flooding occurs as a consequence of excess rainfall when surface runoff cannot be fully drained by the artificial network (i.e. surface drainage deficiency) and/or when the drainage systems overflows (i.e. drainage systems failures). Because of surface drainage deficiencies, however, flooding events occur quite frequently as a consequence of rain events of lower intensity than the design one, even in case of proper dimensioning of the drainage system. Inlets are in those cases the critical nodes, and efficient drainage is only ensured when care is taken on their appropriate design and positioning within the drainage area. This paper focuses on the impact of the variability of the drainage inlets efficiency on pluvial flood hazard.

The existing FLURB-2D model (Aronica and Lanza, 2005), originally developed for simulating rainfall excess propagation over initially dry areas, is here implemented on a selected study area in the town of Genoa (Italy). The study area is located in the eastern part of the town centre developed mainly during the thirties and therefore characterized by a fairly regular urban structure (grid plan). Synthetic hyetographs based on bivariate copula methods (Candela et al. 2014) with suitable return period are used as input. While simulating the design rainfall, inlets operational conditions are varied stochastically using a Monte Carlo approach. The derivation of flooding maps is addressed in a probabilistic framework. As for the probabilistic analysis, flood occurrence probability maps and hazard class maps are computed (Di Baldassarre et al. 2009; Aronica et al. 2012).

Simulation results allow highlighting, as expected, the occurrence of local flooded areas due to drainage failures for all precipitation events. In particular, the combined analysis of flood occurrence probability and hazard class maps confirm that topographic effects have the potential to produce local flooding with significant water depths and that local inlets operational conditions may affect the behavior of the urban drainage system as a whole. In particular, a critical area where the specific spatial distribution of inlets enhances flooding is identified close to the western edge of the domain.
Fig 1: Flood occurrence probability maps for the 2, 10 and 30-years return period rainfall events.

References

NowPAL, a novel system for issuing heavy precipitation alerts in Switzerland

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Abstract

MeteoSwiss recently developed NowPAL (NOWcasting of Precipitation AccumuLations), a now-casting system specifically designed to issue heavy rainfall alerts over pre-defined geographical regions in Switzerland.

Since the impact of heavy precipitation strongly depends on the immediate past rainfall, the tool combines the past observed precipitation accumulation with the forecast rainfall field. The total rainfall is then evaluated within pre-defined geographical regions and compared with threshold values in order to issue the alerts. Since it is fully configurable, the system is appropriate to issue alerts for different customers and applications, ranging from the general alerts for the 159 Swiss official warning regions to more specific alerts for small urban areas or alpine catchments.

In order to find optimal thresholds of precipitation accumulations for the alerts to be issued for official Swiss warning regions, an extreme value analysis exploiting the continuing increasing size of weather radar archives was conducted. The basic assumption is that an alert of a specific level has to be expected the same number of times in every region in a year. The thresholds used for the alerts are thus the rainfall values corresponding to specific return periods.

Quality-checked and homogenized quantitative precipitation estimates produced by combining radar and rain-gauge measurements for the period 2005-2014 were employed to derive Intensity-Duration-Frequency (IDF) curves for precipitation measured over several spatial and temporal scales. IDF were obtained for warm and cold season by fitting monthly rainfall maxima to the Generalized Extreme Value Distribution for each warning region, for each accumulation period and for several statistical quantities representative of the regional rainfall distribution. For example, Figure 1 shows the IDF of 1-hour rainfall accumulation for the region Blenio, whereas Figure 2 shows the 24-hours rainfall amounts corresponding to a return period of 4 years for the warm season for all the 150 Swiss warning regions. The analysis of the spatial continuity of IDF curves in Switzerland will permit to identify regional differences in the behaviour of heavy rainfall.
Fig 1: Intensity-Duration-Frequency curves and relative 95% confidence interval for the warning region Blenio (368 km²) for 1-hour rainfall accumulation derived from radar, for different statistics representative of the regional rainfall: max rainfall, max rainfall in 5x5 km spatial window, max rainfall in 9x9 km spatial window, mean.

Fig 2: Rainfall amounts corresponding to a return periods of 4 years for 24-hours rainfall accumulation in summer, derived from the radar precipitation estimates adjusted with rain-gauge values (CombiPrecip). Thick contours denote the regions for which this information is questionable due to problems in radar data.
On the effects of temporal meteorological variability on ecosystem water and carbon fluxes across scales: a modeling approach

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Abstract

Climate varies across a wide range of temporal and spatial scales and this variability affects and is affected by ecosystem responses. There is strong evidence from observations and climate model projections that due to anthropogenic influences, climate variability is expected to be significantly altered (e.g. scarcer and stronger rainfall events in arid places etc.). This will have an impact on the water and carbon cycles and thus on food production and security, timber production, flood management, irrigation practices etc.

The recognition of the importance of climatic variability especially at fine temporal scales (e.g. hourly) for ecosystem functioning has been pivotal. The last decade several observational and experimental studies have revealed the essential role of climate fluctuations in controlling the water and carbon cycles through their nonlinear feedbacks. Given the expected changes in climate variability, a deep understanding of these feedbacks, and a mechanistic explanation of their effects on the ecosystems is of major importance.

In this study various impacts of meteorological forcing variability on water and carbon fluxes across a range of scales are explored here using numerical simulations (Paschalis et al., 2015). Synthetic meteorological drivers that highlight dynamic features of both short and long temporal scale in time series of precipitation, temperature, and radiation are constructed. These drivers force a mechanistic ecohydrological model (T&C, Fatichi et al, 2012), a tool that integrates essential hydrological and plant physiological processes, and thus propagates information content into the dynamics of water and carbon fluxes for an ensemble of representative ecosystems spanning from semi-arid shrublands to tropical rainforests. The meteorological variability components investigated here are: i) interannual variability of the climate forcing; ii) auto- and cross- correlation of precipitation, temperature and radiation; iii) precipitation structure, and its intermittency patterns (i.e. organization in storm events); iv) distribution of precipitation, temperature, and radiation. The main focus of the analysis is on a cross-scale effect of the short-scale forcing variability on the modeled evapotranspiration and ecosystem carbon assimilation.

The key results of the study (Fig. 1) are:

(a) short-scale variability of meteorological input does affect water and carbon fluxes across a wide range of time scales, spanning from the hourly to the annual and longer scales;
(b) different ecosystems respond to the various characteristics of the short-scale variability of the climate forcing in various ways, depending on dominant factors limiting system productivity;
(c) whenever short-scale variability of meteorological forcing influences primarily fast processes such as photosynthesis, its impact on the slow-scale variability of water and carbon fluxes is small; and
(d) whenever short-scale variability of the meteorological forcing impacts slow processes such as movement and storage of water in the soil, the effects of the variability can propagate to annual and longer time scales.

Fig 1: A schematic representation of the physical mechanisms explaining the effect of high frequency hydrometeorological variability on water/carbon fluxes and transfer of variability across temporal scales.

References


X-band radar vs. C-band radar for urban hydrology applications: two case studies

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Abstract

Recent studies have highlighted the need for high resolution rainfall measurements for a better modelling of urban and peri-urban catchments’ responses. Indeed the catchments are smaller leading to shorter response time and the proportion of water immediately active is high due to increased imperviousness. A consequence is that the available resolution of 1 km in space and 5 min in time, commonly provided by national weather services in Europe, does not seem sufficient (Gires et al. 2014). This issue is investigated in this paper with the help of two types of rainfall data: C-band radar data provided by Météo-France at a resolution of 1 Km in space and 5 min in time and data from a newly installed X-band radar operated by Ecole des Ponts ParisTech and providing data with a resolution of 100 m in space and 2.5 min in time.

Two catchments located in the Paris area and studied in the framework of the European Interreg IV RainGain project are used. They exhibit different features: one is a 144 ha flat urban area in the Seine-Saint-Denis County, and one is a 250 ha urban area with a significant portion of forest located on a steep hillside of the Bièvre River. Interestingly, the catchments are located at different distances from the new X-band radar: 10 Km for the Kodak and 30 Km for the Jouy-en-Josas, which enables to investigate potential influence of the distance to the radar on the results. A fully distributed urban hydrological model currently under development called Multi-Hydro is implemented to represent the catchments’ response. It consists in an interacting core between open source software packages, each of them representing a portion of the water cycle in urban environment. The model was validated on these catchments with 4 extremes rainfall events that occurred between 2010 and 2012 (Gires et al. 2014, 2015). Multi-Hydro is implemented with pixels of size 10 m x 10 m and Figure 1 displays the corresponding catchments’ land use cover along with the sewer network that are inputted into the model.

First, simulations with C-band radar data are performed. Then an ensemble of hydrograph obtained by inputting stochastically downscaled (at the X-band resolution) rainfall fields is generated. More precisely:

(i) An ensemble of realistic downscaled rainfall fields is generated with the help of Universal Multifractal discrete cascades. The downscaling simply consists in stochastically continuing the underlying cascade process whose features are estimated on the available range of scales.

Fig 1: Illustration of the two studied catchments.
(ii) Each realisation of rainfall field is then input into the validated hydrological model and the corresponding hydrograph simulated.

The variability observed within the simulated ensemble corresponds to the uncertainty associated with the small scale rainfall variability not measured by the C-band radar network. Figure 2 displays an illustration of this simulated uncertainty for an event that occurred on 15 December 2011 over the Kodak catchment. Finally the response with the X-band radar data is simulated, which enables to discuss the added value of the improved rainfall data.

![Simulated flow with raw radar data and envelop curves](image.png)

Fig 2: Simulated flow with the raw radar data (black), the envelop curves of the uncertainty interval associated with variability occurring at scales smaller than 1 km in space and 5 min in time [Q0.25 and Q0.75 (dark colour), Q0.1 and Q0.9 (light colour)] for 5 conduits of the Kodak catchment with the help of the Multi-Hydro 10 m model for the December 2011 rainfall event.

Authors acknowledge the financial support of the Interreg IV NEW RainGain project (www.raingain.eu) and the chair “hydrology for resilient cities” endowed by Véolia.

**References**


High-resolution stochastic generation of rainfall for urban drainage model applications

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Abstract

The STREAP (Space-Time Realizations of Areal Precipitation) is a novel stochastic rainfall generator for simulating high-resolution rainfall fields that preserve the rainfall spatio-temporal structure and statistical characteristics (Paschalis et al., 2014; Paschalis et al., 2013). It enables a generation of rain fields at sub-kilometer and minute scale in a fast and computer-efficient way matching the requirements for hydrological analysis of urban drainage systems. High-resolution rainfall ensembles are generated stochastically to simulate (1) the current climate conditions and (2) projected future climates based on different scenarios derived from various global climate models. The STREAP model has a potential of serving as a useful tool for testing the existing urban drainage systems and for future planning.

The STREAP model is composed of three hierarchical modules: (a) the storm arrival process; (b) the temporal evolution of the mean areal intensity and the fraction of the wet area during a storm; and (c) the space–time structure of rainfall during a storm, including the rainfall field advection. In order to setup the model, the following information is required to derive model parameters: distributions of the wet and dry runs, distribution of the advection (i.e., wind - velocity and direction), co-distribution of the wet area ratio and the areal mean rainfall intensity, the rainfall coefficient of variation, and the spatial and temporal correlations of the rainfall. Estimating these parameters is not a straight-forward procedure and requires a combination of datasets at the highest-resolution including rain-gauges, weather radar and climate reanalysis databases.

Fig 1: Example of a single snapshot generated by the STREAP model, representing a rain field over the city of Luzern. Rainfall intensity change from 0 (white) to 5 mm h⁻¹ (red). Domain size is 25 km² and rain pixel size is 100 m x 100 m.
In this study, for the first time, the STREAP model was used to generate rain fields for a 100 m x 100 m spatial resolution and a 5-min temporal resolution over a 25 km² domain (Fig. 1). A sub-catchment in the city of Luzern (Switzerland) was chosen as a case study to demonstrate the relevance for urban drainage modelling exercises. For this we evaluate the channel flow at the catchment outlet predicted by a calibrated hydrodynamic sewer model - further information regarding catchment characteristics, flow monitoring and model development can be found in Tokarczyk et al. (2015). Rainfall observations were derived from a MeteoSwiss 10-min rain gauge that is located 1.8 km west to the sub-catchment, recording since 1981, and from the MeteoSwiss weather radar system (data available from 2004). Several parameters that require a spatial resolution finer than the one given by the weather radar (e.g., rainfall spatial correlation) were estimated based on a data compilation from literature (for example see Peleg et al., 2013). The rainfall model was validated for the period between 1981 and 2014, comparing the observed and simulated statistics of the rainfall intensity, event durations and transitions between wet and dry periods (examples given in Fig. 2). The generated rainfall ensembles are then used as multi-input for the hydrodynamic model. Results show a distinct variability of the peak discharge at the catchment outlet, reflecting the system response on the spatial rainfall variability (see Fig. 2, low right). The comparison with the single-gauge model hydrograph indicate, that valuable information can be gained through feeding urban drainage models with spatially detailed rain data.

Fig 2: Observed annual rainfall (1981-2014) vs. 1,000 realizations simulated by the STREAP model (left) and comparison between the observed and simulated monthly wet duration (right up) for the same dataset. Discharge records (black dots) and simulations (orange line represents uniform rainfall and grey range represent 5-95 quantile discharge range of 100 realizations generated by the STREAP model) are presented in the lower right part of the figure for one rainfall event.

References


Coupling a stochastic rainfall generator and a physically based infiltration and slope-stability model to investigate landslide triggering

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Abstract

Analysis of rainfall conditions potentially leading to landslide triggering is an important task for risk assessment and mitigation. In this paper a Monte Carlo approach based on coupling a stochastic rainfall model with a infiltration and slope stability model is developed and applied to generate synthetic rainfall and associated landslide data. More specifically, generated rainfall series are used as input to a physically based infiltration model, which enables to compute the pressure head response of the soil to rainfall events, given initial conditions. The TRIGRS model is used to compute transient pressure head response, and the initial conditions are derived by a linear-reservoir water table recession model. The resulting long series of landslide triggering and non triggering rainfall events is then analysed to identify most significant rainfall characteristics for defining landslide-triggering thresholds. First, widely adopted power-law thresholds, which is the most commonly encountered in literature, has been investigated. Then other models have been tested, which account for antecedent rainfall. Nonlinear regression techniques based on neural networks have also been exploited to choose the most suited functional form to link landslide triggering to variables. Validation with observed rainfall-landslide data shows the potential of this modelling technique.

1. Introduction

Rainfall thresholds associated to landslide triggering are an important component of early warning systems (cf., e.g., Keefer et al., 1987; Baum and Godt, 2010). The most common way to derive such thresholds is to analyse historical rainfall and landslide data, and to draw an enveloping curve of the triggering event characteristics (e.g., Guzzetti et al., 2007).

Many factors of uncertainty affect the reliability of empirical thresholds, such as rainfall temporal and spatial variability, uncertain knowledge of the triggering instants, simplicity of threshold equation that does not include all control variables, as well as statistical issues. A great part of the uncertainty stems from the availability and quality of the data used to derive the thresholds (e.g., Berti et al., 2012). In fact, adequate historical data on landslides and simultaneous rainfall are in most cases available for a relatively short period, which may not be sufficiently significant from a statistical point of view. Hence, an approach based on synthetic data, obtained by Monte Carlo simulation may be appealing for the derivation of early warning thresholds (Peres and Cancelliere, 2014).

Peres and Cancelliere (2014) have shown that the widely used ID power law threshold form may be suitable to represent landslide triggering due to transient infiltration, but that in general antecedent precipitation may play a significant role and therefore it should be included in the analysis. In this paper the Monte Carlo simulations performed in Peres and Cancelliere (2014) is used for a more in depth analysis, in which different threshold models that include explanatory variables related to the current event (mean intensity, duration, cumulative rainfall, etc.), as well as to antecedent rainfall preceding events (rainfall accumulated over various temporal horizons before the events) are considered. In order to capture non-linearities, Artificial Neural Networks (ANNs) are also employed to derive thresholds and a receiver-operating characteristics analysis (ROC) is carried out for validating the methodology.
2. Methods

The Monte Carlo approach consists in coupling a stochastic rainfall generator with physically
based models for the computation of hillslope response in terms of factor of safety for slope insta-
bility (FS). In our work we use the following models (cf., Peres and Cancelliere, 2014):

1. A seasonal Neyman-Scott rectangular pulses model (NSRP) for the generation of hourly
  rainfall (e.g., Cowpertwait et al., 1996)
2. The TRIGRS model (Baum et al., 2008) to compute response to rainfall events
3. A water table recession model (WTR) to compute initial conditions to the current event
   based on the response at the end of the preceding event
4. An infinite slope formula to compute the minimum FS from the maximum pressure head ψ

Based on the resulting FS, rainfall events are classified as triggering (FS<1) or non-triggering
(FS≥1). We then determine thresholds based on the maximization of a performance function which
is based on receiver-operating characteristics (ROC) analysis. In particular the ROC curve may be
used, which is based on the number of true positives (TP), false positives (FP), true negatives (TN)
and false negatives (FN). A suitable ROC-based indicator is the True Skill Statistics TSS= TPR -
FPR = TP/(TP+FN) - FP/(FP+TN).

First of all, we analyse the performances of I-D power law thresholds, which are the most com-
monly used in literature, and have the form \( I = aD^{-b} \), where \( I \) is critical rainfall intensity, \( D \) is critical
duration, and \( a \) and \( b \) are parameters to be calibrated, for instance by maximizing the TSS.

We then analyse other threshold types, including also variables related to the variability of rainfall
intensity during events and of antecedent precipitation, making use of artificial neural networks \( f(\cdot) \).
In particular, we investigate the following types of ANN thresholds:

\[
\begin{align*}
\psi &= f(H, D) \\
\psi &= f(H, D, V) \\
\psi &= f(H, D, A(d)) \text{ with } d = 3, 7, 15 \text{ and } 30 \text{ days} \\
\psi &= f(H, D, V, A(d)) \text{ with } d = 3, 7, 15 \text{ and } 30 \text{ days}
\end{align*}
\]

where \( H \), \( D \), and \( V \) are respectively the cumulative rainfall, duration of rainfall and the variance
of rainfall intensity within events, while \( A(d) \) is antecedent rainfall accumulated over duration \( d \). Artifi-
cial neural networks are widely used tools to map several variables in a non linear fashion (e.g.
Haykin, 1999). Here feedforward type ANN, with a single hidden layer, and one output neuron rep-
resenting the estimate of the total pressure head \( \psi \), which is directly linked to the safety factor of
slope stability (FS) are adopted. The mean squared error MSE of estimation has been selected as
objective function. To ensure generalization the ANN have been trained using the early-stopping
method. In particular, the entire set of Monte Carlo simulations has been split into three subsets,
namely estimation, validation and test sets. The estimation set is used to determine the parameters
which minimize the objective function. At each iteration, errors are computed on the validation sub-
set and training is stopped as the validation MSE starts to increase. Performances in the test set
are used to compare different models. In addition to the MSE also the well-known Nash-Sutcliffe
efficiency has been used as a performance index of reference. Moreover, the ROC diagram has
been plotted to analyse the predictive power of the ANN-based thresholds. The final performances
obtained provide thus an indication of the suitability of ANN techniques (so far applied only for
landslide susceptibility assessment, Melchiorre et al., 2008) for deriving early warning thresholds.

3. Data

The methodology has been applied to the Peloritani Mountains area in Sicily, which is highly prone
to landslides (cf., e.g., Peres and Cancelliere, 2014, Schiliró et al., 2015). The Monte Carlo simula-
tion has been used to generate 1000 years of rainfall-pressure head hourly series; 10 min resolution data measured at the Fiumedinisi SIAS rain gauge have been used to calibrate the NSPR model. Assumed soil properties are indicated in Table 1.

Table 1: Typical soil and topographic properties for a representative slope of the Peloritani mountains. Symbols have the following meaning: \( \phi' \) friction angle, \( c' \) cohesion, \( \gamma_s \) unit weight of soil, \( \theta_s \) saturated water content, \( \theta_r \) residual water content, \( K_s \) saturated conductivity, \( D_0 \) saturated diffusivity, \( \alpha \) water retention curve parameter, \( d_{LZ} \) soil depth, \( \delta \) slope, and \( c_d \) leakage ratio

<table>
<thead>
<tr>
<th>( \phi' )</th>
<th>( c' )</th>
<th>( \gamma_s )</th>
<th>( \theta_s )</th>
<th>( \theta_r )</th>
<th>( K_s )</th>
<th>( D_0 )</th>
<th>( \alpha )</th>
<th>( d_{LZ} )</th>
<th>( \delta )</th>
<th>( \zeta_{CR} )</th>
<th>( c_d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>37</td>
<td>5.7</td>
<td>19000</td>
<td>0.35</td>
<td>0.045</td>
<td>2 \times 10^{-1}</td>
<td>5 \times 10^{-5}</td>
<td>3.5</td>
<td>2</td>
<td>40</td>
<td>0.4645</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Neural networks threshold models have been calibrated based on the results of the Monte Carlo simulations. Then the various threshold models are validated by using the observed rainfall data considering the following dates on which landslide occurred: 1) 15 September 2006, 2) 25 October 2007, 3) 24 September 2009, and 4) 1 October 2009. The WTR model for the computation of the initial conditions, is based on the specification of a topographic index \( A/B \), given by the ratio of up-slope catchment area \( A \) and the flow width \( B \). Analysis of events occurred in the area show that most of the landslides have an \( A/B \) ratio in the range 5 - 15 m. Thus a representative value for the area may be \( A/B = 10 \) m; other values have however been explored to investigate the role of this parameter: \( A/B = 0 \) m (no memory case), 20 m and 50 m.

4. Results

The results of Monte Carlo simulation for the \( A/B = 10 \) m case (representative of the case-study area) are synthesised in Figure 1a where intensity \( (I) \) and duration \( (D) \) of triggering and non-triggering rainfall events, are plotted in a double-logarithmic plane. From the figure it can be inferred that the triggering points exhibit some scattering, and they partially overlap with the non triggering ones; this is reasonably caused by the effect of rainfall intensity variability during events (see also Fig 1b, where this effect is isolated) as well as to significant antecedent rainfall. Nonetheless, the performance of the best triggering threshold \( I = 71.52 \times D^{0.8} \) is relatively high, since \( TSS = 0.870 \). The figure also shows the threshold proposed by Gariano et al. (2015), which is based on the analysis of triggering events only; as it can be seen this threshold may lead to an excessive number of false alarms, which may result in a "cry-wolf syndrome" (e.g., Barnes et al., 2007). The curved dotted line represents the deterministic threshold under the assumption of uniform hyetographs and no variability of initial conditions; clearly this threshold is too high and may lead to an excessive number of missed alarms, which further proves the importance of taking into account both rainfall intensity variability during events and significant antecedent rainfall.
Performances of neural network models using several rainfall characteristics variables, are shown in Table 2 in terms of the Nash-Sutcliffe index for different A/B ratios. It can be seen that a significant improvement of performances is obtained by including as input the variance $V$ of rainfall events ($NS$ increases from 0.791 to 0.845, for the $A/B = 10$ m case). Results also show that the choice of the time interval to compute antecedent precipitation is critical and, as expected, depends on the $A/B$ ratio. For instance, in the $A/B = 10$ m case, the duration corresponding 7 days yields the best performances (model $f(H,D,V,A(7))$, i.e. $NS = 0.93$. This neural networks perform fairly well in reproducing the pressure head response, as shown by the scatter plot of Figure 2. As the $A/B$ ratio increases, the time interval to compute antecedent rainfall should be increased, as shown by the results for $A/B = 20$ m and 50 m. This confirms that in developing empirical thresholds which include antecedent rainfall, the time interval to compute antecedent precipitation must be linked to soil properties, and in particular to saturated hydraulic conductivity, porosity, slope and the topographic $A/B$ ratio.

### Tab 2: Performances of the calibrated ANN-based models, in terms of the Nash-Sutcliffe index (test set).

<table>
<thead>
<tr>
<th>$A/B$ [m]</th>
<th>$f(H,D)$</th>
<th>$f(H,D,A(3))$</th>
<th>$f(H,D,A(5))$</th>
<th>$f(H,D,A(7))$</th>
<th>$f(H,D,V,A(3))$</th>
<th>$f(H,D,V,A(5))$</th>
<th>$f(H,D,V,A(7))$</th>
<th>$f(H,D,V,A(15))$</th>
<th>$f(H,D,V,A(30))$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.91</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.79</td>
<td>0.963</td>
<td>0.845</td>
<td>0.872</td>
<td>0.882</td>
<td>0.843</td>
<td>0.819</td>
<td><strong>0.930</strong></td>
<td>0.923</td>
<td>0.887</td>
</tr>
<tr>
<td>10</td>
<td>0.845</td>
<td>0.872</td>
<td>0.882</td>
<td>0.843</td>
<td>0.819</td>
<td><strong>0.930</strong></td>
<td>0.923</td>
<td>0.887</td>
<td>0.861</td>
</tr>
<tr>
<td>20</td>
<td>0.689</td>
<td>0.763</td>
<td>0.847</td>
<td>0.812</td>
<td>0.74</td>
<td>0.821</td>
<td><strong>0.883</strong></td>
<td>0.85</td>
<td>0.796</td>
</tr>
<tr>
<td>50</td>
<td>0.518</td>
<td>0.516</td>
<td>0.646</td>
<td>0.733</td>
<td>0.759</td>
<td>0.599</td>
<td>0.694</td>
<td><strong>0.795</strong></td>
<td><strong>0.804</strong></td>
</tr>
</tbody>
</table>
Fig 2: a) Scatter plot comparing the best neural network model output with the target pressure heads (resulting from Monte Carlo simulation). b) ROC curve for the validation of the ANN-based landslide triggering thresholds against real rainfall-landslide data in the period 2002-2014.

The calibrated thresholds have also been tested against real data. To this end, rainfall events have been extracted from the observed hourly rainfall series and the pressure head response has been computed by the calibrated neural network models, for the available period (2002-2014), during which four landslide events have occurred. The results of this test are shown in Figure 2a; the entire ROC curve demonstrates that application of the ANN would have led to a perfect prediction, provided a proper value of the threshold pressure head is chosen, since all and only the 4 events occurred in the period may be predicted by the calibrated model, (the ROC curve has an underlying area \( AUC=1 \)). More specifically, the plot indicates that with reference to the model \( f(H,D,V,A(7)) \) a threshold pressure head different from the \( \zeta_{cr} = 0.4645 \) assumed for the area (see table 1) should be selected, since the corresponding point is not located at the upper left angle of the ROC plot (blue square marker in Figure 2a). The model including 15 days precipitation \( f(H,D,V,A(15)) \) performs better in this test, since the perfect prediction (\( FPR=0, TPR=1 \)) is obtained for the a priori assumed \( \zeta_{cr} = 0.4645 \). This model may thus be preferred.

5. Conclusions

In this paper Monte Carlo simulation has been used as an aid for the derivation of landslide triggering thresholds suitable for early warning. Use of this technique in comparison to direct empirical analysis may be advantageous in most cases because of the incompleteness of the landslide inventories and the limited availability of high resolution rainfall records. The output of Monte Carlo simulations has been analysed to derive best performing thresholds, taking into account several rainfall variables, including the variance of rainfall intensity within events, as well as antecedent precipitation accumulated at different temporal horizons, making use of ANN models. Results show that ANNs are able to capture the dependence between the rainfall characteristics and the occurrence of landslides. Hence this modelling technique seems promising for the derivation of the rainfall thresholds. Moreover, results confirm that inclusion of antecedent rainfall in the thresholds may lead to an improvement of performances, provided that the temporal horizon on which to accumulate rainfall is correctly chosen on the basis of soil and topographic properties.

It may be worthwhile to point out that our framework takes into account only the uncertainty due to the variability of rainfall intensity within events and of antecedent precipitation, whereas application to real data may include many other uncertainty factors. Thus, the results presented here have to be taken at best as theoretical predictive potential of the proposed threshold models.

References


Extreme events in the summer of 2014 in North-Rhine Westfalia

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Abstract

The Emschergenossenschaft and the Lippeverband operate a dense network of rain gauges which is used in the context with their multiple water management tasks. Therefore they dispose of a few long time series of precipitation data allowing carrying out trend analysis over more than 80 years. Especially in the summer of 2014, EG/LV recorded an unusual sequence of heavy rain events, some of them extreme events challenging their operational flood management. This paper focuses on three of them, causing a lot of damages. The investigations of the extreme events in 2014 are supplemented by radar data analysis provided by the German Weather Service. By this means, the local limitations of convective rainfall could be outlined in an impressive fashion and could be compared with ground based rainfall recording. The long time series analysis in the Emscher and Lippe river basins does not show a rising intensity of storm events yet. But nevertheless, the number of days in a year with heavy rainfall is in the average already increasing in the last two decades.

1. Introduction

The Emschergenossenschaft (EG) and the Lippeverband (LV) are both self-governing water boards in North-Rhine Westfalia (NRW) under special law responsible for flood protection, stormwater management and further water management tasks (EG/LV, 2015). Therefore EG and LV operate a dense network of rain gauges. The first rain gauge was established in the year 1930. Based on this extensive data basis a lot of studies have been carried out regarding for example the trend analysis or the development of the frequency of extreme values (DWA, 2012). As a result of the long time series analysis of about more than 80 years in the catchment areas of Emscher and Lippe, no significant trends of increasing storm intensities can be observed in the rain gauge measurements (Pfister and Verworn, 2002). However, the number of days within a year where heavy rain occurs has increased in the last two decades since 1991. On that account a water utility responsible for river management has to deal with this changing distribution of the amount of yearly rainfall. This paper focuses on the characteristics of three extreme events observed in the summer of 2014.

2. Methods

In the water management, EG and LV operate their rain gauges according to the set of rules published by the German Association for water, wastewater and waste (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V. (e.g. DWA, 2012)). The stormwater events in 2014 are as well documented by radar rainfall data of the German Weather Service (DWD). Within this contribution, especially radar raw data and adjusted data of the RADOLAN (Radar-Online-Adjustment) routine (see description in DWD, 2004) are compared. Some details are presented in the following section 3.

3. Data and results

In the summer of 2014 the water management authorities in NRW were confronted with a series of heavy rain events, some of them extreme events, challenging their operational flood management.
This paper focuses on the catchment areas of EG/LV on three of these severe events, causing a lot of damages in North-Rhine Westfalia. It is supplemented by radar data analysis provided by the German Weather Service.

### 3.1 Thunderstorm “ELA” on the 9th of June 2014

Beginning with an extreme storm event accompanied with heavy rainfall at Pentecost, on the 9th of June 2014, the whole region was struck unexpectedly, because the forecasting time has been too short (see example photos in Figure 1). In this precipitation event the rainfall amount with about 30 mm in 20 minutes leads to a return period of more than 100 years. But the totals are not impressive. In this case the storm has been the major subject. The peaks of the wind speed reached 100 to 140 km/h causing the whole traffic to a halt, even at Düsseldorf airport.

During the following days and weeks the damages of the infrastructure in NRW became visible and there are still damages left in the green areas and forests of the cities. Regarding the overall balance of costs in Germany, this thunderstorm was the second expensive storm for the last 15 years. The German Insurance Association (GDV) payed about 400 Mill. € for the damages.

From the point of view from EG/LV this event caused charges exceeding the normal costs with 2,3 Mill. € in the following months until the end of the year 2014. During the most critical situation the 9th of June and the following days, a huge number of staff members in the operational board of EG/LV have been night and day at work. The flood early warning system (Grün et al., 2014) proved essential in that situation. Fortunately, no personal injury occurred and most of the concerned citizens showed themselves quite patient during the following months of cleanup.

![Fig 1: Damages of the thunderstorm from 9th of June 2014 in the central Emscher region at the operating plants of the Groppenbach (left) and the Lanferbach (middle) with radar scene at 22:00 h.](image)

### 3.2 Extreme rainfall on the 28th of July 2014

The second extraordinarily severe event happened only seven weeks later on 28th of July 2014, as an extreme rainfall hit the city of Münster. A similar event had up to present not occurred in a comparable intensity the urban area and caused a lot of damages with even two fatalities. The local government registered a total rainfall amount of 292 mm that day (Grüning and Grimm, 2015). This is close to the highest ever measured value in Germany of 312 mm/d in August 2002 in the Elbe region.

The GDV figures out the overall balance of costs for this heavy rainfall event in July 2014 with 140 Mill. €. The DWD analysed the event on the basis of adjusted radar data based on the RADOLAN routine comparing operational real time data with an additionally offline adjustment, taking further rain gauges into account. Hereby, as shown in Figure 2, the local limitation could be impressively pointed out.
In the online routine of RADOLAN (Fig. 2, left) the maximum value of precipitation reaches 192 mm. In contrast, taking into account two other offline rain gauges, the RADOLAN offline routine comes up to 285 mm in the maximum pixels. Furthermore the local extension of the convective rainfall cell is much better exposed. This more realistic rainfall information can be used in additional offline rainfall runoff modelling investigations.

3.3 Flash flood on the 18th of September 2014

Finally an extreme event occurring in the region of the Lipperverband on the 18th of September 2014 is pointed out. In the city of Hamm, not far away from Münster, during a time span of six to nine hours a significant rainfall amount caused heavy flooding in the catchment area of the Hoppeibach.

As shown in Figure 3, the raw data of the EG/LV rain gauges network outline a spatial amount of 50 mm to 80 mm in total. The according radar scene shows the whole precipitation field.
The frequency analysis for all rain gauges shows that at several rain gauges the return periods exceed 100 years. But, the following rainfall runoff modelling of the local conditions proved the return period of the river flood rising up to 50 years. Nevertheless it exceeded the discharge capacity of the local drainage system including a river pumping station due to subsidence caused by mining industries and caused a severe flash flood, as shown in Figure 4.

Fig 3: Daily rainfall for the 18th of September 2014 (7:30 until 7:30 MEZ) (left: EG/LV gauge network; right: DWD, C-band radar data).

The maximum rainfall was recorded at the rain gauge Hamm Pelkumer Bach, which is near the flooded area in the Hoppeibach catchment. The precipitation observation reached 81 mm/d in total. As an example Table 1 outline some details of the return periods in the region of Hamm.

Table 1: Results of the statistical analysis of the observed rainfall on the 18th of September 2014.

<table>
<thead>
<tr>
<th>Rain gauge, ID number</th>
<th>Time interval [hour]</th>
<th>Precipitation [per time interval]</th>
<th>Return period [a]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamm Kissinger Weg, 8701</td>
<td>2</td>
<td>54,5 mm</td>
<td>&gt; 100</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>67,4 mm</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>Hamm Pelkumer Bach, 8736</td>
<td>1</td>
<td>39,4 mm</td>
<td>&gt; 100</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>60,2 mm</td>
<td>&gt; 100</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>76,0 mm</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>Hamm Herringen, 8721</td>
<td>2</td>
<td>48,1 mm</td>
<td>&gt; 100</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>62,7 mm</td>
<td>&gt; 100</td>
</tr>
</tbody>
</table>

Fig 4: Flash flood in the catchment area of the Hoppeibach on the 19th of September 2014.
4. Conclusions

In this paper, three critical stormwater events in the river Emscher and river Lippe region are presented. They are only part of a series of some more seldom occurring heavy local rainfall events in the summer of 2014. Nevertheless, the long time series trend investigations of EG/LV expose that the rainfall intensity is not rising for the last 80 years. But the distribution in the means of the number of days with rain events exceeding 20 mm/d is changing since 1991. You can see this on the three events presented in this paper.

On that account – and on the perspective of future development of precipitation behavior under changing climate conditions – a water board responsible for river management has to deal with this changing distribution. Therefore, an early flood warning system combining radar rainfall, ground based measurements, modelling and numerical weather forecasts proved very helpful under critical conditions. Nevertheless, the unusual events of the year 2014 caused a lot of costs. These costs have to be put on the top of the normal running costs.

Moreover EG/LV will continue recording the rainfall gauges and especially repeat trend analysis decade for decade in the future. Therefore, historical long time series investigations can be the reference for future rainfall situations. They help as well in the development of flood warning systems which are crucial for water management tasks in a highly populated region of Germany.

References

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How to deal with extreme pluvial flooding – experiences and consequences from the heavy rain of the 12 of July 2014

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Abstract

Accurate precipitation information is of fundamental importance for water boards, water management companies and local authorities involved in preventing and mitigating flood risks. As extreme flood events pose a challenge in their mastering, the knowledge of the already measured and actual precipitation as well as rainfall forecast data are essential for preventing potentially dangerous or damaging situations. These data can be analyzed by using a flood forecasting system. In urban areas and small catchments floods are typically generated by heavy rain. Sometimes even with high sophisticated flood prevention systems, it is impossible to avoid flooding by convective events in summer. This paper focuses on a rainfall event from 12th of July, which caused some damages in the Emscher region. Here, the reconstruction of the Emscher system induces a huge number of construction sites. One of the retention basins actually under construction had been flooded. The overflow caused damages to some houses in the surrounding urban area. In the following workup of this event it appears that an awareness of the remaining risks of extreme storm events and flooding needs to be raised among the responsible decision-makers and the public as well.

1. Introduction

Water boards usually measure the local rainfall behavior in a continuous way. One important task is to prevent and mitigate flooding risks. As extreme heavy rainfall events pose a challenge in their mastering, the knowledge of the already measured and actual precipitation as well as rainfall forecast data is steadily analyzed using a flood forecasting system. In urban areas and small catchments floods are typically generated by heavy rain (DWA, 2013). Especially in the Emscher region with a concentration time of flood runoffs less than 6 hours, even with the usage of a flood early warning system there is no much time left to prevent pluvial flooding damages. In addition to this challenge, the reconstruction of the Emscher system – one of the largest water management projects in Europe – makes it necessary to install a large number of construction sites along the rivers, making the region temporarily even more vulnerable to flash floods (EG, 2015).

The Emschergenossenschaft (EG), as a self-governing water board under special law, manages the natural catchment area of the Emscher with its tributaries (865 km²) and is among others responsible for flood protection and stormwater management. Therefore EG operates today 22 floodwater retention basins with a volume of 2.7 Mill. m³. The flood management is based on a reliable operational flood forecasting system (FEWS – Flood Early Warning System), providing the hydrologists with radar and terrestrial rainfall measurement information as well as meteorological forecast data and runoff measurements (Grün et al., 2014 and 2015). The primary function of FEWS is the integration of various input data, the analysis of this data and the combining with hydrologic modelling within a single platform. Since it provides the data in real time, it has grown in an important manner during the last few years. In 2014 from June to September the operational department of the EG had to handle more than five exceptional heavy rain events. This paper focuses on the rainfall event from 12th of July.
2. Case study – Extreme event the 12th of July 2014

This extreme event caused a lot of damages in a part of the city of Dortmund. The retention basin Schmechtingsbach, which has been under reconstruction, had been flooded (see Figure 1), its overflow causing a severe impact on the surrounding urban area.

Fig 1: Photos of the flooded construction site retention basin Schmechtingsbach from the 13th of July 2014.

The convective rainfall event concentrated locally and struck a catchment area, which had been already saturated by a lot of rainfall during the week before. For this reason the runoff coefficient in the area was about 0.55, compared to normally 0.26. Table 1 gives an example of three rainfall gauges near the catchment area of the retention basin.

Table 1: Recorded rainfall totals

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dortmund Kruckel</td>
<td>126 mm</td>
<td>47.4 mm (with 43.4 in 2h)</td>
</tr>
<tr>
<td>Dortmund Oespeler Bach</td>
<td>116 mm</td>
<td>16.9 mm (with 10.0 in 1h)</td>
</tr>
<tr>
<td>Dortmund Eving</td>
<td>102 mm</td>
<td>1.1 mm</td>
</tr>
</tbody>
</table>

The radar raw data of the 12th of July 2014 show more obvious the local extension of the rainfall area (Pfister et al., 2015). This is outlined in Figure 2 and can be compared to local gauges data.

Fig 2: Radar rainfall raw data the 12th of July 2014 from radar site Essen of the German Weather Service (left) and 48 h totals from selected rain gauges in that region (right).
The frequency analysis of the rainfall event shows very small return period values around the city of Dortmund, because the local gauges have not been in the center of the rainfall cells. A few kilometers north, in the city of Recklinghausen, the occurrence of the return period rises up to once in 100 to 200 years with more than 52 mm in two hours. As the statistical analysis for the rain gauges with all long term time series data in Dortmund shows, the return period of the precipitation only amounts to less than 50 years. This was caused by the pluviometers not being at the center of the precipitation cell. Solely the radar data analysis gave a clear indicator of the flash points of that event.

By mischance for the inhabitants, the event of 2014 had a predecessor only six years earlier, in which almost the same districts of Dortmund were affected. On the 26th of July 2008 an extremely heavy rain event provoked damages of approx. 20. Mill. €. During this event 114 mm have been recorded within two hours at the rain gauge Dortmund Oespeler Bach and 203 mm nearby in another gauge site at the university of Dortmund within three hours. On that Saturday evening the 12th of July 2014 once again, the region was hit unexpectedly because – similar to the situation in 2008 – the precipitation cell developed localized and stayed stationary. With less than two hours, the forecast time has in both cases been quite short.

3. Offline investigations

Due to the provoked impacts, the event has been investigated in detail from the hydrologic point of view. Fortunately, the radar data had been available in the flood early warning system and could by analyzed to show the consequences in the catchment area of the retention basin (see Figure 3, red line). Here the flash points of that event and the flash flood locations are demonstrated by the radar grid results (pixel size approx. 1 km²). Based on this information, the simulation using the hydrologic model of the catchment area Schmechtingsbach leads to a flood peak estimation with a recurrence interval of approx. 100 years. In addition, the presentation of the detailed radar grid rainfall sum in the form of GIS-generated maps, proved to be an invaluable benefit for the discussion with the concerned residents (Krieger and Schmitt, 2015).

Fig 3: Radar rainfall pixel (maximum three hours sum) during the event from 12th of July 2014 in the catchment area of the retention basin Schmechtingsbach in the city of Dortmund.
4. Conclusions

As a consequence from the evaluation of the heavy rain event in July 2008, this flood retention basin Schmechtingsbach was under reconstruction in 2014. It had to be enlarged from 125,000 m³ to 150,000 m³. Model runs proof, that the basin’s overflow was unavoidable with the original basin design as well as during reconstruction. With activating the whole future retention volume, the flooding of the Schmechtingsbach could have been avoided. The occurrence of rainfall events like the 26th of July 2008 or the 12th of July 2014 is always possible. The unfortunate coincidence had been the construction phase in July 2014. Some weeks later, the overflow would have been less important with less damage.

However, a risk of pluvial flooding with flash floods in urban areas is always present. Extreme rainfall events belong to natural hazards. In that context the communication with the local residents and the stakeholders of the municipality is one important task in managing flood events. In the second half of the year 2014, it has been very difficult to outline to the residents, that this kind of event always could cause damages, especially, if heavy rainfall occurs, which exceeds the design of the draining water systems. In the demonstrated case of the retention basin Schmechtingsbach, the analysis of the spatial distribution of the rainfall amount by radar data has been very helpful. Once more, this event shows, that in the communication with the concerned residents, the topic is a rising risk awareness (Schmitt, 2011).

Furthermore, in the communication with concerned people it is substantial to raise the awareness of residual risks of weather extremes and to make clear that technical flood protection has natural limits.

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Evaluating wind-induced uncertainty on rainfall measurements by means of CFD modelling and field observations

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Abstract

The most widely used device to measure rainfall is the tipping bucket rain gauge (TBR), although there is no standard design. The precision and accuracy of TBR measurements vary, and calibration procedures are dependent upon the organisation or institution operating a network. Consequently, rainfall datasets may be heterogeneous and not easily comparable. Environmental conditions at the gauge orifice also adversely influence the accuracy of measurement. The height at which the gauge is mounted has a significant influence on the gauge catch. Reference measurements can be made using a rain gauge in a pit structure, with the gauge orifice positioned at ground level. Different types of rainfall events, occurring in differing geographical and micro-topographical contexts, vary the influence of the wind on rainfall measurement. Hence, it is difficult to develop and apply an all-encompassing correction procedure for wind using empirical observational methods alone. Computational Fluid Dynamics (CFD) provides an ideal framework within which to develop an understanding of how wind affects catch accuracy. Observational data from the field can be used to validate CFD simulations and enhance correction algorithms.

1. Introduction

From Jevons (1861) to Strangeways (2004), much has been written about the rainfall measurement problem, and a lot of the focus gravitated towards the environmental impact of the wind's influence on rainfall catch. Scientific consensus dictates that the physical presence of a rain gauge causes an acceleration of the airflow over the orifice, distorting the trajectories of rainfall particles and leading to an 'undercatching' effect. Additionally, the shape of the rain gauge has an influence on the catch performance. Despite numerous intercomparison studies, the rainfall undercatch problem remains unresolved. Studies such as those by Sevruk and Hamon (1984), Goodison, Louie and Yang (1997) and Nespor and Sevruk (1999) significantly advanced knowledge and succeeded in raising further research questions, but the complexity involved ensures the solution to this problem remains elusive.

The WMO laboratory (2005) and field (2007-2009) intercomparisons on rainfall intensity took the necessary step of linking the meteorological and metrological communities, moving the science in the direction of operational standardisation. These studies have contributed to improvements in measurement over the last decade, particularly with regards to TBR counting errors. Now, the wind issue is coming back into focus once again, for example Wolff et al. (2015) and Colli et al. (2015).
2. Methods

The experimental design of this project aims to use field data from empirical observations to support theoretical analysis conducted in the context of Computational Fluid Dynamics (CFD) simulations. It is hoped that the results produced by both methods will converge to improve the understanding of the aerodynamic influence of gauge shape on rainfall catch.

Field observation data

A detailed rainfall experiment is set out to understand wind-induced undercatch (Pollock et al. 2014). Four UK sites are instrumented, representing lowland, upland, westerly and easterly rainfall regimes, Figure 1. Conventional knowledge describes how prevailing winds in the UK blow from the west/south-west. These winds whip up moisture from the Atlantic and the Irish Sea, delivering it as orographic enhanced rainfall along the UK’s west coast. Wilkinson (2009) describes the difficulty of ‘closing’ the water balance in Cumbria, western England, due to the impact of undercatch. Two sites in the west of the country were selected to capture this prevailing UK weather pattern, one site representative of the lowlands and one of the uplands. The significance of this lies in the varying level of exposure to the wind across the UK’s undulating terrain. Convective rainfall events are more common in the east of the UK, particularly in the summer months. Again, an upland and a lowland site are selected to represent the eastern rainfall regime.

CFD modelling of precipitation gauges

CFD is used to model the airflow over the rain gauge orifice and study the effects. Recent studies have demonstrated that modelled collection efficiencies agree well with field measurements for snowfall. Variations in the precipitation characteristics (particle size distribution and precipitation type) helps explain a large part of the collection efficiency variability generally observed in field investigations (Colli et. al., 2015).
CFD provides a flexible framework which is capable of generating a wide variety of wind regimes. High resolution three dimensional wind measurements from field observations are used to compute the turbulence intensity boundary conditions according to the mean wind speed magnitude. A constant vertical profile of the wind is assumed to simulate time averaged fields such as vector air velocity and turbulent kinetic energy. A finite volume technique is implemented by solving Reynolds-Averaged Navier Stokes equations, using the SST k-Omega model. The effect of gauge shape on the aerodynamic response is investigated by modeling different gauge geometries. Gauge profiles designed on the basis of empirical evidence to decrease the air resistance (Strangeways, 2004) are compared against conventional cylindrical-shaped gauges, and the effect on wind speed and turbulence is studied.

3. Results

A subset of the field data collected at the upland/western research station, Talla Reservoir, are analysed in this section. Two rainfall events are selected, with different wind characteristics, for analysis. CFD model simulations are also presented, explaining the physical basis for the results observed in the field data visualisations.

Field observation data

Data plotted in Figure 2 show the cumulative totals for two rainfall events at Talla Reservoir. These events are observed to be typical for this site. Event (A) is characterised as a low wind event and (B) is classified as a high wind event. Cumulative rainfall totals are provided for (1) a pit gauge, (2) a ground mounted aerodynamic gauge, (3) a pedestal mounted (1m) aerodynamic gauge and (4) a ground mounted straight-sided gauge. In both events the pit gauge records consistently the highest amount of rainfall. The ratio of the ground mounted aerodynamic rain gauge to the pit was 0.91 and 0.93 for events (A) and (B), respectively. In contrast the 1m mounted aerodynamic gauge’s equivalent ratios were 0.84 and 0.83. Of particular interest is that the pedestal mounted aerodynamic gauge registers a very similar collection efficiency to the straight-sided gauge at ground level.

The same trend is also observed when the cumulative data is plotted over spring and summer periods, as shown in Figure 3. If the pit gauge measurement is assumed to be the “truth”, the 1-metre mounted aerodynamic gauge and the comparable ground mounted straight-sided gauge are deficient by between 17 – 20% across the time intervals selected.

CFD modelling of precipitation gauges

The two types of rain gauge used in the field study at Talla Reservoir are modelled using CFD, and visualisations of their aerodynamic performance are presented in Figure 4.

The plots are presented as vertical pairs to allow a direct vertical comparison between the different shapes. The ARG100 aerodynamic rain gauge is presented along the top row (1a – 3a), and a conventional straight-sided gauge is displayed along the bottom row of the figure (1b – 3b). The magnitude of velocity $U_m$ represented on a stream-wise vertical plane for the two gauges (1a-1b) confirms the presence of a shear layer (white band). This separates the region characterised by strong airflow regimes above the collector ($U_w < U_m$, red colour), from the recirculating airflow inside the gauge ($U_w > U_m$, blue colour). In the case of the ARG100 this shear layer spans over the orifice and touches the downwind rim of the collector, whereas in the case of the straight-sided gauge it develops far beyond the downwind edge of the collector and reaches higher vertical levels. This behaviour is partially explained by the stronger downdraft occurring inside the ARG100 collector (Figure 2a-2b). The straight-sided gauge shape also causes higher turbulent kinetic energy values just above the collector (Figure 3a-3b), demonstrating an improved aerodynamic behaviour of the ARG100. The actual implications of this evidence on the rainfall trajectories should be evaluated by coupling the CFD airflows with Lagrangian particle tracking models.
Fig 2: Two events from Talla Reservoir research station. (A) is a rainfall event where wind speeds ranging from 0-3 m/s. (B) is a rainfall event where wind speeds range from 1-11 m/s. The cumulative totals (mm) of rain gauges mounted at different heights are plotted.

Fig 3: Cumulative rainfall totals for the four chosen rain gauges, covering a spring period lasting 52 days and a summer period lasting 74 days.
Fig 4: CFD visualisations of the stream-wise vertical view of different parameters, for wind speeds of 7m/s. The figures are displayed as pairs, with the aerodynamic profile of the ARG100 on the top row (1a, 2a and 3a), and the conventional straight-sided gauge shown on the bottom row (1b, 2b, and 3b). 1a and 1b show the air velocity magnitude colour Um (m/s) plot and vector plot of the airflow. 2a and 2b show the air vertical velocity component Uz (m/s) plot and vector plot of the airflow. 3a and 3b show the turbulent kinetic energy k (m2s-2) plot and vector plot of the airflow.

4. Conclusions and recommendations

The CFD study shows that the shape of the rain gauge is significant when considering catch efficiency. The aerodynamic shape of the ARG100 is less affected by turbulence than the conventional straight-sided gauge. Data from the field site at Talla Reservoir supported this assumption because the rain gauge in the reference pit consistently recorded more rainfall than other co-located rain gauges mounted at different heights.

Work is still to be undertaken to explain the undercatch issue more clearly before attempting to resolve it. There are also other considerations such as the influence of the drop size distribution, intensity, and how the characteristics of a site’s macro and micro topography, influence rainfall measurement accuracy. Furthermore, new European (CEN) calibration standards soon to be published will improve the interoperability of rainfall measurements. It will be interesting to see how applying a retrospective calibration coefficient to TBRs will influence datasets. Future work will include this goal. Deeper analysis of the observational data is needed to better understand the phenomenon of wind-induced undercatching. CFD simulations aimed at predicting rainfall particle trajectories using the Langrangian tracking model is recommended. This method has already been tested and optimised for solid precipitation measurements by Colli et al. (2015).

References


Analysis of precipitation forecasts for the Emscher catchment within the COSMO-LEPS Model

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Abstract

The accuracy of the model COSMO-LEPS for precipitation forecasts was investigated during a project, which was conducted within three sub-projects on behalf of the water management association Emschergenossenschaft. The aim of the investigation on precipitation forecasts was to estimate the accuracy of flood event forecasts in the catchments of the Emschergenossenschaft. The first sub-project focused on the analysis of precipitation forecasts within the COSMO-LEPS model for chosen flood events. For the second sub-project events were chosen that had high values for the accumulated precipitation in the COSMO-LEPS forecast. The choice of data was independent of the measured height of the accumulated precipitation. In the third and last sub-project it was investigated whether there are indicators that result in a higher accuracy of precipitation event forecasts that lead to flood events.

1. Introduction

Both water management associations, Emschergenossenschaft and Lipperverband (EG/LV, 2015), use data of various sources for the estimation of flood events in their catchment area. Measured data of precipitations (of their own rain gauge network and weather radar data of the German Weather Service (DWD)) are one source. Numerical weather forecasts of the DWD are another source of data. For the short-to-medium range forecast precipitation forecasts of the COSMO-LEPS model are used.

COSMO-LEPS is the Limited Area Ensemble Prediction System and it was developed within COSMO consortium in order to improve the short-to-medium range forecast of extreme and localised weather events (Marsigli et al., 2005; COSMO, 2008). It implements a dynamical downscaling of the global ensemble prediction system running at the European Centre for Medium-Range Weather Forecasts ECMWF-EPS (DWD, 2015). The German Weather Service (DWD) uses COSMO-LEPS data to calculate 16 forecasts (so-called members) with slightly different starting conditions. The different starting conditions are used to take the uncertainty of the present atmospheric conditions into account. Forecasts of the COSMO-LEPS model are given for Europe twice a day (at 00:00 a.m. and 12:00 noon) with a temporal resolution of three hours (Montani et al., 2014). The forecasts are valid for the following 5.5 days.

2. Catchment and data

The investigation areas for the three sub-projects were parts of the catchment area of the river Emscher, which is 865 km² in size. COSMO-LEPS precipitation forecasts were compared to areal precipitation data from the rain gauges in the catchment. The number of investigated sub-catchments varied for the three sub-projects (table 1). Figure 1 shows the spatial distribution of the gauging sites 10000 – 11040 corresponding to the sub-catchments. Nevertheless, the following results presented in this paper refer only to forecasts for the entire catchment of the Emscher
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(gauging site 10000). For all squares of the grid the average of the COSMO-LEPS precipitation data was taken (figure 1). The areal precipitation data of the rain gauges is the arithmetic average of 20 measuring points which are evenly distributed over the catchment area (Fig. 1, rain gauges number 1 to 20).

Table 1: data base of the three sub-projects COSMO-LEPS I - III

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>COSMO-LEPS I</th>
<th>COSMO-LEPS II</th>
<th>COSMO-LEPS III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of events</td>
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<td>51</td>
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<td>Investigated sub-catchments</td>
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<td>4</td>
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<td>COSMO-LEPS forecast</td>
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<td>Rain gauges</td>
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<td></td>
<td></td>
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<tr>
<td>Areal precipitation of the sub-catchments</td>
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<td></td>
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<tr>
<td>Areal precipitation (measuring data)</td>
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<tr>
<td>Comparison of precipitation</td>
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<td>Accumulated precipitation</td>
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<tr>
<td>Accumulated precipitation, threshold values</td>
<td></td>
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</tr>
</tbody>
</table>

Fig 1: Emscher catchment (gauging site 10000) and sub-catchments (gauging sites 10003 – 11040), COSMO-LEPS grid and rain gauges (no. 1 – 20).

3. Methods

Three sub-projects have been used to investigate the applicability of precipitation forecasts of the COSMO-LEPS model to forecast runoffs in the catchment. The investigation has been conducted by the following procedure:

1. Analysis of precipitation forecasts within the COSMO-LEPS model for chosen flood events: 
   => Is it feasible to predict major flood events with COSMO-LEPS?
2. Analysis of precipitation forecasts within the COSMO-LEPS model for chosen precipitation events: 
   => Do high precipitation forecasts necessarily result in major flood events?
3. Additional analysis of precipitation forecasts within the COSMO-LEPS model for chosen precipitation events:
3.1. Analysis of precipitation forecasts within the COSMO-LEPS model for chosen flood events

The first sub-project focused on ten flood events in the Emscher catchment in the years of 2007 until 2011. The data of the ten chosen flood events and its corresponding measured precipitation were analyzed (averaged areal precipitation). The crucial question of this sub-project was: Is it feasible to predict major flood events with COSMO-LEPS?

The measured accumulated precipitation of the Emscher catchment (averaged areal precipitation) for lead times of 1 to 5 days was compared to
- the member with the maximum accumulated precipitation,
- the arithmetic mean of the accumulated precipitation of all 16 members
- and the arithmetic mean of the three members with the highest accumulated precipitation.

3.2. Analysis of precipitation forecasts within the COSMO-LEPS model for chosen precipitation events

For the second sub-project 43 events were selected. The events were chosen because of their high values for the accumulated precipitation in the COSMO-LEPS forecast. The actual height of the accumulated precipitation was not taken into account by the selection of the events. The crucial question of this sub-project was: Do high precipitation forecasts necessarily result in major flood events? The significance of this question arises from the fact that water management associations use precipitation forecasts in their operational prediction of floods. This investigation is based on the same lead time and parameters as the first sub-project.

3.3. Additional analysis of precipitation forecasts within the COSMO-LEPS model for chosen precipitation events

The third sub-project is based on the results of the first two sub-projects. Its aim was to investigate whether COSMO-LEPS forecasts contain indicators that could help to identify extreme precipitation events that cause floodings. All 51 events of the first two sub-projects were taken into account. The evaluation considered the lead time with the highest intensity of precipitation of all lead times for each event.

The following parameters have been examined:
- Is there a correlation between the value of the standard deviation and the quality of the forecast?
- Does a specific range (number of members) exist, that can be used to forecast measured accumulated precipitation (hit rate / deviation)?
- Is it possible to identify extreme precipitation events that lead to flood events with the help of the maximum intensities of precipitation (above a threshold value)?
- Is it possible to forecast appropriate peak intensities for measured precipitation data (as a trigger for maximum runoff) on the basis of maximum intensities of COSMO-LEPS precipitation forecasts?

4. Results

The result of the first sub-project is that neither the arithmetic mean nor the median of the 16 used members are suitable to forecast extreme precipitation events that have led to flood events in the past. The findings show an underestimation of the actual accumulated precipitation. The member with the maximum accumulated precipitation can only function as an indicator for weather...
conditions with convective extreme precipitation. Background for this conclusion is that the measured data for rare extreme precipitations is considerably underestimated, whereas more frequent extreme precipitation events are overestimated which is significant for the maximum member as well. In addition to the height of precipitation it is also not possible to forecast the exact place (sub-catchment) and time of a precipitation event. This difficulty is especially valid in summer season. The highest consistency between forecasted and measured precipitation has been achieved with the arithmetic mean of the members with the three highest accumulated precipitations. The accumulated precipitations vary less than ±20 % for three events and less than ±40 % for 5 other events. The greatest differences (underestimation of about 50 %) have been found for two events in summer season. A reason for this finding is that small scale convective extreme precipitation events have a negative effect on the forecast quality.

The second sub-project showed that the forecast of high accumulated precipitation with the help of the three highest members does not necessarily result in high measured precipitation values. A comparison of accumulated precipitation of COSMO-LEPS forecasts (arithmetic mean of the three highest members) and measured precipitation in the Emscher catchment gave the following result: Only 35 % of the events in winter season and even only 17 % of the events in summer season are placed in a range of 70 % - 150 %. There was no significant underestimation (< 70 %) found in the precipitation forecasts compared to the measured accumulated precipitation. It was quite different regarding the overestimation of events. Some of the forecasted accumulated precipitations were more than 10-times (> 1000 %) higher than the measured precipitation. A consequence of this finding for the operational flood service is that also in winter only every third extreme precipitation event forecast leads to a flood event. The arithmetic mean of all members gives better forecasts for all 43 events. But it should not be used because in the first sub-project was found that this parameter is not proper to forecast flood relevant precipitation events.

The investigation in the third sub-project is based on the finding of high error rates for precipitation forecasts in the first two sub-projects. In this sub-project it was examined whether there are other parameters that have a higher probability to indicate extreme events that lead to floodings. The indication was independent of the ability to forecast exact accumulated precipitation. The assumption could not be verified that there is a correlation between the value of the standard deviation for all 16 members and the forecast quality. And there were no other specific ranges (number of members) found to give more exact precipitation forecasts than the arithmetic mean of the three highest members.

But for events in winter season it could be proved that the maximum precipitation intensities (sum over three hours) of COSMO-LEPS forecasts can be used as an indicator for maximum precipitation intensities (sum over three hours) for measured data and also for high accumulated precipitation (event sum) (figure 2). If peak intensities of $I = 10 \text{mm} / 3\text{h} – 20 \text{mm} / 3\text{h}$ occur during winter season in COSMO-LEPS forecasts, it can be expected that the measured peak intensities are in the same range and that the sum of the event exceeds 30 mm ($I > 30 \text{mm}$). If the forecasted peak intensities in winter season are in the range of $I = 5 \text{mm} / 3\text{h} – 10 \text{mm} / 3\text{h}$, it can be expected that the measured peak intensities are in the same range and that the sum of the event is between $I = 10 \text{mm} – 20 \text{mm}$. This conclusion was found to be true for 13 of 16 events (81 %) in winter season. A similar correlation is not detectable for summer season. A reason is the character of precipitation events in summer that are small scaled and convective.
Fig 2: maximum precipitation intensities (sum over three hours) of COSMO-LEPS forecasts as an indicator for maximum precipitation intensities (sum over three hours) for measured data and for accumulated precipitation (event sum).

5. Conclusions

Finally, the required probability of detection and accuracy demands of the user determine the usability of the COSMO-LEPS data. At least COSMO-LEPS data can help to classify the data for the also available deterministic precipitation forecasts of the DWD. The water management association Emschergenossenschaft evaluates COSMO-LEPS forecasts as a useful product for flood forecasts. This statement applies especially for flood events in winter season. In the following years further analyses will evaluate the significance of this statement. In the end, the usage of COSMO-LEPS data for flood forecast is depending on the particular meteorological and hydrologic situation. Hydrologists can use COSMO-LEPS forecasts additionally to a range of different other tools for flood forecasts.

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Abstract

A statistical downscaling model was developed to downscale annual maximum daily (AM) rainfall at four selected rainfall stations in the Onkaparinga catchment in South Australia (SA) using a Generalized Linear Model for Location, Scale and Shape (GAMLSS) where AM rainfall was considered as the predictand and large scale atmospheric and circulation variables of the NCEP/NCAR reanalysis datasets were considered as predictors. The model was able to reproduce well the observed variability of AM rainfall at all stations for both the calibration (1961-1990) and validation periods (1991–2010). Almost all the observed AM rainfall data were found within the simulation envelope (2.5th and 97.5th percentile) at the 95% confidence level. This model could be used to downscale AM rainfall from General Circulation Model (GCM) output datasets and to assess future changes due to climate change.

1. Introduction

Information on extreme rainfall is important for the sustainable design and management of water resource infrastructure such as sewerage and urban drainage systems, highways, tunnels and flood protection structures. Extreme rainfall events are a primary cause of flooding hazards, which have adverse impacts on communities and their assets. In particular, the annual maximum (AM) daily rainfall is a basic hydrological metric for the analysis of flood risk. Hence investigation of extreme rainfall is important for impact assessment and adaptation studies. Changes in extreme rainfall due to increased greenhouse gases have already been reported in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC, 2007) as well as in the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (IPCC, 2012). While General Circulation Models (GCMs) are often used for climate change impact studies, the coarse resolution of GCM outputs restricts their direct application for catchment scale climate impact studies. Moreover, even a high resolution coupled atmospheric-ocean Regional Climate Model is generally not able to reproduce extreme rainfall events with accuracy, as demonstrated in the Mediterranean region by Ricard et al. (2009). Therefore, GCM outputs are often downscaled to a finer resolution using either statistical or dynamic techniques. The basic concept of statistical downscaling is to develop a statistical relationship between large scale reanalysis or GCM variables (termed predictors) and local climate variables such as rainfall (termed predictands). This relationship is used to transfer large scale information to the local scale.

The performance of any given downscaling model to reproduce the mean and inter-annual variability of AM rainfall is limited when downscaled daily rainfall from NCEP reanalysis and GCM output datasets (Rashid et al. (under review)). This is due to the fact that the distributions used in downscaling models are generally limited in terms of their ability to reproduce extreme rainfall. Although hybrid distributions have been proposed to capture the full spectrum of daily rainfall, these are generally not adequate to reproduce AM rainfall (Rashid et al., 2014). Some previous
studies have directly downscaled extreme rainfall from reanalysis and GCM output datasets by considering extreme rainfall as predictands using extreme value theory (Friederichs, 2010; Wang and Zhang, 2008). Kallache et al. (2011) considered a probabilistic downscaling approach where the cumulative distribution functions (CDFs) of large and local scale extreme rainfall obtained by fitting a Generalized Pareto distribution (GPD), were linked by means of a transfer function. However modelling and downscaling of AM rainfall is still a challenging research topic due to its high spatial and temporal variability, non-linear and non-stationary nature.

The Generalized Additive Model in Location, Scale and Shape (GAMLSS) (Rigby and Stasinopoulos, 2005) provides a flexible framework for non-stationary modelling. The dependence of the distribution parameters on the covariates can be represented in terms of linear or nonlinear, parametric and/or additive nonparametric functions. GAMLSS has been used successfully to model different hydroclimatic variables such as rainfall, temperature, flood peaks and stream-flows (López and Francés, 2013; Villarini and Serinaldi, 2012). Rashid et al. (2015) proposed a downscaling model integrating wavelet decomposition and GAMLSS to downscale monthly rainfall from NCEP reanalysis and CMIP5 GCMs output datasets for the Onkaparinga catchment in South Australia (SA). In this study GAMLSS modelling framework has been used to downscale AM rainfall from NCEP reanalysis datasets at four rainfall stations within the Onkaparinga catchment.

3. Study area and data

Four rainfall stations within the Onkaparinga catchment were considered to demonstrate the downscaling methodology developed in this study. The catchment is located approximately 25 km southeast of the city of Adelaide in the Mount Lofty Ranges (MLR) and has an area of 553 km$^2$. There is a significant gradient ranging from the low-lying coastal plain to an elevation of 700m in the upper catchment in the MLR. Observed daily rainfall data for the selected stations were obtained from the SILO database of the Queensland Climate Change Centre of Excellence for the period 1960 to 2010. The National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis datasets (termed as NCEP reanalysis hereafter) were collected from the National Oceanic and Atmospheric Administration/Earth System Research Laboratory (NOAA/ESRL) for the period 1960 to 2010. The NCEP reanalysis data were extracted from twelve reanalysis grid points surrounding the selected stations (Figure 1).

Fig 1: Location of the Onkaparinga catchment and NCEP reanalysis grid points (2.5° X 2.5°) around the Onkaparinga catchment. 1, 2, 3,……., 12 represent the grid points.

2. Methods

GAMLSS (Rigby and Stasinopoulos, 2005) has a flexible modelling framework that is suitable for non-stationary modelling. In GAMLSS the random response variable (AM rainfall for this study) has a parametric distribution function whose parameters can be modelled as a function of selected covariates (NCEP reanalysis data in this study). While the GAMLSS framework has several different possible models, a semi-parametric additive model formulation was used in this study as follows:
\[ g_k(\theta_k) = \eta_k = X_k \beta_k + \sum_{j=1}^{j_k} h_{jk}(x_{jk}) \]  

where \( \theta_k \) and \( \eta_k \) are vectors of length \( n \), \( X_k \) is a matrix of covariates of order \( n \times j_k \), \( \beta_k (\beta_{1k}, \ldots, \beta_{jk}) \) is a parameter vector of length \( j_k \), and \( h_{jk}(\cdot) \) represents the dependence function of the distribution parameters on covariates. Five distribution functions were considered in this study, namely the Gamma (GA), Lognormal (LOGNO), Gumbel (GU), Weibull (WEI) and Exponential (EXP) distributions. Predictor variables such as geopotential height (GPH) and relative humidity (RH) at 850 hPa and meridional wind (VW) at 700 hPa were extracted from 12 reanalysis grid points around the selected rainfall stations as shown in Figure 1. The model was calibrated over the period 1960-1990 and validated for the period 1991-2010.

Significant predictors and their linear or smooth dependence on distribution parameters were selected using Akaike Information Criteria (AIC). In order to avoid over-fitting of the model, the shape parameters (\( \theta_2 \)) of the distributions were kept constant. A stepwise procedure was followed to select the final models for each individual stations using AIC as a selection criterion. Moreover, the normality and independence of the residuals were assessed by examining the first four moments of the residuals, the Filliben correlation coefficient and by visual inspection of a diagnostic plot of the residuals. Once the model was developed, 100 simulations were stochastically generated for both the calibration and validation periods.

### 4. Results

GAMLSS models were fitted separately for each selected rainfall stations. Table 1 shows the selected distributions, the significant covariates for each distribution and the type of dependence of distribution parameters as a function of external covariates. It was found that the Gamma and Lognormal distributions offered the best overall results in terms of modelling AM rainfall over the Onkaparinga catchment. Significant predictors and their dependences varied among the stations. The normality and independence of the residuals, the first four statistical moments, the Filliben correlation coefficients and worm plots of the residuals indicated that the models adequately fitted the data.

### Table 1: Summary of fitted models for each rainfall station indicating the selected distribution, the significant covariates and their dependence with the distribution parameters. cs() represent the dependence via the cubic spline. **:refers to an interaction term and ct refers to a parameter that is independent of covariates (constant).

<table>
<thead>
<tr>
<th>Station number</th>
<th>Distribution</th>
<th>Scale parameter (( \theta_1 ))</th>
<th>Shape parameter (( \theta_2 ))</th>
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<td>GA</td>
<td>GPH + cs(RH) + VW + GPH:VW</td>
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<td>G2</td>
<td>LOGNO</td>
<td>cs(GPH) + RH</td>
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<td>G4</td>
<td>GA</td>
<td>GPH + cs(RH) + VW + GPH:VW</td>
<td>ct</td>
<td></td>
</tr>
</tbody>
</table>

The model was able to reproduce the general temporal pattern of AM rainfall at all stations. The inter-annual variability of the observed AM rainfall was reasonably captured by the simulated AM rainfall in both the calibration and validation periods. Figure 2 shows the observed and simulated AM rainfall for selected stations for the calibration (1960-1990) and validation (1991-2010) periods. It was found that almost all observations were within the 2.5th and 97.5th percentiles of the simulated outputs for both the calibration and validation periods. While the variances of the observed AM rainfall were reasonable at all rainfall stations, inclusion of more predictor variables (covariates) and allowing the shape parameter to vary enabled the model to reproduce the variability of the observed AM rainfall more accurately in the calibration period but the model performance generally deteriorated in the validation period due to over-fitting of the model.
Therefore in this study the model was kept as simple as possible, and yet it provided very good performance.

Fig 2: Observed and downscaled AM rainfall for the calibration (upper row) and validation (bottom row) periods at rainfall stations G1, G2, G3 and G4.

Fig 3: Simulated and observed mean (top row) and standard deviation (bottom row) of AM daily rainfall for the calibration (left column) and validation (right column) periods. The box plot depicts the range of 100 simulations, the median and the inter-quartile range (IQR) for each model. Whiskers represent the 1.5 IQR from the box end. Solid squares represent the observations.
Figure 3 shows the simulated and observed mean and standard deviation of AM rainfall for both the calibration and validation periods. The box plot represent the 100 simulations for each stations. It has been observed that in general the observed mean and standard deviations of AM rainfall within the simulation envelope for almost all stations. It has also been observed that there were significant change in the standard deviation of the observed AM rainfall over the validation period compare to the calibration period for rainfall stations G3 and G4, which were reasonably reproduced by the model simulations. This indicates that the model is capable of capturing the non-stationary characteristics of the observed AM rainfall. However, the model showed relatively low efficiency for rainfall station G4. The standard deviation of the observed AM rainfall for this station was not within the simulation envelope for the validation period. This might be due to the relatively high reduction (around 56%) of the standard deviation of AM rainfall over the validation period compared to calibration period for that station.

5. Conclusion

While statistical downscaling of daily rainfall is generally limited in terms of adequately reproducing the variability of AM rainfall, downscaling using GAMLSS considering only three predictor variables from NCEP reanalysis datasets was found to reproduce the observed variability. However, the model efficiency could be still be further improved for example by inclusion of a bias correction technique.

References


Polarimetric X-Band weather radar: high-resolution rainfall estimation

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Abstract

Weather observations are conventionally performed by C-band weather radars with spatial and temporal resolution of 1 km and 5 min, respectively. However, in recent years, C-band weather radars have been upgraded from single to dual-polarimetric to improve the quality of their measurements. Still, these spatial and temporal resolutions might be undesirable for the detection of localized heavy rainfall which might be necessary to model fast rainfall-runoff processes in urbanized areas. Therefore, X-band weather radars have been introduced to increase the resolution of rainfall rate ($R$) estimation. For example, in the USA, a network of dual-polarimetric X-band radars has been used to estimate rainfall rates of severe storms at high-resolution (Wang and Chandrasekar, 2010). In Western Europe, the RainGain project includes a network of X-band radars to obtain high-resolution rainfall rates to cope with urban flooding (http://www.raingain.edu).

For dual-polarimetric radars, several rainfall rate estimators have been based on the specific differential phase ($K_{dp}$) because of its independence to radar miscalibration and attenuation. However, typical estimations of $K_{dp}$ require a substantial amount of smoothing processes. In this work, a new method to estimate $K_{dp}$ for X-band frequencies is introduced. The method is a modified version of the one given by Otto and Russchenberg (2011) in order to control its inherent bias-variance dilemma. In addition, the variance of the $K_{dp}$ estimator was mathematically formulated for a quality control scheme. For moderate and convective storms, the estimation of rainfall rate was given by a $R$–$K_{dp}$ power-law relation.

The new method was applied to a storm event observed by the dual-polarimetric X-band weather radar, IDRA hereafter, in the Netherlands on June 28 2011. To show the performance of the $K_{dp}$ estimator, the propagation differential phase ($\Phi_{dp}$) was successfully reconstructed as shown in Fig 1a). Moreover, the impact of spatial and temporal resolutions on the variability of rainfall rates is shown in Fig 1b). Estimated rainfall rates at 30 m and 1 min resolutions using IDRA were averaged.
and under-sampled at 1 km and 5 min, respectively, to simulate rainfall rates from C-band radars. Results have shown that the estimated $K_{dp}$ and rainfall rate were able to retain the spatial variability of the storm at scales of tens of meters. Furthermore, they were able to produce a variance similar to or less than those of conventional methods. It is foreseen that the proposed method for dual-polarimetric X-band weather radars will improve the quality of radar-based rainfall estimations in real-time as recommended by the urban-hydrology community.

Acknowledgements

This work was supported by INTERREG IVB NWE project RainGain.

References


Impacts of local climatology on heavy rain cells: case study in the southeast of France

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Abstract

The Lyon area, strongly built up, is grouping 58 towns and a population of 1.3 million in approximately 500 sq km. The flood risk is high as the territory is crossed by two large water courses and by streams with torrential flow. The whole territory can therefore be affected and it is necessary to possess in-depth knowledge of the depths, causes and consequences of rainfall to achieve better management of precipitation in urban areas and to reduce flood risk. This study is thus focused of the effects of topography and land cover on the occurrence, intensity and area of intense rainfall cells. They are identified by local radar meteorology (C-band) combined with a processing algorithm running in a GIS which identified weighted mean centers of them in a sample composed of the five most intense rainfall events from 2001 to 2005. First, analysis of spatial distribution at an overall scale is performed, completed by study at a more detailed scale. The results show that the distribution of high intensity rainfall cells is spread in cluster form. Subsequently, comparison of intense rainfall cells with the topography shows that cell density is closely linked with land slope but that, above all, urbanized zones feature nearly twice as many rainfall cells as farm land or forest, with more intense intensity.

1. Introduction

The Greater Lyon has a population of 1.3 million. The flood risk is high as the territory is crossed by two large water courses and by streams with torrential flow. Floods may also occur in case of runoff after heavy rain or because of a rise in the groundwater level. The whole territory can therefore be affected and it is necessary to possess in-depth knowledge of rainfall to achieve better management of heavy rains in urban areas and to reduce flood risk. This study is thus focused of the effects of topography and land cover on the occurrence, intensity and area of heavy rainfall cells. They are identified by local weather radar (C-band) combined with a processing algorithm running in a GIS (Renard, 2010 – fig. 1). This was used to describe 109979 weighted mean centers of intense rainfall cells during the five most intense events from 2001 to 2005.

Fig 1: Topography and location of the weather radar and the greater Lyon.
2. Methodology

It is first necessary to study the spatial distribution of the cells using a density calculation to confirm the inhomogeneous distribution of rainfall cells (fig. 2). Then, the spatial distribution trends (clustering, dispersal or random) of rainfall cells are studied. Subsequently, statistically significant spatial clusters (hot and cold spots) of cells of strong intensity that may provide information about any local effects are identified. The aim is identifying key sectors with the highest concentration of high intensity rainfall cells, going beyond the framework of simple mapping. The spatial auto-correlation is determined using the global Moran's index (Goodchild, 1987) and the degree of clustering of the high and low intensity values is measured using the Getis-Ord General G statistic (Getis and Ord, 1992). These global spatial statistics are completed with local ones using techniques of Local Indicators of Spatial Association (LISA - Anselin L., 1995) and Getis-Ord Gi* statistic (Getis et Ord, 1992).

Secondly, density calculations are made to study the concentration of cells in relation to altitude, slope, exposure and land use. The cell density is the number of occurrence per unit area. It is expressed by classes (for altitude and slope) or categories (for exposure and land use) in cells per square kilometer. Intensities and areas of the cells are considered as variables to be explained and topographic variables (elevation, slope and exposure) are considered as explanatory variables. The determination coefficients are calculated between the variables to be explained and the explanatory variables when they are continuous quantitative values (elevation and slope). Averages and standard deviations are calculated when the explanatory variables are nominal (exposure and land cover).

In complement, statistical tests are used to study the relationship between the cell characteristics (intensity and area), the exposure and land use. The Jarque-Berra test confirms that the normality assumption of the samples can be rejected. In order to overcome the normality assumption to the use of multiple comparison tests (ANOVA), the nonparametric Kruskal-Wallis test is used. If the p-value indicates that the null hypothesis (H0) has to be rejected, this means that at least one group is different from another. In order to identify which groups are responsible for the rejection of H0, the Steel-Dwass-Critchlow-Fligner procedure is used.
3. Results

According to density maps, intense rain cells are not distributed in a homogeneous way. The Moran’s index indicates that the spatial distribution of intense cell is aggregated, and the General G statistic shows a concentration of intensive cells. The local adaptations of these spatial statistics confirm these initial results.

The density of cells depending on the altitude does not vary and remains close to the average (0.57 cells / km²). On the contrary, there is a net increase in cell density depending on the slope. The coefficients of determination of the effect of the altitude and slope on the intensity and area of the cells are close to zero. Regarding exposure of the slope, the cell density is almost constant and does not vary much. In complement, there is influence of it neither on the intensity nor on the area.

When one focuses on the distribution of cells according to land cover, there is a significantly higher density above the artificial areas, with a density of 1.1 cells / km². In contrast, it falls to 0.6 and 0.5 above agricultural lands and forests and semi-natural environments, respectively. The Kruskal-Wallis test followed by the method of Steel-Dwass-Critchlow-Fligner indicates that the intensity is highest above the artificial areas, with 28.4 mm/h on average, followed by the agricultural territories (27.8 mm/h) and semi-natural forests and environments (25.9 mm/h). For cell surfaces, the tests indicate that the largest are located over the forests and semi-natural environments (7.3 km²), followed by artificial areas (6.3 km²) and agricultural areas (5.5 km²).

In conclusion, it appears that the cells are not distributed homogenously and the steep slope areas and artificial areas concentrate the most, according to the spatial statistics. This confirms the results of density calculations previously obtained. In addition, it should be noted that a higher average intensity is obtained over the artificial areas. Different explanations related to urban local effects can explain these results, such as heat islands, city roughness or pollution. Consequently, even more heavy rain in urban systems could be expected if these factors are increasing, especially in the climate change context.

References

Intensification of rainfall related to climate change and its impact on urban water management

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1. Introduction: urban water management in the context of climate change

Heavily urbanized, the Greater Lyon (France) has 1.3 million inhabitants for about 500 km². Flood risk is high, with two major rivers (Rhône and Saône), torrential streams and large impervious areas (fig. 1). It is necessary to have a deep knowledge of the rainfall for the sustainable management of urban water and a reduction of this risk. A previous study (Renard, 2010) studied rainfall causes of flooding, and when the problem is not related to the management or maintenance of the network, it appears that 75% of floods are caused by heavy rainfall. In the context of climate change, it is important to study the behaviour and trends of heavy rains to adapt water management structures in urban areas. Indeed, increased rainfall could lead to question the urban water management strategies. The aim of this work is thus to identify the Greater Lyon heavy rain trends in the future, in particular to know if these rains are going to be more frequent. For this, the changes are studied with the classification of Hess-Brezowsky (from 1881 to 2013) and the climate types with the method of Köppen-Geiger (from 1922 to 2013).

Fig 1: Greater Lyon topography.

2. Methods: Circulation patterns and climate types

The study of trends in types of precipitation is carried out by analyzing the regimes of synoptic circulations. A literature review of existing catalogs has been completed and the Hess-Brezowsky
one was chosen (Gestengarbe and Werner, 1999). It is currently updated by the Deutscher Wetterdienst service, freely accessible¹ and goes back to 1881. It is based on five main weather regimes (aka Großwettetypen: GWT – southerly circulations, westerly, northwesterly and northerly, northeasterly and easterly, main high/low pressure area over Central Europe), divided into 29 sub-types of situations (Großwetterlagen: GWL). First, trends in the number of days of rain per year and annual heights are analyzed, using the Mann-Kendall test. Then, the proportion and trends of GWL and GWT during rainy days are studied, especially the types of circulation causing heavy rainfall, from 1881 to 2013, based on the Lyon-Bron (Météo-France) gauge.

Developed in the early 20th century, the Köppen-Geiger climate classification is the most used method to categorize the types of global climate. It is based on a classification of the world into five zones (equatorial arid, warm temperate, snow and polar), subdivided by rainfall and temperature regimes. The methodology used is described in Kottek et al. (2006) and Rubel and Kottek (2010). Rainfall and temperature data are also from the Lyon-Bron weather station (from 1922 to 2013).

3. Results: more heavy rain to come

From 1881 to 2013, the number of rainy days is almost constant, no trend can be detected ($\bar{x} = 149.8, \sigma = 17$). The annual rainfall amount, subject to strong inter-annual differences ($\bar{x} = 823$ and $\sigma = 133.8$) is very slightly increasing (Kendall's tau = 0.12). 31% of rainy days are due to westerly circulations (24% for dry days), 24% are due to northwesterly and northerly (25%), and 22% are southerly (14%). Northeasterly and easterly circulations and main high/low pressure area over Central Europe contribute to 11% (12% for dry days) and 12% (24%) (fig. 2).

![Fig 2: Daily rainfall circulations in Lyon from 1881 to 2014.](image)

The proportion of weather regimes causing rainy days are all in decline since 1881 (in different proportions), except for southerly circulation, which is experiencing a strong and constant increase, with a 0.49 Kendall's tau (fig. 3).

¹ http://www.dwd.de/GWL
In terms of intense rainfall, southerly circulations are responsible for 34%. Main high/low pressure area over Central Europe contributes to 23%, and westerly to 18%. Regarding the GWL, the “Zonal Ridge across Central Europe” is causing the most of intense rain, with 13%. It is followed by the GWLs WZ “Cyclonic Westerly”, SWZ “Cyclonic South-Westerly” and TRW “Trough over Western Europe” that are all causing 11% of intense rain. Their trends are all dramatically increasing (except for BM that is stationary). Indeed, for BM, SWZ and TRW, their Kendall's tau are respectively 0.31; 0.52 and 0.46 (Fig. 1).

The climate types were calculated, for each year from 1922 to 2013, according to the Köppen-Geiger method. All years are in the warm temperate climate category, with the exception of the years 1940, 1945, 1956 and 1963 that had a snow climate (fig. 4). Two temperature types are identified in Lyon since 1922: warm and hot summer. Since 1965, hot summer years are increasing, while warm summer years are less frequent. Indeed, absent for the decade 1965-1975, hot summer years are present at 30%, 40%, 80% and 70% for the following decades (fig. 5). In addition, the Mann-Whitney test (preceded by Shapiro-Wilk test) indicates that dangerous GWLs (BM, TRW and SWZ) are more present during the hot summer years. These GWL causing intense precipitation, more frequent flooding are expected in the near future, if the current climate change continues and rain management techniques do not adapt quickly.
Fig 4: Weather types in Lyon from 1925 – 2014 according to the Hess-Brezowsky classification.

Fig 5: Summer (left) and rainfall (right) types by decades, according to the Köppen-Geiger method.

References


Optimal adaptation level in current and future climate

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Abstract

More intense and frequent rainfalls have increased the number of urban flooding events in recent years, prompting adaptation efforts. Economic optimisation is considered an efficient tool to decide on the design level for adaptation. The costs associated with a flooding event to the T-year level and the annual capital costs of adapting to the T-year level are described with log-linear relations. The total flooding costs are developed as the expected annual damage of flooding events above the T-year level and the corresponding annual adaptation capital costs. The value of T that corresponds to the minimum of the sum of the two costs will then be the optimal adaptation level.

The change in climate, however, is expected to continue in the next century, which calls for expansion of the above model. The change can be expressed in terms of a climate factor, which is assumed to increase in time. Also, the log-linear cost relation is expected to increase with the 100-year climate factor. It is further anticipated that the adaptation is carried out in year t*. Thus, a search for the minimum costs should be sought by varying both T and t*. A comparison of the different options should be done in terms of the net present value (NPV) of all incurred costs. The optimal set of (t*, T) providing minimum total NPV can then be identified and its sensitivity to the chosen model parameters analysed.
Comparing extreme values of weather radar observations and rain gauge measurements: conclusions and open issues

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Abstract

1. Introduction

Meanwhile more than 10 years of quality radar measurements for the use of precipitation evaluations are available. In North Rhine-Westphalia (NRW), Germany the radar data were corrected and calibrated “offline” by the water boards in addition to different historical analysis. Due to positive first experience in the use of the continuum also for climatological and statistical issues in relation to water management tasks (Scheibel et al., 2012), the Wupperverband further investigated together with hydro & meteo requirements to systematically incorporate radar data into planning and operating processes of water management. First attempts of statistical comparisons were performed with data sets from rain gauges and various radar products. The objective was the quantification of uncertainties and differences between the different data pools and evaluation methods (event based, extreme value based, single radar, composite, calibrating with and without image interpolation). These results were presented (e.g. Einfalt et al., 2014), discussed and compared to other investigations, leading to open issues on which we had to look even closer. The whole process of deepening the knowledge on radar data and the discussions within will help to improve the knowledge in using and combining the different sources for hydrological modelling and the understanding of possible uncertainties in hydrological design and forecast.

Results from extreme value statistics of long time series (> 30 years) of rain gauge measurements are traditionally used in hydrology, for the choice and design of measures (e.g early warning systems or hydrological structures). These statistics are neither necessarily directly available for the locations where they are required for nor in adequate density. Therefore, statistics from rain gauges are often not representative for these locations, leading to uncertainties when using them for hydrological calculations. Archived radar data in good quality have now been observed in Germany for more than 10 years, and provide a higher spatial data density than gauge measurements. But are both comparable and easy to combine?

In comparing extreme values of both methods different aspects have to be taken into account:

Radar data
- are volumetric measurements and therefore much different from the gauge measurements taken at an area of 200 cm²
- is an instantaneous measurement method and rain gauge measurements are continuous ones
- may be corrupted by undetected effects such as attenuation and in such cases, radar underestimates precipitation
- are measured at a given height above the ground – precipitation and its intensity may change in the course of approaching the ground (e.g. evaporation, mountain effects). Other undetected effects (bright band, snow, etc.) may be responsible for other uncertainties
- are indirect measurements. A relationship to convert the reflectivity factor to intensities has to be found and is usually a relationship for a specific type of rainfall, averaged in time only or in time and space
is normally adjusted with rain gauges to use the data for hydrological matters. The adjustment outcome depends on the amount of stations available and the resolution used.

So the question investigated is if extreme events observed by rain gauges and by weather radar are comparable, what are the differences (qualitative and quantitative) for different durations and what is the sensitivity for a hydrological outcome?

2. Results

Radar statistics at a point have the tendency to be lower than the ones from rain gauges (own results and other investigations with same radar data base). Related to the aspects above that means:

- Instantaneous measurement: The question is answered how the extreme values differ for different adjustment schemes: with and without image interpolation (Jasper-Tönnies et al., 2014).
- Volumetric measurements and attenuation: here it has to be investigated how beam geometry and sampling volume influence extremes of the measured reflectivity – results will be available at the workshop.
- Measured at a given height above the ground: it is shown how the rainfall intensity differs in a pixel neighbourhood (the variation over the 9-pixel-neighbourhood can be large).
- Adjustment with rain gauges: the gradients on extreme events are compared between rain gauges and radar data.
- Coincidence: it is shown how large the differences are between the event analysis and the extreme-value based analysis (even small-scale events over an area of 9 pixels show a significantly lower areal precipitation amount than single pixels, in particular for rare events).
- For practical use the intercomparison is not the only important aspect – more important are differences in simulated effects and observed processes. So one main question to answer is: What are the consequences from such differences at least for the applications (forecast, hydrological modelling and design)?

References

Rain data from gauges and weather radar for hydrological modelling: competition or complement?

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Abstract

Meanwhile the analysis of single heavy rain events by using radar data to improve knowledge of the areal precipitation is already common. This is driven by scientific interest as well related to compensation questions. Due to following hydrological processes and flow pathes, the location of even a convective storm event is not necessarily the place the damage take place (Einfalt et al., 2008). Therefore hydrological modelling for such individual extreme events increased. The basic applications of precipitation data from weather radar measurements in hydrology are far more in the field of updating hydrologic forecast-models including nowcasting. To use Weather radar data for the general calibration and long-term simulation of hydrological models is so far still accompanied by much scepticism.

The first reason is the question about the comparability of weather radar and rain gauges. While data from rain gauges already exist since decades, quality radar data mostly exist for about 15 years. The representativeness of the short-term period compared to rain gauges is a gap in the sense of climatology. Also there is the discussion about the different time and spatial distribution and the relation between the precipitation-volume measured by weather radar in higher altitudes and the intensity on the ground by the pluviographs.

The second reason is the fear of the need to calibrate and maintain “two” models: one with station data and once with weather radar data. However, due to the different input data not only new uncertainties arise, there is also a chance to improve hydrological model quality by combining the advantages of both data bases instead of only comparing the differences.

Because of the good experiences already made with first examples (Scheibel et al., 2012) the process of implementing radar data in the hydrological modelling within the Wupper-Association was successfully continued. Enabled by the cooperation with the German Weather forecast the Wupper-Association has access not only to single event data. Calibrated long-term series evaluated from weather radar can be used to maintain hydrological models for planning, designing and operating flood protection measures. The experience was growing with every project case and leads to results such as adequate calibration of hydrological models sometimes are only possible by the additional use of weather radar data (Scheibel, 2014).

After undertaking several projects and collecting more data base it is time to investigate the results altogether. Collecting and comparing the result of different models (by scale and resolution) it is possible to already find conclusions for further ongoing.

The results are
- For individual heavy rainfall events in the aftermath: extreme storm events are mostly local and therefore not representative covered by rain gauges (over- or underestimation). But even with station and radar data there might be some gaps left in reproducing the events (extreme events causes some chaos in systems, which can not reproduce by models).
- Flood simulations in the “online” case: due to the lack of time for preprocessing and different products the results are often not adequate. Improvement will be made by learning from “offline” preprocessing and simulation.
- Calibration of hydrological models with level and flow gauges: for the Wupper area there is no need to maintain two models. In practise it is common to calibrate hydrological models with addition of short period stations to rise up the spatial information. The long-term simulation than is operated only with the long-term station and this as well with the same model. Another result is: even in very small catchments the areal precipitation can vary a lot – the effect is visible due to dense measurements in the water system.
- Results of long-term simulations design values: also the time series from radar data is not long and representative enough for climatology radar data is valuable to improve the knowledge of the local areal precipitation and thereby the calculation of runoff peaks and volumes during the observation period. This can be used to find factors to calculate realistic areal precipitation from the gauges causing realistic observed discharges. With these factors long-term simulation for climatology with long-term stations estimates better design values.
- Uncertainties between models and measurements: for different sets of rain data (single station, combined stations and radar data) quality criterions are compared. The outcome is mostly a better performance of radar data.

With the examples and results it can be shown that using the advantages of both measurements and combine them uncertainties will not disappear, but the quality of modelling can be improved.

References

Experimental design approach for optimal selection and placement of rain sensors

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Abstract

Traditional rain gauge and weather radar measurement alone often do not provide precipitation information in the high spatial resolution desired for urban drainage modelling. For this reason a growing number of alternative rainfall sensors have been developed to complement traditional measurements. Examples are micro wave links (MWLs) (Atlas and Ulbrich, 1977), modified marine radars (Rasmussen, 2008), simple acoustic rain gauges (Nystuen, 1999), or even sensors of car windshield wipers (Haberlandt and Sester, 2010).

Given the growing number of different rain sensors it is unclear which configuration of sensors provides the best information or how to optimally improve upon existing configurations. For example, is it more beneficial to install ten simple binary rain sensors, two traditional rain gauges, or one MWL? Furthermore, in many situation some sensors (e.g. rain gauges, weather radar) are already in place and the question arises as to what information is gained by adding additional sensors.

This depends on the properties of the different sensors in question, their placement, and the quantity of interest. Sensors differ in the scale of the signal (e.g. continuous or binary), measurement uncertainty, temporal resolution, and may have different integration characteristics. The latter point describes that most sensors do not measure rain intensities but rather the rain intensity integrated over some domain in time and/or space. For example, tipping buckets observe the rain intensities at one point but with variable temporal integration. MWLs are examples for spatial integration as they measure the intensity integrated along the link. Depending on what quantity of the rain field are of interest different sensor configurations are optimal. For example a five kilometer long MWL may provide better information about the current average rain intensity of a large area, whereas a rain gauge may provide more accurate daily rain sums.

We present an approach to assess the value of a specific sensor configuration based on the assimilation method CAIRS (Scheidegger and Rieckermann, 2014). The main advantage of this approach is that the different sensor properties mentioned above are explicitly considered. However, instead of assimilating measured signals we propose to perform computer experiments using CAIRS to optimize the measurement set-up, i.e. to find an optimal, economical sensor configuration. Figure 1 shows a preliminary result of such simulation. However, instead of reconstructing rain fields, we plan to modify CAIRS to directly compute the quantity of interest (such as the 10 minute rain sum over an certain area) and its uncertainty. The reduction of this uncertainty quantifies the relative value of a sensor configuration and enables comparisons.
Alternative rain sensors usually have larger measurement uncertainties compared to designated rain sensors. However, as many of these novel sensors are either cheap or based on existing infrastructure, they offer the opportunity to improve inputs for hydrological models considerably at a low cost. Our approach can aid in designing sensor networks in an optimized manner to ensure that the highest informational value is obtained.

References


Beyond scalar multifractal precipitation modelling: multifractal interactions between dynamics and water content across scales

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Abstract

The introduction of the multifractals in hydro-meteorology to analyse and simulate clouds and rainfall represented an important paradigm shift at the beginning of the 1980's with respect to the then current (linear) stochastic modeling. They were physically based on the idea of interacting cascades of respectively the wind fields and the water content across scales. For various reasons—including the classical use of rain rate in hydro-meteorology, computer limitations and the lack of vector multifractal simulations—they were reduced to a unique, multiplicative cascade of the rain rate. This oversimplification was initially quite helpful to quickly grasp qualitatively new insights, including for applications (e.g. extremes and radar meteorology), and became widespread. Nevertheless, it also introduced limitations and discrepancies with empirical data that it is timely to resolve.

Although vector multifractals are indispensable to analyse and simulate interaction between processes or between their components and have been investigated since the 1990's, they have remained rather abstract.

In this talk, we present on the contrary a concrete and generic class of multifractal vector fields that should be helpful to analyse and simulate rainfall in urban areas remotely sensed by high resolution radars. Their cascade generators combine indeed robust statistics (Lévy stable processes) and anti-commutation structural properties (Clifford algebras that broadly generalise complex numbers and quaternions).

This research was partially supported by the Chair “Hydrology for Resilient Cities” endowed by Veolia (http://www.enpc.fr/hydrologie-pour-une-ville-resiliente) and the EU Interreg NWE RainGain project (http://www.raingain.eu/).
The German radar precipitation climatology and its fields of application in urbanized areas and urban flood risk mapping

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Abstract

Currently, heavy and small scale (convective type) precipitation events like last year's Münster/Westfalen incident seem to occur more frequently. Unlike continuous rainfall events, heavy rain implicates a relatively short reaction time for setting up counter-measures to prevent great damages, especially in urbanized areas. Therefore knowledge about the distribution and hotspots of such convective events in a climatological sense is important to react anticipatorily. For this purpose the German radar precipitation climatology which covers data since 2001 is currently being developed. By homogenising data, adding new station data for adjustment as well as correcting different types of radar artefacts data quality is improved continuously over the two-year project period. Simultaneously, to guarantee a smooth application of the project's results, user-specific products are developed in a separate module. This paper focuses on the user-specific products, while for more detailed information on the radar-based precipitation reanalysis the reader is referred to Brendel et al. (2015).

1. Introduction

An increasing number of fire brigade operations as well as the subjective impression of a rising number of extreme precipitation events in the context of climate change, evoke the question on how frequency and intensity of heavy rain events have changed in Germany over the last decade. Given, that precipitation is a highly variable parameter and can occur on a quite small scale, high-resolution precipitation data is necessary for research on this topic.

The 2-year-project “Radar climatology” under the leadership of Deutscher Wetterdienst (DWD) and in cooperation with four other public authorities, the Bundesamt für Bevölkerungsschutz und Katastrophenhilfe (BBK), the Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR), the Bundesanstalt Technisches Hilfswerk (THW) and the Umweltbundesamt (UBA) therefore has the objective to develop a 15-year German radar climatology based on the DWD RADOLAN (radar online adjustment) data since 2001.

2. Data and Methods

RADOLAN combines reflectivity data of the 17 German C-band radar stations with precipitation data of numerous German rain gauge stations resulting in a high spatio-temporal resolution (1km, 1h) quantitative precipitation analysis (Weigl and Winterrath, 2010; Winterrath, Rosenow and Weigl, 2012). A first reanalysis was conducted in spring 2015 based on radar reflectivity data since 2001. Improved reanalysis versions are planned for winter 2015/2016 and spring 2016, step by step implementing homogenization of the data set, applying further correction methods and adding supplementary rain gauge data. The first reanalysis version can be analysed now using GIS techniques and represents a basis for testing user-specific products.

In the technical work packages (module 1 and 2) measures were taken to address diverse radar artefacts. Bright-band correction with the POLARA (polarimetric radar algorithms) toolbox was tested as well as an automated spoke correction was developed. Another task was to set up
range-correction methods to improve the reanalysis run. Concerning additional rain gauge stations a daily station data disaggregation method (DIAGG) was developed to gain artificial hourly data for use in radar measurement adjustment (s. Brendel et al., 2015). The acquisition of station data is in progress. Yet obtained station data from partner networks will be included in the next reanalysis versions after being quality checked.

To guarantee a real benefit for applicants, in work package 3 of the project, importance is put on a user-specific processing as well as a user-friendly format of the results. Yet in an early project phase users were identified and a first workshop was conducted to find out the requirements for a smooth application of results in the field of urban planning, civil protection, agriculture and hydrology. Additionally a discussion forum was established to enable a subject-specific exchange with the end-users during the project.

3. Results

Below, the focus of the project’s interim results is set on module 3- user communication. For more information on the technical work see the contribution of C. Brendel. All interim results are based on the first RADOLAN reanalysis.

Currently, a shifting paradigm from flood protection to integrated flood risk management presumes a forward-looking urban planning as well as an involvement of and communication with the public/residents themselves in taking flood provision measures, as the entire runoff could no longer be discharged by sewage systems.

In this context hazard analyses (risk quantification) for urban flood risk maps are getting more and more fundamental. Urban flood risk maps may help to decide where to build up new urban settlements and where to establish technical and non-technical preventive measures (in the sense of an integrated urban planning) to mitigate or minimize damage. Those maps can be seen as communication measure to inform residents as well as public authorities about their estimated flood-risk as well as to provoke self-protection and priority setting in spending public funds, respectively. A key role though plays a user-specific communication and design in risk assessment.

Here, the German radar precipitation climatology with its high spatio-temporal resolution (1x1 km) can be seen as an important component (besides tackling questions of agriculture, hydrology and civil protection) in developing strategies for urban (risk) management and planning. It may represent a new possibility of detailed analysis of vulnerability and resilience in urban areas. Module 3 therefore mainly focuses on user-friendly standardized formats of the products to be integrated smoothly by the applicants, an appropriate map design as well as a permanent exchange with and a transparent and comprehensible communication of the results for end users.

So far combined products comprising for example high-resolution reanalysis precipitation data, fire brigade operations and population density have proved to be useful considering past single events in the sense of “lessons learned”.

Further, first tests were undertaken in extreme value statistics. Therefore, the area of the predecessor project Köln21 (41x41km) was used. Based on the directive DWA-A 531 (DWA 2012), design depths for various return periods (1a-20a) and durations (1h-72h) were computed with an automated outlier control. Those analyses were compared to a station-based DWA analysis (s. Figure 1 for a 1h-duration), which has a significantly lower resolution revealing the importance of radar-based products especially for urban regions. It becomes also noticeable, comparing the analysis without outlier control and a slightly different processing (quality control, composite technique), and the analysis with up to two outliers removed, that there can be a great influence of a single statistical outlier on the determination of design depths. The 6.5 year period and the complete investigation interval (2001-2014) each with up to two outliers removed show similar patterns for the duration of one hour and a return interval of one year.
In an attempt to make design depths understood properly also by the public, communication measures like heavy rain indices were applied and tested with the reanalysis data. Figure 2 shows the heavy rain index (SRI) by T. Schmitt (2014) for an event in Cologne for different durations. It can be recognized easily that this event had larger indices for low durations revealing a more convective characteristic. Moreover site-related indices like the weather extremity index (Müller and Kaspar 2014) are planned to be analysed in the project. Thereby different reference areas like raster, landscapes or geopolitical boundaries can be used.

Run-off modelling, where models first have to be adjusted to the high resolution of the radar climatology, is also an interesting field of application for the final RADOLAN reanalysis.
4. Conclusions

In a two-year project, the German radar precipitation climatology is developed based on radar data available since 2001 processed with RADOLAN. Working on radar artefact correction, adding new rain gauge data for adjustment and generally homogenising the dataset, data quality is improving continuously. Meanwhile different user-specific approaches are tested with a first reanalysis’ data to secure a smooth usability of prospective products in different fields of application. In urban planning a changing paradigm from flood protection to integrated flood risk management necessitates improved communication with public authorities as well as the residents themselves. This implies new approaches in communicating flood risks like the usage of heavy rain indices or combined products with user specific information, presented in this paper.

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Nowcasting and Large-Radar-Archive statistical learning in Switzerland

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Abstract

We are presenting a novel approach on producing probabilistic short-term-forecasts (nowcasts) based on statistically-reduced kinematic and precipitation intensity data of numerous storm systems recorded in the MeteoSwiss radar archive over a period of ten years.

Numerical weather prediction (NWP) models are commonly characterized by limited accuracy in the first few hours after real time. This limitation has motivated the development of several applications which focus on producing fast and accurate forecasts for these first few hours. The practice is traditionally called “nowcasting” and employs statistical methods only, while the complex, computationally expensive, dynamical relations that are found in NWP models are typically absent. Nowcasting tools employ an analysis of the most resent radar images in order to compute the flow of a storm system; then they advance the storm accordingly into the future. Such schemes are not perfect, but for the few hours following real time they are commonly superior to the NWP solution, and play a central role in the decision-making chain related to weather alerts.

Precipitation research in Switzerland has always dealt with the complex topography, a persistent impediment to the desired accuracy. For example, physical mechanisms associated with the interaction between weather patterns and a mountainous terrain are difficult to be taken properly into account by nowcasting applications. Our efforts focused on amplifying the nowcasting paradigm in a novel fashion and are based on two pillars. First, the technology of one of the state-of-the-art nowcasting applications, MAPLE, originally developed in McGill University, in Montreal, Canada. Second, ten years of very high quality radar images in multiple aggregations stored in the database of MeteoSwiss.

The project we are presenting has involved large-scale statistical learning. Using MAPLE, we computed the storm flows for all storms between year 2005 and 2015. Then we organized these data into a large database which practically provides the paths followed by each individual pixel on the radar raster for each hour of the ten years. Eventually we employed advanced statistical learning techniques to reduce this sizeable database into a small number of flexible decision trees. The latter can be used as efficient regression tools for probabilistic forecast prediction. Alternatively phrased, we attempted to merge a typical nowcasting process with collective information on repeated weather patterns detected in a multi-year radar-archive. The result practically unearths critical dynamical information from the radar archive and places it directly at the fingertips of the user. Moreover, this technique, being based on learning-by-historical-data is probabilistic in its foundation, and ensembles of nowcasts for a unique storm system can be easily produced.

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Quarterly Journal of the Royal Meteorological Society 137.661, 2106-2123.
Precipitation seasonality and daily extremes across neighbouring natural and urban environment in central Poland

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Abstract

In this study, the seasonality index and daily extremes are studied to characterize the precipitation and gradients at the interface of natural and urban environment in central Poland. Particular questions are: (1) What is the precipitation seasonality across neighboring natural and urban environment? (2) How big are observed precipitation extremes at a daily time-scale? (3) Are there significant differences between seasonality and extremes detected in natural and urban environment? Results have shown that seasonality regimes evaluated by the Seasonality Index exhibit similarities. However extreme daily precipitation are often much higher within urban zone (city of Warsaw) than in the surrounding open area environment.

1. Introduction

Many hydrological studies need accurate estimates of precipitation. Different precipitation characteristics can support the water balance studies, distributed hydrological modeling in gauged and un-gauged catchments as well as hydrological prediction. Therefore precipitation estimates from different instrumentation technologies (rain-gauges, weather radars, satellites) might substantially contribute to hydrological characterization of catchments. Recently, weather radar and satellite data are increasingly often used in support to ground collection of rainfall. They can significantly refine the spatial image of rainfall extreme events and seasonal cumulative totals. Although radar techniques have been increasingly often applied in urban hydrology, point data from rain gauges remains still an important basic reference. Urban areas might be effectively controlled by ground, dense precipitation monitoring networks (e.g., Licznar et al., 2015).

A range of different rainfall statistics and indices is already in use to detect and characterize point and spatial precipitation patterns. One of them is the Markham index of seasonality and concentration, proposed in 70thies (Markham, 1970), further sequentially modified (Walsh and Lawler, 1981, Bayliss and Jones, 1993, Burn, 1997) and used until present in many hydrological applications. It has a potential to study past and current seasonality regimes of different meteorological and hydrological variables (e.g., Pryor and Schoff, 2008, Parajka et al., 2009) and is useful in prediction of future conditions (e.g., Vormoor et al., 2015).

Focus of this study is on precipitation and its variability at the interface of urban and sub-urban environment in central Poland. This concerns the urban area of Warsaw (Poland) and its surroundings. Particular research questions are: (1) What is the precipitation seasonality across neighboring natural and urban environment? (2) How big are observed precipitation extremes at a daily time-scale? (3) Are there significant differences between seasonality and extremes detected in natural and urban environment? Here the question on ‘urban rain’ magnitude appears in the context of impact of city landscape on rain, which primarily should be attributed to the urban land use causing the urban heat island and urban aerosols. Additional factor is dominant wind direction blowing predominantly from the west. Being far from explaining the bunch of factors influencing the urban rain, this study answers the question on spatial differences in extreme daily precipitation and seasonal cumulative.
2. Methods

The level of irregularity of annual precipitation was estimated using the Seasonality Index defined by Walsh and Laurer (1981), as follows:

\[ SI = \frac{1}{R} \sum_{n=1}^{12} \left| \bar{x}_n - \frac{\bar{R}}{12} \right| \]

where \( \bar{R} \) is mean annual rainfall and \( x_n \) is mean rainfall of month \( n (n=1, 2, ..., 12) \). This index was calculated for rain gauges with relatively long time series of observations, available in years 2000-2014 (Fig. 1, rain gauges no. 01-16).

Extreme daily rainfall in months April-September was analysed based on angular characteristics following the approach introduced by Bayliss and Jones (1993) and Burn (1997). The angular mean Julian date of occurrence of the rainfall was calculated to show the distribution and mean timing of daily extreme events. The mean date of occurrence \( (D) \) represents an average position of particular event occurrences plotted in polar coordinates. The position of the event occurrence on a unit circle is defined by the angle calculated as \( \theta_i = D \times 2\pi/365 \), where the Julian date \( D = 1 \) is assumed for the 1st January and \( D = 365 \) is valid for the 31st December. The \( \bar{x} \) and \( \bar{y} \) coordinates for the position of the mean date expressed as an angular date are calculated from the sample of \( n \) events as follows: \( \bar{x} = 1/n \sum_{i=1}^{n} \cos \theta_i \), \( \bar{y} = 1/n \sum_{i=1}^{n} \sin \theta_i \), \( \Theta = \tan^{-1}(\bar{y}/\bar{x}) \). Peaks-over-threshold approach was applied to extract daily extreme rainfall events for particular rain gauges. Wet-day 24h amounts were analysed to estimate 95th percentile as a threshold for rain gauges with long time series of observations available in years 1985-2014. Daily rainfall equal or larger than 20mm was assumed as a threshold.
3. Data

Data were acquired from 14 rain gauges located across a lowland watershed in the UNESCO Biosphere Reserve (52°15’–52°24’ and E20°15’–E20°57’) and 2 rain gauges located within boundary of Warsaw agglomeration (rain gauges no. 11 and no.16, Fig. 1). Rain gauges no. 1-9 belong to the Kampinos National Park Monitoring Network, whereas those numbered as 10-16 to the national network operated by the Institute of Meteorology and Water Management (IMWM) in Warsaw. They have long-term consistent recording. In former study (Somorowska, 2012), spatial patterns of precipitation have been analyzed based on data derived from radar situated in Legionowo (location same as rain gauge no. 10, Fig. 1). Radar data were quality controlled, adjusted to rain gauges and aggregated to daily, monthly and annual values in years 2003-2008. Analysis has proved that relatively large differences exist. Highest precipitation appeared in the vicinity of Warsaw agglomeration and within the city. As the access to radar data is relatively limited, in this study data from dense urban precipitation network are used (Fig. 1). The network was installed in 2009. It consists of 25 rain gauges (rain gauges no. R01-R25, Fig. 1) recording precipitation at 1-min time intervals. Data were made available by the Municipal Water Supply and Sewerage Company (MVSSC) in Warsaw. 1-min time series were aggregated to 24h sums to study daily extremes and selected seasonal patterns in years 2009-2014.

4. Results

The Seasonality Index calculated for rain gauges no. 01-16 was within the range 0.299-0.311. This comprises rain gauges situated within the city (no. 11), at the boundary of city (no. 16) and those situated outside Warsaw agglomeration. Such a small range of SI proves that the regime is similar with precipitation spread throughout the year, but with a definite wetter season. The highest monthly rainfall occurs in summer in months July and August. In particular years, relatively high monthly sums occur also in May and June, as it happened e.g. during extreme flood in 2010.

Table 1: Summary of extreme daily rainfall at selected rain gauges in years 2009-2014.

<table>
<thead>
<tr>
<th>Rain gauge</th>
<th>No of days with extremes above threshold (20mm)</th>
<th>Highest five values of extreme daily precipitation (mm/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01 (KNP) Miszory</td>
<td>17</td>
<td>53.1 53.0 51.5 43.4 39.0</td>
</tr>
<tr>
<td>02 (KNP) Granica</td>
<td>24</td>
<td>60.5 51.9 37.5 35.0 34.7</td>
</tr>
<tr>
<td>03 (KNP) Wilkow</td>
<td>11</td>
<td>40.5 38.0 37.5 34.0 28.5</td>
</tr>
<tr>
<td>04 (KNP) Rybietw</td>
<td>20</td>
<td>40.3 36.2 34.1 33.8 33.2</td>
</tr>
<tr>
<td>05 (KNP) Kiscienne</td>
<td>16</td>
<td>48.9 36.3 30.1 30.1 30.0</td>
</tr>
<tr>
<td>06 (KNP) Leszno</td>
<td>21</td>
<td>42.5 38.0 35.3 35.0 32.0</td>
</tr>
<tr>
<td>07 (KNP) Pociecha</td>
<td>14</td>
<td>57.3 53.0 32.2 27.5 27.5</td>
</tr>
<tr>
<td>08 (KNP) Dziekanow</td>
<td>15</td>
<td>62.7 52.5 51.2 46.1 32.1</td>
</tr>
<tr>
<td>09 (KNP) Izabelin</td>
<td>23</td>
<td>44.5 42.5 33.0 32.6 31.0</td>
</tr>
<tr>
<td>10 (IMWM) Legionowo</td>
<td>18</td>
<td>74.5 48.9 43.4 42.7 40.8</td>
</tr>
<tr>
<td>11 (IMWM) Warsaw-Bielany</td>
<td>27</td>
<td>44.9 40.9 40.5 40.2 38.9</td>
</tr>
<tr>
<td>13 (IMWM) Zakroczym</td>
<td>18</td>
<td>40.5 36.0 33.3 33.2 31.9</td>
</tr>
<tr>
<td>14 (IMWM) Zielonki</td>
<td>23</td>
<td>48.4 42.9 36.6 33.2 32.0</td>
</tr>
<tr>
<td>15 (IMWM) Farnuki</td>
<td>18</td>
<td>51.4 47.6 46.0 43.2 36.4</td>
</tr>
<tr>
<td>16 (IMWM) Warsaw-Okręcie</td>
<td>24</td>
<td>46.4 39.2 36.4 32.6 29.8</td>
</tr>
<tr>
<td>R01 (Warsaw)</td>
<td>25</td>
<td>107.9 70.9 66.7 55.8 50.0</td>
</tr>
<tr>
<td>R09 (Warsaw)</td>
<td>41</td>
<td>142.1 76.1 60.7 44.5 42.2</td>
</tr>
<tr>
<td>R10 (Warsaw)</td>
<td>32</td>
<td>84.6 78.2 64.7 54.3 45.6</td>
</tr>
<tr>
<td>R14 (Warsaw)</td>
<td>32</td>
<td>90.3 42.6 41.5 41.2 39.8</td>
</tr>
<tr>
<td>R15 (Warsaw)</td>
<td>31</td>
<td>65.8 53.8 44.7 39.8 38.4</td>
</tr>
<tr>
<td>R16 (Warsaw)</td>
<td>22</td>
<td>63.7 59.3 40.5 40.4 33.0</td>
</tr>
<tr>
<td>R17 (Warsaw)</td>
<td>28</td>
<td>84.6 59.3 44.5 43.2 42.4</td>
</tr>
<tr>
<td>R18 (Warsaw)</td>
<td>20</td>
<td>63.6 56.1 49.3 46.3 40.5</td>
</tr>
<tr>
<td>R20 (Warsaw)</td>
<td>28</td>
<td>69.2 51.2 42.8 41.8 40.6</td>
</tr>
<tr>
<td>R24 (Warsaw)</td>
<td>37</td>
<td>79.2 52.8 46.0 45.0 43.5</td>
</tr>
<tr>
<td>R25 (Warsaw)</td>
<td>29</td>
<td>69.2 59.8 48.1 46.4 45.0</td>
</tr>
</tbody>
</table>
Fig 2: Extreme daily rainfall (mm/day) within the city (rain gauges no. R01, R09, R14, R17) and outside Warsaw agglomeration (rain gauges no. 06, 07, 13, 14).

Fig 3: Seasonal precipitation (May-August) (a) and annual sum (b) in 2013.
Chosen statistics of extreme daily rainfall were summarized for selected rain gauges and presented at table 1. Number of days with extremes above threshold of 20mm is usually higher in Warsaw than outside the city. It ranges from 20 to 37 events. Outside city number of extremes above assumed threshold is much lower, from 11 (rain gauge no. 03) to 24 (rain gauge no. 02). Comparison of highest extremes shows that much higher values were registered by selected rain gauges within the city. Here the highest precipitation events ranges from 44.5-142.1mm whereas outside Warsaw – from 40.3-74.5mm. This is visualized at figure 2 which consists of polar coordinate plots of the angle theta (Θ) versus the radius rho. Theta is the angle from the x-axis to the radius vector specified in radians; rho is the length of the radius vector equalled to extreme daily rainfall (mm/day). Angular labels (0°-360°) in polar plots were substituted by the day of the year (1-365) to visualize at which day of the year the extremes occur. In both cases (upper part of figure 2 represents area outside city, lower part – city of Warsaw) extremes occur in all month from April till September. Extremely high rainfall in Warsaw occurred in May, June and August.

Although extreme daily rainfall within urban area are on average higher than in the neighbour, the hypothesis that seasonal and annual sums are also higher here, cannot be unequivocally confirmed. Example of spatial patterns of seasonal and annual sums in 2013 are presented at figure 3a and 3b. High gradients across the city occur. Further validation of data from urban monitoring system is foreseen to exclude uncertainties.

5. Conclusions

The comparative assessment of precipitation regimes of urban area and neighbouring natural environment proved that seasonality of rainfall doesn’t vary considerably. This was reflected by relatively small range of Seasonality Index. Precipitation in both areas is spread throughout the year, but with a definite wetter season occurring in summer months, especially in July and August. Although there are similarities in seasonality, clearly, differences in extremes occur. Assessment of rainfall in years 2009-2014 indicates that summer extreme rainfall events occur in city more often than in neighbouring land within a distance of approximately 50-100 km. Extreme daily rainfall in urban area in some places were much higher than that registered outside the city. In order to validate the data from a dense urban precipitation monitoring network it is planned to compare the data with satellite atmosphere products.

References

Using the three points approach to see beyond extremes for urban hydrology

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Abstract

In a changed climate precipitation has to be assessed not only with regard to extremes but for all aspects relevant in urban hydrology. The everyday domain, the design domain and the extreme domain delineated by the Three Points Approach provides a relevant framework for doing so (see Figure 1) (Sørup et al. (submitted)). Thus, precipitation has to be assessed at event level for different return periods representing the different domains to give a full picture of how precipitation patterns affect urban hydrology.

Precipitation from Regional Climate Models (RCMs) tend to produce smaller extreme intensities than what is observed from point observations (Figure 2) and produce extreme event that has too large spatial extent (Gregersen et al., 2013, Mayer et al., 2015). High resolution RCMs, as presented by Mayer et al. (2015), do a much better job than coarser resolution models like the ENSEMBLES models presented in Gregersen et al. (2013). Kendon et al. (2014) run an RCM at radar resolution (1.5 km spatial resolution) and show that the performance with regard to short term local extremes is increased markedly. However, this approach is extremely computationally costly compared to statistical downscaling which can provide some of the same benefits (Maraun et al., 2010). Sørup et al. (2015), for instance, uses a Neyman-Scott weather generator for spatial downscaling and show how this downscaling product with respect to extremes behave much more realistic for both intensities and for spatial extent.

Figure 2 sums up the intensities from extremes from the precipitation product from the ENSEMBLES models used in Gregersen et al. (2013), the high resolution RCMs presented by Mayer et al. (2015) and from the weather generator presented by Sørup et al. (2015). The ENSEMBLES RCMs perform ok for domain A events and less and less well for domain B and C events when more and more extreme extremes are considered. The high resolution RCMs and the weather generator is able to produce realistic precipitation across all domains.
In contrary to most other downscaling techniques the weather generator provides us with useful
time series that can be used for modelling of urban hydrological systems in all situations not just
extreme ones.

![Intensity-duration-frequency plots for representative events from the three domains of the
three points approach for all considered data sets.](image)

Fig 2: Intensity-duration-frequency plots for representative events from the three domains of the
three points approach for all considered data sets.

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Urban hydrology simulation of a semi-urban catchment with Multi-Hydro comparing X-band and C-band radar data

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Abstract

The complexity of urban hydrology results both from that of urban systems and that of rainfall, especially their extreme variability across scales. This complexity is furthermore increasing with climate change potentially yielding stronger extremes according to IPCC, as well as with continued urban development. Cities should be increasingly incorporated not only into their hydrological basin, but also into their climatic evolution. This leads to an expansion of the spatial and temporal scales to be considered when analysing and simulating hydrological behaviour of urban areas. It should include the possible feedbacks within the water cycle at small scale, such as local extremes causing large scale effects and numerous numerical representation failures.

This paper aims to make substantial progresses in numerical modelling of the urban segments water cycle, using data from C-band and X-band radars. This will be done in an efficient way with the help of a multi-model approach based on Multi-Hydro developed at Ecole des Ponts ParisTech. It is a fully distributed model that integrates validated modules dealing with surface flow, saturated and unsaturated subsurface flow, and sewer flow; and using advanced geoprocessing techniques for the input of different data.

We will study a 6.326 km² semi-urban area located in Massy (South of Paris, France). Various sizes of pixels will be tested to represent the catchment. Figure 1.a shows a representation of the catchment with pixels of size 10 m. Two weather radar rainfall products covering the area will be used. One based on the C-band radar of located in Trappes (approx. 21 km East of catchment) and operated by Météo-France whose resolution is a 1km x 1km x 5min. Another one based on an X-band radar operated by the Ecole des Ponts ParisTech on its campus (approx. 27 km North-West of the catchment). The resolution is 125 m x 125 m x 2.5 min. See Figure 1.b for an illustration of radar image. First rainfall data at the initial resolution will be used. Second, each data set will be stochastically downscaled to 10m scale mainly used for the hydrological modelling. Ensemble of realisations will be input in the model, and simulations will be compared along with in-situ measurements to evaluate the benefits of a finer-scale data.

Fig 1: (a) Representation of the Massy catchment with pixels of size 10 m (b) Snapshot of the reflectivity field measured by the X-Band radar of Ecole des Ponts ParisTech on 19 May 2015.
Authors acknowledge the financial support of the Interreg IV NEW RainGain project (www.raingain.eu) and the chair “Hydrology for resilient cities” endowed by Véolia.

References


Analysis of small scale convective precipitation events in Austria

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Abstract

Flash floods represent an unknown risk in the context of climate change. In order to address this issue the spatial and temporal structure of strong convective cells are analysed as a part of the Austrian Climate Research Programmes (ARCP7) project SAFFER-CC - Sensitivity Assessment of critical condition for local Flash Floods - Evaluating the Recurrence under Climate Change. Both radar data and station data, including a unique network of 151 closely spaced stations, will be used in order to derive characteristic parameters of convective cells. The goal is to construct prototype convective cells based on these parameters. The prototype cells can be used in a statistical downscaling procedure necessary to adapt the climate model outputs to the needs of hydrological modelling of potential future flash flood events. This paper provides a first example of an analysis of one precipitation event based on a subset of the observational data. It is shown that SCOUT, a radar data analysis and visualization software, is capable of both tracking precipitation cells and providing cell characteristics suitable for constructing prototype precipitation cells.

1. Introduction

Flash floods which are characterized by short, local convective cells with high precipitation intensities can cause flooding of endangered objects. Especially in the last two decades an increase in the number of flash flood events was observed. This gives rise to the necessity to assess the risk of flash floods under climate change conditions. The fine temporal and spatial scales required for hydrological modelling together with the uncertainties in modelling small scale convective precipitation, make statistical downscaling an essential intermediate step between the output from regional climate models and the input to hydrological models (Christensen et al., 2008; Wood et al., 2004). The strength of precipitation events can be linked to other meteorological parameters from observations and climate models, e.g. temperature, relative humidity and Showalter index. The underlying assumption is that these parameters can be modelled more reliably than precipitation itself. Therefore the goal is to construct prototype precipitation cells, whose parameters (e.g. size, precipitation intensity) can be modified corresponding to the observed and modelled indicator variables with an additional random component. These modified cells can then serve as input to the hydrological models.

2. Methods

All datasets are analysed with the software SCOUT (Einfalt et al., 1990), further developed by hydro&meteo for the analysis and visualization of radar data. SCOUT routinely identifies and tracks precipitation cells as a part of its nowcasting algorithm. In a first step a threshold is defined based on the mean intensity of the radar image. Only areas with values above the threshold are considered in the cell tracking algorithm in order to concentrate on the most prominent features. The nowcasting algorithm calculates motion vectors for individual cells. In order to do so the cells have to be tracked based on a number of geometrical and statistical features. These features include the centre of mass, elongation, sum of intensities within the cell, size and a histogram for each cell. This results in a small set of parameters characterising each cell. The prototype cells will be defined based on these parameters and can be adapted to changing meteorological conditions by
altering one or several parameters like the size, the mean intensity, or the shape. A description of the basic cell tracking and nowcasting algorithm is given in Einfalt et al. (1990). A shorter but more up to date summary of the nowcasting approach used by SCOUT can be found in Tessendorf & Einfalt (2012).

In order to utilize the features which are already build into SCOUT the data from the WegenerNet (http://www.wegenernet.org, operated by the Wegener Centre for Climate and Global Change, University of Graz, Austria; Kirchengast et al., 2014) is converted to a suitable format.

3. Data

The derivation of the prototype cells will be based on a combination of radar and station data. This combines the strengths of the two measuring systems, which are the high accuracy of station data and the good spatial resolution and spatial coverage of radar data. Also two different study regions will be used to define the prototype cells.

The first region is in Styria, Austria, and represents a unique opportunity to study the spatial and temporal structure of precipitation cells thanks to the WegenerNet, a dense rain gauge network. The second region is in Upper Austria, where a number of past flash flood events were identified. Analysing the precipitation cells related to these events guaranties the relevance of the results to the context of this project.

The WegenerNet is an infrastructure which is ideally suited to study small scale convective precipitation. It consists of a network of 150 stations spread over 300 km² (20 km x 15 km) in the area of Feldbach (see Figure 1). The data available from the network includes precipitation amounts, air temperature and relative humidity with a native resolution of 5 minutes. The stations form a quasi-regular 1.4 km x 1.4 km grid. In addition to station data, gridded data of all the main parameters are derived on a regular 200 m x 200 m Universal Transverse Mercator grid and provided over the WegenerNet web interface. To complement the data measured by the WegenerNet stations, data from the radar Zirbitzkogel of Austrocontrol are planned to be analysed.

A second study region is in Upper Austria. For this region the radar Salzburg/Feldkirchen will be analysed. In addition rain gauge station data will be used, including station data from the national weather service (ZAMG) and the hydrographic service upper Austria (HD OOE).

Fig 1: Locations of the measuring stations of the WegenerNet (projection WGS84/UTM Zone 33N, grid origin at 557600 m and 5190600 m), right: http://wegcenter.uni-graz.at/de/wegenernet/wegenernet-home/.
4. Results

Here we present preliminary results in the form of one example based on station data of the WegenerNet only. Ten events were preselected based on the maximum precipitation intensity amongst other criteria. Screening the list of preselected events it became apparent that, although the WegenerNet is an invaluable source of data, in many cases the combination of station and radar data will be needed to cover the complete cycle of a convective precipitation cell from its development to its decay. Here we have selected an example from the 31.05.2012. Figure 2 shows the IDW interpolated gridded station data provided by the WegenerNet along with the centre of mass of the precipitation cells identified by SCOUT. A precipitation cell starts to develop at 4.05 p.m. and moves southward as it strengthens until 4.15 p.m., when intensities up to 9mm/5min are measured. Afterwards it continues on its southward path with decreasing intensities. From this example we can see that a fine temporal and spatial resolution is needed to correctly capture the evolution of convective cells. Furthermore it can be seen that the centre of the precipitation cells is correctly identified by SCOUT. At 4.10 p.m. and 4.15 p.m. two cells are found. Based on the criteria described in section 2 the lower left cell is matched with its precursor.

Fig 2: Rainfall intensities as observed by the WegenerNet station network on the 31.05.2012. The centre of mass of the cells identified by SCOUT is indicated by black circles.

Additional cell parameters derived by SCOUT are given in Table 1. The centre of mass is given in pixels counted from the origin of the grid in the upper left corner. The distance of the cells in consecutive images, which is derived from these coordinates, is an important criterion for the cell matching. After cell matching these coordinates can also be used to calculate motion vectors of the precipitation cells. The measure of elongation given in the third column of table 1, together with the speed and direction given by the motion vector, is another important characteristic in assessing the risk associated with precipitation cells. The size of the cell remains relatively constant over the period covered here except for the first time step, in which it appears that the two cells found in the next time step were still considered to be only one connected cell. This is possibly an artefact which arises because of the limited spatial extent of the data since the centre of the second cell identified in the next image is not yet inside the observation area. This again highlights the need for radar data.
Table 1: Summary of characteristic features of the tracked precipitation cell.

<table>
<thead>
<tr>
<th>time</th>
<th>centre of mass [pixel]</th>
<th>measure of elongation [pixel]</th>
<th>size [pixel]</th>
</tr>
</thead>
<tbody>
<tr>
<td>16:05</td>
<td>33.7 19.0</td>
<td>57</td>
<td>931</td>
</tr>
<tr>
<td>16:10</td>
<td>19.3 30.6</td>
<td>63</td>
<td>541</td>
</tr>
<tr>
<td>16:15</td>
<td>20.5 34.2</td>
<td>49</td>
<td>590</td>
</tr>
<tr>
<td>16:20</td>
<td>24.3 40.4</td>
<td>17</td>
<td>596</td>
</tr>
<tr>
<td>16:25</td>
<td>31.9 49.4</td>
<td>30</td>
<td>687</td>
</tr>
<tr>
<td>16:30</td>
<td>37.0 54.4</td>
<td>53</td>
<td>550</td>
</tr>
</tbody>
</table>

Figure 3 shows a histogram of the main cell as it evolves from 4.05 p.m. to 4.30 p.m.. This gives insights into the distribution of precipitation intensities within the cell. In this example the highest intensity classes can be found at 4.15 p.m.. The example covers nearly the full life time of the observed cell – which is little more than 30 minutes in this case.

5. Conclusions

Statistical and geometrical parameters of precipitation cells are derived from observational data. In a first example data from the WegenerNet station network is analysed with the help of the radar data analysis and visualization software SCOUT. It is found that SCOUT is a suitable tool to track individual precipitation cells also with this type of data and to derive cell characteristics which can be used to construct prototype precipitation cells. The WegenerNet station network proved to have the required temporal and spatial resolution needed to observe the evolution of small scale features such as convective precipitation cells. However, due to the limited area of the network only a small number of cells can be described completely using this data alone. Therefore radar data will be used additionally in future analysis to increase the number of events from which prototype cells will be derived.

References

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Innovative, multi-disciplinary sensing of rainfall and flood response in urban environments

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Abstract

On 28 July, a cloudburst hit Amsterdam, pouring 90 mm of rainfall over the city with intense rainfall peaks of up to 150 mm/h (Amsterdam Rainproof, 2014). Sewer and drainage systems were unable to cope with this amount of water and flooding occurred at many locations. This example illustrates the disruptive effects that intense storms can have on urban societies, the economy and infrastructure.

Extreme rainfall is expected to occur more often in the future as a result of climate change. To be able to react to this, urban water managers need to accurately know vulnerable spots in the city, as well as the potential impact to society. Currently, detailed information about rainfall intensities in cities, and effects of intense storm events on urban societies is lacking. Collection of these detailed data would require the installation of a highly granular network of weather stations, making preparation of cities around the globe for extreme weather costly. Moreover, as demonstrated by Sips et al. (2013), the costs associated with sensing infrastructure may cause abandoning the implementation thereof.

In this study, we will present first results of an “Urban Weather Sensing Lab” that is created in the city of Amsterdam to provide high resolution, real-time, directly accessible information on rainfall and urban water/drainage system conditions. In this Lab, innovative sensing techniques will be utilised, based on routinely collected data and existing infrastructure, including rainfall estimation from microwave links (Overeem et al., 2011), low-cost acoustic rainfall sensors and low-cost sensors in the drainage system. These will be combined with Social Sensing; information provided by citizens in an active way through smartphone apps and in a passive way by information retrieval from social media posts (Twitter, Flickr etc.) (Gaitan et al., 2014). Sensor information will be integrated, visualised and made accessible to citizens to help raise citizen awareness of urban water management challenges and promote resilience by providing information on how citizens can contribute in addressing these. Moreover, citizens and businesses can benefit from reliable weather information in planning their social and commercial activities.

In an initial deployment in the city of Amsterdam, we aim to derive 2 main results: (1) results from social sensing experiments using a prototype smartphone app; (2) results from high resolution hydrodynamic modelling fuelled by the input from Innovative sensing.

Citizens will be actively involved in collecting rainfall and other weather information using a smartphone app (figure 1). The smartphone app can be used to collect weather information through opportunistic as well through participatory or request-driven social sensing. Experiments will be conducted in Amsterdam, where citizens will first autonomously use the app to collect data. In a next step, users will be requested by the app to measure the weather at a certain moment. This will eventually allow water managers and emergency services to collect information from critical locations where information is lacking, in real-time. Results of the first app experiments, to be conducted in summer 2015, will be presented.
High resolution data collected will be entered into 3Di, a new versatile water management instrument capable of detailed, extremely fast hydraulic computations (www.3Di.nu). The collected high density datasets will for the first time enable testing of the high resolution capabilities of the modelling software and validate outcomes of the simulations. Results of simulations using rainfall derived from microwave links will be presented.

References


Analysis of one decade of heavy rainfall events from a radar rainfall dataset

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Abstract

In order to design and optimize urban drainage systems, it is important to analyse the variability of rainfall in urban areas in order to estimate loads on urban watercourses and drainage systems. Both the spatial and temporal variability within an event is important, but it is also important to know how frequent an event of a given size is expected to strike a specific location. The more we understand past critical rainfall events, the more we can prepare for more severe and more frequent events in the future climate. The long term objective of this is to reduce impacts of especially pluvial flood producing rainfall events.

This paper will provide insights into how weather radar observations can be used to analyse rainfall variability in an eastern part of Denmark – especially focusing on the heaviest and occasionally flood producing events.

In Denmark we have a somewhat dense network of rain gauges in urban areas which currently contain more than 30 years of observations. The network, however, is not dense enough to capture the peak intensities and the variability of the heavy rainfall events. It is therefore relevant to investigate whether radar data provides more information on the spatial and temporal structure of heavy rainfall compared to distributed point measurements from gauges. Quality controlled and corrected radar rainfall series now extend 10 years in Denmark, which makes it possible to perform reliable spatial statistics and to study local variability of rainfall.

Thorndahl et al. (2014b) have developed a high resolution radar rainfall dataset with data from 2002 to 2012 based on the Stevns radar operated by the Danish Meteorological Institute. It covers an area of ~31400 km² of the greater Copenhagen area and the island of Sealand in Denmark as well as parts of south-western Sweden. The spatial resolution of the dataset is 500x500 m². The temporal resolution of the original dataset is 10 min, but the developed dataset has been regenerated by using the advection interpolated method by Nielsen et al. (2014) to 1 min resolution. Data is quality controlled and mean field bias adjusted against up to 67 rain gauges.

Using different criteria for accumulated rainfall and maximum rainfall intensity for different durations we rank the “heaviest” days (00-00 UTC) from the dataset. For this study 50 days are characterised as heavy events. From the derived heavy events we analyse: The storm path and speed; lifetime of storms; size of rainfall area with intensities larger than specified thresholds; maximum daily accumulations; maximum intensities for different durations; diurnal variability, etc.

These analyses are inspired by Thorndahl et al. (2014a) who performed similar analyses on a dataset from Wisconsin, USA.

We use the parameters above to develop composite rainfall statistics of the heavy events in order to be able to identify potential spatial heterogeneity in number of events as well as rainfall intensities and accumulations; characteristic time and length scales, and other features which can be used to describe similarity or discrepancy between events. Preliminary results suggest that the greater Copenhagen area in fact has been impacted by more heavy events, and that the events have been more severe, compared to surrounding rural areas. Whether this is due to orographic
effects, anthropogenic forcing effects or other hydrometeorological effects is so far an unanswered question. Fig 1 shows accumulated rainfall from the heaviest recorded event in Copenhagen on 2 July 2011.

Fig 1: Accumulated radar and rain gauge rainfall in the greater Copenhagen area 2 July 2011.

References

How to benefit from radar data in water management – Experiences in the Emscher and Lippe region

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Abstract

The tasks of water management are manifold and cover a wide spatial and temporal range. Accordingly, the requirements on the usage of radar precipitation data in terms of quality, spatial and temporal resolution as well as coverage also vary greatly. This article focuses on the practical applications of radar precipitation data from the point of view of a water management association in North-Rhine Westphalia. Emschergenossenschaft (EG) and Lippeverband (LV) are responsible for the river basin management in the Emscher and lower Lippe catchments and therefore operate a great number of water management plants. In addition to a network of precipitation gauges, the usage of radar precipitation data from three different radar sites is meanwhile standard. Divided in real-time and offline applications as well as quality improved and original data, an overview of different radar products and their appropriate use cases will be given in this contribution. The advantages and also the limits of radar precipitation data application are presented.

1. Introduction

The knowledge of place, time and amount of a precipitation event is of great importance in water management. Up to present rain gauge measurements commonly provide the precipitation information for hydrologic analysis and planning. The advantages of the direct measurement method consist of an accurate precipitation estimation and a continuous recording of events. What is more, the temporal data availability comprises long term time series, allowing statistical analysis. In contrast the precipitation quantity is based on a collecting area of 200 cm² and limited to the measuring site. As a consequence the regionalization of the point precipitation is one major source of error for applications in water management. In comparison radar measurements provide the possibility of an area wide detection of precipitation (VDI, 2014). In addition to a dense network of precipitation gauges the usage of radar precipitation data from the three radar sites Essen, Neuheilenbach and Flechtdorf, operated by the German National Weather Service (DWD), has been established by EG/LV. In different projects and cooperations the application of these data has been developed since the year 2007. Showing some examples from the daily practice in water management, the benefits and experiences of using radar data are presented in the following text. An overview of the applied radar products and their typical applications is given in table 1.

Table 1: Applied radar products and their context of usage.

<table>
<thead>
<tr>
<th>product</th>
<th>resolution temporal</th>
<th>resolution spatial</th>
<th>on-line</th>
<th>off-line</th>
<th>usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>DX (DWD)</td>
<td>5-min</td>
<td>1km * 1°</td>
<td>x</td>
<td></td>
<td>visualization, modelling</td>
</tr>
<tr>
<td>DX-Offline (EG)</td>
<td>5-min</td>
<td>1km * 1°</td>
<td>x</td>
<td></td>
<td>visualization, modelling, statistics, climatology</td>
</tr>
<tr>
<td>DX-attenuation corrected</td>
<td>5-min</td>
<td>1km * 1 km</td>
<td>x</td>
<td></td>
<td>visualization, modelling</td>
</tr>
<tr>
<td>RY (DWD)</td>
<td>5-min</td>
<td>1km * 1km</td>
<td>x</td>
<td></td>
<td>Visualization, modelling</td>
</tr>
<tr>
<td>RW (DWD)</td>
<td>60-min</td>
<td>1km</td>
<td>x</td>
<td></td>
<td>Visualization, modelling</td>
</tr>
<tr>
<td>PG (DWD)</td>
<td>15-Min</td>
<td>1km * 1 km</td>
<td>x</td>
<td></td>
<td>Visualization, modelling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2km * 2km</td>
<td>x</td>
<td></td>
<td>Visualization (National Picture Germany)</td>
</tr>
</tbody>
</table>

2. Online Application – Flood Early Warning System

The most common qualitative application of radar data is the real-time display of the precipitation area, providing a general overview of the current situation. However, for the assessment of the current hydrologic situation and the risk of flooding, a quantitative precipitation estimation using radar data is necessary. As precipitation is the most sensitive input variable in water management, the relevant target for the design and operation of water management systems is the runoff resulting from precipitation and catchment characteristics. Consequently for the usage of Radar precipitation data in flood management, a binding with runoff precipitation models must be realized.

What is more, the application of radar data should be adapted to the hydrologic characteristics of the catchments and to the quality of the radar products. In the Emscher catchment, large industrial areas, a high population density, extensive ground settlements as a consequence of mining activities and the short concentration time of flood discharges present major challenges especially for the flood protection (Pfister et al., 2015). As a consequence, real time radar products with a high spatial, temporal and quantitative resolution are necessary. In this case the short-term availability is more important than an adjustment or correction of the radar data. In the more agricultural Lippe Catchment, a provision interval and a temporal resolution of 1 hour is sufficient, making the use of corrected and adjusted radar products possible. Basis of the radar data usage of EG/LV is the Flood Early Warning System (FEWS), which provides a platform for the integration, display and analysis of various data from different sources, combining them with hydrologic modelling (Figure 1, Treis, 2014).

During critical flood situations, radar data play a crucial role in the assessment of the actual precipitation (Krämer et al., 2012). In combination with nowcasting and meteorological forecast data it supplies real time information, making an estimation of the further development of the situation possible. Based on this information, an online status report of the current weather and flood situation is generated and published in the Intranet of EG/LV. The report is updated daily, if required several times a day. In addition to this daily report, an alert and warning system for construction sites along the rivers has been established to inform the operational department automatically in case of critical situations (Figure 2). In contrast, this system can also be used to inform in times of
dry weather conditions for the planning of specific dry weather measurement programs or operational tasks.

Fig 2: Assessment of the actual hydrologic situation and information of the operational department by the hydrologist on duty and via automated SMS-warning.

Figure 3 shows the advantages of combining radar data with hydrologic models in the catchment of the flood retention basin Borbecker Mühlenbach. Especially for convective precipitation events, the estimation of flood peaks using the actual areal precipitation from radar measurement could lead to much better results. For the storm event from the 23rd of July 2013, the comparison between different precipitation data and the resulting model runoff shows the quality improvement using radar data. Especially corrected (RY-product) and adjusted radar data (RW-product) lead to much better simulation results.

Fig 3: Retention basin Borbecker Mühlenbach: Comparison of 48h-precipitation sums with simulated discharges using different precipitation input data. Event from the 23rd of July 2013.
3. Offline Applications – Post processing of flood events

With a large number of heavy precipitation events in recent years, the demand of a post processing of flood events has increased steadily. This analysis is not only done for internal purposes, additionally EG und LV also support their members (municipality, industry, …) with prepared radar information, created by offline applications. Even with a dense network of rain gauges, there is always the chance of missing the center of convection cells. Using the example of a storm rainfall event from the 28th of April 2011, that caused serious damages by flooding, figure 4 illustrates the immediate benefit from the usage of radar precipitation. As the comparison of the hourly precipitation sum of the nearest rain gauge (7 mm) with the adjusted radar precipitation (37.5 mm) shows, the maximum precipitation is located in a small region with an extent of only 4 km². In the discussion with the affected citizens, the quantitative and qualitative analysis based on the radar data can help to illustrate the dimension of the storm event. Assuming that the radar precipitation sum of 37.5 mm was measured at the rain gauge, the event shows the second highest 1-hour precipitation sum ever measured and is close to the return period of once in a hundred of years.

![Hourly precipitation sums from single point measurement (left) and radar data in Bottrop. Event from the 28th of April 2011.](image)

Based on these positive experiences, EG and LV have decided to develop an event-based, automated approach for a GIS-supported visualization and quantitative representation of radar data using Python-Scripting. The advantages are fast processing times, a standardized analysis procedure and the connection with variable GIS-layers. For an estimation of a statistical classification, a comparison with rain gauge statistics is possible. As an example, figure 5 shows the maximum three hour precipitation sum for the storm event from July, 12th 2014 in the catchment of the flood retention basin Schmechtingsbach. The assessment of the return period is based on the precipitation statistics of the rain gauge Dortmund Oespeler Bach. This comparison can help to illustrate the magnitude of the precipitation event to affected citizens.
Fig 5: Maximum 3-h Sum of precipitation [mm] and return period in comparison of the rain gauge Oespeler Bach in the catchment of the retention basin Schmechtingsbach. – Event from July, 12th, 2014, 7:55 p.a. to 00:50 a.m. (MEST).

4. Conclusions

The usage of radar precipitation data is meanwhile daily practice for EG and LV and the demand of these data is increasing steadily. The positive experiences shown in this article encourage EG and LV to further intensify the usage of radar precipitation data and to cooperate with partners like the DWD or other water boards in the development of useful applications for water management tasks.

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The June 2013 and August 2002 flood events in Central and Eastern Europe: how much worse can it get?

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Abstract

Large-scale floods are of growing concern due to their impacts on the societies and economies of the affected regions, while there are worries that their intensity, frequency and duration will be increased. Two major events took place in Central and Eastern Europe hitting the Elbe and Danube basins in just 12 years; the floods of August 2002 and June 2013. They caused in total 64 fatalities, whereas the total direct economic losses were 29 billion USD as summarized on Table 1 (Munich Re, 2013).

Both events were caused by synoptic developments, classified as “Vb” tracks, which can trigger widespread flooding across Central Europe (Nissen et al., 2013). Typically, Vb events are depressions which bring large amounts of moisture from the Mediterranean Sea and then they collide with cold air coming from the North, northside of the Alps. The low usually moves away and does not trigger floods, however in these events it remained stationary at its peak and precipitation was intensified even further as the airflow was forced over the Northern Alpine Ridge (van der Schrier et al., 2013). This kind of depressions allow cyclonic circulation advecting Mediterranean moisture leading to extreme precipitation amounts.

Table 1: Fatalities, Economic and Insured Losses caused by the floods of August 2002 and June 2013 (Munich Re, 2013).

<table>
<thead>
<tr>
<th>Month</th>
<th>Affected countries</th>
<th>Economic Losses (USD m)</th>
<th>Insured Losses (USD m)</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>August 2002</td>
<td>DE, AT, CZ, HU, CH, SK, MD</td>
<td>16500</td>
<td>3400</td>
<td>39</td>
</tr>
<tr>
<td>June 2013</td>
<td>DE, AT, CZ, HU, CH, SK, MD, PL</td>
<td>12600</td>
<td>3100</td>
<td>25</td>
</tr>
</tbody>
</table>

The events of 2002 and 2013 were triggered by heavy rainfall of similar pattern, however there are some important differences between the two events. In 2002, precipitation concentrated in 48 hours, whereas in 2013 the rainfall event was more prolonged and similar amounts occurred over 4 days. The latter event may not have had so intense precipitation, but it had wet antecedent conditions, thus the soil moisture was particularly high in most of the catchments of Danube and Elbe when the event began. The low soil storage left along with the low temperatures, which consequently led to snowfall, part of which melted, resulted in small flood responses (Blöschl et al., 2013).

Yet, a combination of the characteristics of these two events could result in a “perfect storm” that could, potentially, cause unparalleled damages. In this study, we mix the hydrometeorological forcings (e.g. temperature, radiation, surface pressure) that preceded the floods of June 2013 with the precipitation pattern of 2002 to estimate the impact of an extreme, but not unrealistic, scenario. Such a scenario could cause peak discharges of more than 50% higher than the ones recorded at the two events, and subsequently lead to higher flood depths and more extended flooding areas, which can locally be even 3 times larger than the 2002 flood extent as depicted at Figure 1.
The main conclusion of this analysis is that precipitation and antecedent conditions can be equally important in generating floods and when the worst combination occurs it can result in high financial losses, while there is a high risk for many fatalities. The relationships between precipitation, streamflow and economic losses are strongly non-linear, as a result our analysis indicates that losses can be 4 times higher than August 2002, which has been the most extreme flood event in Europe the last decades. Given that Central and Easter Europe is prone to flooding area, this scenario also underlines the importance of flood protection measures in order to reduce vulnerability.

Fig 1: Floodmaps at Riesa (Elbe) as modelled for (left) the event of August 2002, and (right) the event combining the precipitation of August 2002 with the antecedent conditions of June 2013.

References


Munich Re. (2013), NatCatSERVICE Database.

Generation of high-temporal resolution QPEs through temporal interpolation of radar images: evaluation over multiple spatial-scales

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Abstract

Radar quantitative precipitation estimates (QPEs) are playing an increasingly important role in urban hydrology due to their better description of the spatial and temporal characteristics of rainfall. However, the operational radar QPE products provided by national weather services (typically at 1 km / 5-10 min resolution) still fail to meet the stringent resolution requirements of urban hydrological applications. While the spatial and temporal resolution of rainfall inputs are strongly related, recent studies suggest that the latter generally constitutes a more critical factor and that temporal resolutions of ~1-2 min are required for urban hydrological applications, while spatial resolutions of ~1 km appear to be sufficient (Ochoa-Rodríguez et al., 2015).

Traditional strategies for obtaining higher temporal-resolution radar QPEs include changes in radar scanning strategies and stochastic downscaling. However, the former is not always possible, due to hardware limitations, and the latter results in impractical large ensembles. In this work, an advection-based temporal interpolation method, based upon the multi-scale variational optical flow technique, is proposed to generate high temporal-resolution radar QPEs (Brox et al., 2004; Wang et al., 2015). The proposed method was used to generate radar QPEs at 1-min temporal resolutions from UK Met Office C-band radar QPEs originally at 5-min temporal resolution and varying spatial resolutions of 1 km, 500 m and 100 m (the former two are generated with C-band radar operating in ‘long-pulse’ mode, whereas the latter is generated with ‘short-pulse’ mode).

Fig 1: Snapshot images of the observed (images with red borders) and the temporally-interpolated radar rainfall fields across multiple spatial scales (from top to bottom: 1 km, 500 m and 100 m) during the peak intensity period of the event on 19th September 2014.
The performance of the temporally-interpolated radar QPEs, across a range of spatial resolutions, was assessed through comparison against local rain gauge records and through hydrological verification using as case study 3 storm events observed in a small urban catchment (~865 ha) in London for which dense rain gauge and sewer flow records, as well as a recently-calibrated high-resolution urban drainage model were available. Fig 1 shows the snapshot images of the observed and the interpolated radar images at different spatial resolutions (from top to bottom: 1 km, 500 m and 100 m) during the peak period of an event on 19th Sep 2014. As can be seen, the impact and added value of temporal interpolation is in particular evident for the radar images at higher spatial resolution. This is also confirmed by the comparison with local rain gauge records (Fig 2). Preliminary hydraulic results (which are not shown here) suggest that the temporally-interpolated rainfall estimates can better reproduce the small-scale dynamics of the storm events, leading to improved reproduction of urban runoff.

![Cranbrook-E15: Rainfall intensity at BHS](image)

**Fig 2:** Comparison of rain gauge records (dark solid and dashed lines) against coincidental radar rainfall estimates at different spatial (1 km: blue lines, 500 m: green lines, 100m: orange lines) and temporal (5 min and 1 min) resolutions for the 19th September 2014 event.

**References**


Estimation of the point-to-area rainfall correction factors in the context of climate change

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Abstract

The main objective of the present paper is to propose a methodology for constructing the point-to-area rainfall relations in the context of climate change. In particular, a comparative study was carried out to assess the accuracy and reliability of the proposed method as compared to other existing methods using observed daily rainfall data from raingages and climate simulations from the Canadian Regional Climate Model (CRCM) and General Circulation Models (GCMs) for the southern Quebec and southern Alberta regions in Canada with different climatic conditions. The popular SDSM statistical downscaling method, the quantile-mapping, and the bias correction method were used to describe the linkage between large-scale climate variables given by the considered CRCM and GCMs and local rainfall characteristics. Results of this illustrative application have indicated that the use of downscaling methods could provide the most accurate point-to-area rainfall relations as compared to the observed empirical ones, while the results given by the GCMs without downscaling and the CRCM were not accurate and displayed a very high level of uncertainty for both regions.

1. Introduction

For hydraulic structure design purposes, precipitation at a given site or over an area for a specified duration and return period is commonly used in the estimation of floods. The use of design precipitation to estimate floods is particularly valuable in those situations where flood records are not available or not long enough at the site of interest, or they are not homogeneous due to changes of watershed characteristics (e.g., urbanization). In particular, for large drainage basins, especially with basin areas exceeding about 25 km², a catchment average design rainfall is often required for design flood estimation since rainfall observations at a single station, even if it is at the centre of the catchment area, will usually be inadequate. In such cases, all rainfall records within the catchment and its immediate surroundings must be analyzed to take proper account of the spatial and temporal variations of rainfall over the basin. More specifically, for the areas which are large enough to depart appreciably from the average rainfall depth, it has been found beneficial to convert point values to areal values. Frequency values for area-averaged precipitation are generally obtained using the point-to-area rainfall relations or by applying an Areal Correction Factor (ACF) to point precipitation values (Nguyen et al., 1981).

These relations or the ACF estimates depend on the raingage network density, and, consequently, on the accuracy of estimating the mean precipitation over an area (Svensson and Jones, 2010). The point-to-area relations and ACFs depend on local climatological conditions and, therefore, whenever possible should be derived from the local data. Furthermore, the ACF estimation has traditionally been based on statistical analysis of historical records, assuming that the intensity and frequency of past events are statistically representative of what could happen in the near future (Mailhot et al., 2007). However, in the context of climate change, this hypothesis must be revised to take into consideration the expected changes in the intensity and frequency of heavy rainfall events. General Circulation Models (GCMs) and Regional Climate Models (RCMs) have been recognized to be able to represent reasonably well the main features of the distribution of basic climate parameters at global and regional scales, but outputs from these models are often characterized by coarse resolutions that limit their direct application for many impact studies. Hence, statisti-
Downscaling methods have been used for describing the linkage between the large-scale climate variables given by GCMs or RCMs to the observed rainfall characteristics at a local site (Nguyen et al., 2006).

In view of the above-mentioned issues, the main objective of the present paper is to propose a method for estimating the ACF within the framework of a changing climate. In addition, a comparative study was carried out to assess the accuracy and uncertainty of various methods for constructing the point-to-area rainfall relations using observed raingage data, NCEP re-analysis data, data from the Canadian RCM (CRCM) as well as from different GCMs. It was found that the use of the statistical downscaling method could provide accurate point-to-area rainfall relations as compared to the observed empirical ones, while without downscaling the relations given by the GCMs and the CRCM showed a high inaccuracy and a high level of uncertainty.

2. Methodology

In practice, engineers have been thwarted in attempting to relate an expected mean rainfall over a jurisdiction to a historical record at a first-order weather station. This is because prior research, as mentioned above, has been confined to spatial properties of moving storms rather than to catchments and reference raingages fixed in space. That is, attention has been focused on either a moving area coupled with a moving storm center or a fixed area and a moving reference point (Hershfield, 1962). With the moving reference point being the peak portion of the storm rainfall at each particular time interval, it follows that areal mean rainfall so evaluated will always be an attenuation of the moving reference point rainfall. Hence, for practical application purposes, it is necessary to develop the relationship between the mean rainfall over a fixed area and the associated rainfall for a fixed point in that area. More specifically, the present study will deal with the following problem (Nguyen et al., 1981): “Given the point rainfall for a certain level of probability at a geographically fixed location on a fixed surface, what is the mean rainfall over the surface for the same level of probability?” The proposed method for solving this problem consists therefore of deriving the frequency curves for both point and areal mean rainfalls. Then, the ACFs will be computed for the same level of exceedance probability as illustrated in Figure 1. In addition, in the present study the frequency curves for point and areal mean rainfalls can be developed in consideration of climate change using some popular statistical downscaling methods.

Fig 1: Estimation of Areal Correction Factor (ACF).

Downscaling procedures attempt to resolve the scale discrepancy between large scale climate change scenarios and the resolution required for hydraulic structure design and other impact assessment studies at a given local site. These downscaling methods are based on the assumption that large-scale weather exhibits a strong influence on local-scale weather conditions. In general, there are two broad downscaling methods: dynamical downscaling and statistical downscaling (Nguyen et al., 2006). Dynamic downscaling methods or Regional Climate Models (RCM) are based on physical dynamics between synoptic variables (as predictors) and local-scale variables (as predictands) and it uses GCM variables to define time-varying atmospheric boundary conditions around a finite domain, while the statistical downscaling methods rely on the empirical rela-
tionship between regional scale predictors and local scale predictands (Wilby and Dawson, 2007). Each of these downscaling methods has their own strengths and weaknesses that have been summarized in several review papers (Maraun et al., 2010). In the present study, the popular SDSM regression-based statistical downscaling method (Wilby et al., 2002), the quantile-mapping (Dobler and Ahrens, 2008), and the bias correction method (Widmann et al., 2003) were used to describe the linkage between large-scale climate variables given by the considered GCMs and local rainfall characteristics.

3. Numerical Application

As mentioned above, two study areas with different climate and topography features have been selected to evaluate the feasibility of the proposed methods: the Montreal region located in southern Quebec province and the Calgary region in southern Alberta province in Canada. For this study, daily rainfall data for the 1961-1990 period from different sources were used: the observed daily rainfall data from a network of 42 raingages in Montreal and 47 raingages in Calgary, the NCEP re-analysis data, the CRCM simulation data, and the outputs from the Canadian GCM (CGCM3), Germany Max Planck Institute for Meteorology GCM (ECHAM5), and UK Hadley Centre GCM (HadCM3).

Tables 1 and 2 show the estimates of the ACF as the ratio of the mean areal rainfall to the reference point rainfall having the same frequency for 2-, 5-, 10-, 25-, and 50-year return periods for Montreal and Calgary region respectively. There is a high variation in ACF values with return periods and smaller ACF values are associated with high return periods (i.e., for large rainfalls). In addition, the estimated values of ACFs for Calgary region have a higher variation while the estimated ACFs for Montreal has a smaller variation.

Table 1: Observed and estimated ACFs for different methods and return periods for Montreal.
Table 2: Observed and estimated ACFs for different methods and return periods for Calgary.

<table>
<thead>
<tr>
<th>Return Period (years)</th>
<th>Area (km$^2$)</th>
<th>ECHAM5</th>
<th>CGCM</th>
<th>Obs.</th>
<th>QM</th>
<th>SDSM</th>
<th>HadCM3</th>
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Figure 2 shows the comparison between observed and estimated values of ACFs for different climate models and downscaling methods. Results shown in Tables 1 and 2 and by Figure 2 have indicated that the computed ACFs given by the statistical downscaling methods (SDSM and Quantile Mapping) were the most accurate as compared to the empirical (observed) values, while the ACFs given by the CRCM dynamic downscaling, and the CGCM3, ECHAM5 and HadCM3 without downscaling were not accurate and displayed a high level of uncertainty.

4. Summary and Conclusions

An approach has been proposed in the present study for constructing the point-to-area rainfall relations within the framework of a changing climate. The proposed method relies on the use of statistical downscaling methods to describe the linkage between large-scale daily climate variables to annual maximum daily precipitations at a given location and over a given area. The feasibility and reliability of the suggested procedure have been assessed on the basis of available raingage data, NCEP reanalysis data, and climate simulation outputs from CRCM, CGCM3, ECHAM5 and HadCM3 for southern Quebec and southern Alberta regions with distinct climatic conditions. Results of this numerical application have indicated that it is feasible to link daily large-scale climate variables to annual maximum daily precipitations at a given location and over areas of different sizes. Furthermore, it was found that the computed ACFs given by the statistical downscaling methods (SDSM and the QM) are more accurate than those values given by the dynamic downscaling (CRCM), and the CGCM3, ECHAM5 and HadCM3 without downscaling.
Fig 2: Comparison between observed and estimated ACFs: Observed (black solid); SDSM (black dotted); CGCM (black dashed); ECHAM5 (gray solid); CRCM (gray dashed); bias correction (gray dotted), and HadCM3 (gray dashed dotted) for (a) 2-year; (b) 5-year; (c) 10-year; (d) 25-year, and (e) 50-year return periods for Montreal study area, and (f) 2-year; (g) 10-year; (h) 25-year, and (i) 50-year return periods for Calgary study area.

References


Retrieval of rainfall fields in urban areas using attenuation measurements from commercial microwave links: a feasibility study

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Abstract

The accurate rainfall measurement is a major challenge for urban hydrological applications such as flood warning, water resource and sewer management systems. These systems operate at relatively small scales; therefore, rainfall measurements at high spatial and temporal resolutions are needed. Many cities are not equipped with rain gauge networks or surveyed by weather radar. A few years ago, the commercial microwave links employed by cellular communication networks was proposed as a new way of estimating space-time rainfall (Messer et al., 2006). The idea behind the approach is based on the fact that the measurements of signal attenuation caused by rain alongside the microwave links can be used for estimating rainfall fields. Since many cities worldwide are well-equipped with commercial microwave links, they could provide an alternative and integrative solution to monitor space-time rainfall in location where estimates based on traditional techniques are neither available nor satisfactory (Doumounia et al., 2014).

The objective of this study is to assess the feasibility of mapping rainfall fields in urban areas using attenuation measurements from microwave links used for cellular networks. In particular, we focus on the development of a new rainfall retrieval method within the framework of inverse problem. The study region covers ~1368 km² area of Nantes, France which consists of 256 microwave links operating at 18, 23 and 38 GHz. We use 15 rainfall events consisting of more than two hundred rainfall fields at high spatial (250m x 250m) and temporal (5 minutes) resolutions provided by Météo-France C band weather radar located about 10 km north of the center of Nantes. These rainfall maps will be used to generate attenuation measurements and considered as reference rainfall fields.

We conduct a simulation experiment which consists of two parts, namely generation of rain attenuation data and retrieval of rainfall maps. The purpose of the first part is to generate attenuation data that can be substituted for the signal power received from real microwave links. We simulate the measurement of the total attenuation using well-known k-R power law which relates the rain intensity to the specific attenuation with the assumption that a drop size distribution is known. This procedure is applied for 256 real radio links in the study domain. Error sources affecting measurement accuracy are introduced as a zero-mean Gaussian distributed random variable with variance of total attenuation. Then, the generated signal attenuation is quantized at 0.1 dB resolution in order to reflect the effects of a hardware equipment of microwave link antennas. In the second part, the objective is to retrieve rainfall using a nonlinear inverse model (Tarantola and Valette, 1982). An a priori knowledge used to initialize the algorithm heavily influences the model outcome if the problem to be solved is under-determined which seems to be the case in our study. The retrieval method is performed at 3 interdependent steps. Step 1, the study domain is divided into square grids at 2x2, 1x1 and 0.5x0.5 km² resolutions. Step 2, the algorithm starts the retrieval at 2x2 km² with the a priori rain derived from the attenuation values of the links applying the k-R relation. Subsequently, the algorithm finds a solution at 1x1 and 0.5x0.5 km² with the a priori values obtained from the previous solution at 2x2 and 1x1 km², respectively. Step 3, retrieved rainfall values at all resolutions are combined to refine the regions that are not crossed by the link. The advantage of
such subsequent steps is self-evident since the network density decreases from the city center to the suburbs.

We carry out more than 200 rainfall retrieval tests light rain, shower, unorganized and organized storm events which considerably differ from each other in spatial and temporal variability structure. As an example, a comparison of estimated rainfall map with observed map by weather radar at 1x1 km² resolution is given in Fig 1a. This simulation experiment is performed in the presence of measurement, model and quantization errors of which magnitude are parameters. The example is based on the chosen model parameters (the choice of a priori knowledge, decorrelation distance) which have been defined in the sensitivity analysis test. The retrieval efficiency of the monitoring system depending on the network topology is also performed as follows. We divide the study domain into 4 different zones, namely high, moderate, low and whole density regions. This evaluation of the retrieval efficiency is based on the quality map (Fig. 1c) which represents the density level of the network. Fig. 1b demonstrates such evaluation process in storm event (organized and unorganized types) during 365-h period. Achieved results will certainly lead to further works in order to validate the proposed approach using a large set of rainfall data and include analysis of network topologies in other cities worldwide.

Fig 1: a) Comparison between observed and estimated rainfall map at 1x1 km² resolution in storm event; b) The retrieval efficiency at 1x1 km² resolution for 4 different zones of the study domain (high, moderate low and whole density) in storm event during 365-h period; c) Quality map at 2x2 km² resolution. Note that the colors in fig 1b and fig. 1c are interdependent. The standard deviation of the measurement, model and quantization errors is 5%, 5% and 0.1 dB, respectively.

References


Tomographic reconstruction of rainfall maps using attenuation data from cellular networks: the first results based on the Mojette Transform

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Abstract

The real time monitoring of rainfall over urban areas is a critical issue for hydrological applications such as flood warning and water resource systems. Despite the fact that traditional techniques such as networks of rain gauges and weather radars are used to measure rainfall many cities worldwide are not well equipped with these devices. However, they are generally equipped with mobile telecommunication networks. Mobile networks use atmospheric Hyper-Frequency (HF) links whose transmitted signal power is attenuated by rainfall. Measuring that signal attenuation along each link could allow the measurement of path-averaged rainfall. As HF links are concentrated in cities, these networks could constitute a self-sufficient approach to monitoring rainfall.

We propose a simulation approach in order to evaluate the feasibility of reconstruction of rainfall maps by means of tomographic processing applied to attenuation measurements from HF links. A discrete tomographic algorithm based on the Mojette Transform (MT) is applied to reconstruct 2D rainfall map. Before applying the algorithm, specific adjustment procedures, which take into account the geometry of the network topology and non-uniform distribution of links frequency and lengths, are performed. The study domain is the city of Nantes (France) where the density of HF links is greatest. A series of rainfall fields recorded at high spatial (250m x 250m) and temporal (5 minute) resolutions are used to simulate the attenuation data and are considered as reference rainfall fields. These maps are obtained from C-band weather radar located about 10 km north of the center of Nantes (France) and are considered as reference rainfall fields.

We carry out more than 100 reconstruction tests in light rain, shower and storm events to compare the reconstructed rainfall fields to reference ones. Initially obtained results are a subject to further works: (i) improvement on the adjustment procedures of the tomographic reconstruction algorithm, (ii) Implementation of the method in the presence of the error sources.

1. Introduction

The real time monitoring of rainfall is an important issue for urban hydrological applications such as flood warning and water resource management systems. Even though, rain gauges and weather radars are widely used for rainfall measurement, most urban areas worldwide lack such devices. Instead, they are equipped with cellular communication networks. These networks make use of atmospheric Hyper-Frequency (HF) links whose transmitted signal is attenuated by rainfall. The signal attenuation measured along the multiple HF links can be used to retrieve rainfall fields. The retrieval principle is based on the conversion of 1D attenuation vector into 2D rainfall map using well known k-R empirical relation (Olsen, et al., 1978). However, such procedure cannot be directly performed since it is not straightforward and requires a specific inversion technique. The use of tomographic reconstruction algorithms, in this context, is an original approach proposed by (Giuli, et al., 1991) about two decades ago. In the same line of this study, taking advantages of a large number of HF links (Cuccoli, et al., 2011) and (Zinevich, et al., 2008) also applied adaptive
tomographic reconstruction algorithms which process signal attenuation measured along the HF links to retrieve rainfall fields. However, the challenges in the tomographic approach have not been completely explored yet. Therefore, following the same direction as previously cited studies, we evaluate the feasibility of rainfall retrieval using a discrete tomographic technique, which uses the Mojette Filtered Back projection (Guédon & Normand, 2005), applied to attenuation data from HF links in a simulation framework. Section 2 presents how the signal attenuation caused by rain is simulated and the tomographic algorithm used to reconstruct rainfall maps based on the simulated attenuation data. A brief description of the study area and data are given in section 3. The results are detailed in section 4, and conclusion and further works are presented in section 5.

2. Methods

To formulate the problem, the power law model is adopted to relate a signal attenuation to a rain intensity as follows (Olsen, et al., 1978):

\[ A = L \ast aR^b \]  

(1)

Where, \( A \) – total signal attenuation, dB; \( L \) – link length, km; \( R \) – rain intensity along the link, mm/hour; \( a \) and \( b \) – power law coefficient which is a function of frequency, polarization, temperature and drop size distribution. In Figure 1b, the network area is represented by \( n \) square grids in 2D space (Zinevich, et al., 2008). A rain rate value \( R_j \) in the \( j \)th pixel is assumed to be constant. Each HF link connects two locations at a distance \( l_i \). We assume that the microwave signal is a straight line travelling through the network area and intersected at a length \( l_{ij} \) in the \( j \)th pixel:

\[ A_i = a_i \sum_{j=1}^{n} l_{ij} R_j^b + \varepsilon_i, i = 1...m \]  

(2)

Where, \( n \) - number of pixels crossed by the links; \( R_j \) – the rain rate in \( j \)th pixel, [mm/hour]; \( l_{ij} \) - the length of the crossed part of the \( i \)th link in \( j \)th pixel, [km]; \( a_i \) and \( b_i \) – the power law coefficients at the \( i \)th link frequency and \( \varepsilon_i \) – measurement error (Atlas & Ulbrich, 1977). As a starting point, we assume that the power law relation is linear and attenuation along the HF link is not influenced by the measurement error. The exponents of power law relations at all frequencies are assumed to be homogenous and linear, that \( b_i \) is equal to 1. Then, the eq.(2) will take the following form for \( m \) number of links:

\[ \begin{bmatrix} A_1 \\ \vdots \\ A_m \end{bmatrix} = \begin{bmatrix} a_1l_{11} & \cdots & a_1l_{1n} \\ \vdots & \ddots & \vdots \\ a_ml_{m1} & \cdots & a_ml_{mn} \end{bmatrix} \begin{bmatrix} R_1 \\ \vdots \\ R_n \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \vdots \\ \varepsilon_m \end{bmatrix} \]  

(3)

As a starting point, a total attenuation along the HF link was simulated using eq.(3) in the absence of \( \varepsilon_i \). The procedure is applied to 256 real HF links operating at 18, 23 and 38 GHz. The power law coefficients \( a, b \) are obtained from (ITU-R, 2005).

Tomographic reconstruction algorithm

The objective is to reconstruct rainfall map values \( R_1, R_2, ... , R_n \) using attenuation data \( A_1, A_2, ... , A_m \) see eq.(3). The tomographic reconstruction algorithm used to solve the problem is based on the principles of the Mojette Transform (MT) developed by Guédon et al. The MT is a discrete version of Radon Transform. It uses simple linear operations such as addition, subtraction to reconstruct any image from a number of projections \( (p_i, q_i) \). A projection value (called a "bin" as in tomography) on a projection \( (p, q) \) is the sum of pixels value centered on the line as shown in Figure 1:
\[ M_r(b, p_i, q_i) = \text{proj}_{p_i,q_i}(b) = \sum_{i=0}^{M-1} \sum_{l=0}^{N-1} R(k, l) \Delta (b + q_i * k + p_i * l) \]  \hfill (4)

Where, \( R(k, l) \) – a pixel value in \((k, l)\) indices of MxN image; \((p_i, q_i)\) - a set of projection direction defined by Farey-Haros series (Servières, et al., 2005); \( b \) – a projection value;

Let us consider an example of a 3x3 image in which pixels represent rainfall rate \( R_1 \ldots R_9 \), see Figure 1a. The transform domain for the image consists of two projections, namely \( p_1, q_1 = (1,0) \), \( p_2, q_2 = (1,1) \). The way of taking projection from the sample image is shown for those two projection directions. Along each projection, bin values are computed by summing up the pixel values in the image. Unlike other tomographic algorithms, the MT has an exceptional property that a number of bins \( B(i) \) in each projection depend on the chosen angle \( \theta = \tan \left( \frac{q_i}{p_i} \right) \):

\[ B(i) = (M - 1)|p_i| (N - 1)q_i + 1 \]  \hfill (5)

The Mojette Filtered Back Projection algorithm is applied to reconstruct the rainfall map. However, the algorithm is not directly applicable due to (i) the arbitrary geometry of the network topology, (ii) non-uniform distribution of links frequency and lengths. Therefore, we do specific adjustment procedures before applying the algorithm. In total, the reconstruction process consists of 4 steps including the adjustments:

**Step 1. Grids selection:** The objective is to select valid grids for Mojette projection (acquisition) in the network area. Only zones totally crossed by the HF link are chosen to be reconstructed. We divide the reconstructed zone into sub-grid so that each zone can be reconstructed independently with respect to the attenuation measured through it. In Figure 1b, this is depicted as black rectangles with different area sizes over the study region. In this preliminary study these regions are selected visually.

**Step 2. Projections direction matching:** A set of projections \( M_{p,q} \) with discrete Mojette directions are found for the MT acquisition in each grid. We choose discrete \((p, q)\) projections directions fitting the best HF link directions and minimizing the number of bins. These possible directions depend on the reconstructed region size. However, only very few bins onto each projection are filled;

**Step 3. Interpolation:** An angular interpolation technique proposed by (Servières, et al., 2006) is applied to fill empty bins in each projection based on nearby values. The interpolation is performed in all selected grids of the network area;

Fig 1: a) An example of Mojette projection at two angles: \((p_1, q_1) = (1,0), (p_2, q_2) = (1,1)\); b) Microwave links at 18, 23 and 38 GHz in Nantes city. Black rectangles in different sizes illustrate the selected grids for projection and reconstruction of attenuation data.
Step 4. Back Projection: Mojette Filtered Back Projection algorithm (Guédon & Normand, 2005) is used to reconstruct the attenuation map from the projection values. These 4 steps are performed in all selected grids of the network. Reconstructed images are assembled, and then normalized with the maximum attenuation value. In the end, the reconstructed map represents a specific attenuation field that could be converted to rainfall map.

Evaluation of the system performance

The reconstructed rainfall map is compared with reference rainfall field using root mean square error (RMSE), which represents the standard deviation of the residuals:

\[
RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (R_i - R_i')^2}
\]

Where, \( R_i \) – reconstructed rainfall rate; \( R_i' \) – reference rainfall rate; \( n \) – a length of a rain vector;

3. Data

The study domain is the city of Nantes (France), where the density of HF links is greatest (Figure 1b. We have, at our disposal, hundreds of weather radar images recorded at high spatial (250m x 250m) and temporal (5 minute) resolutions in 7 different periods (Table 1). This C band weather radar of Treillières is located about 10 km north of the center of Nantes. The radar reflectivity images were converted to rain fields with a power law Z-R relation and considered as reference rainfall maps (Emmanuel, et al., 2012).

Table 1. Characteristics of the selected rainfall events.

<table>
<thead>
<tr>
<th>Rain type</th>
<th>Duration</th>
<th>Number of fields</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light rain</td>
<td>9h 25 min</td>
<td>113</td>
</tr>
<tr>
<td>Unorganized storm</td>
<td>2h 50 min</td>
<td>34</td>
</tr>
<tr>
<td>Organized storm</td>
<td>2h 50 min</td>
<td>34</td>
</tr>
<tr>
<td>Shower</td>
<td>2h 10 min</td>
<td>26</td>
</tr>
</tbody>
</table>

4. Results

To evaluate the monitoring system performance, we carry out a series of rainfall retrieval tests for various rain events such as light rain, shower, organized and unorganized storm. Figure 2 shows a comparison between reconstructed and reference rainfall map by weather radar in a storm event in a linear case with the absence of measurement noise.

Fig 2: Comparison between reference and reconstructed rainfall maps at 2x2 km2 resolution in storm.
It is worth noting that the MT algorithm was applied to an inhomogeneous network topology for the first time. One can see that the reconstruction by the MT is generally consistent with reference rainfall. The poor performance of the algorithm is due to the following reasons: (i) the accuracy of the MT algorithm strongly depends on a number of projections which are not sufficient along the HF links. In other words, this is called under-determined problem; (ii) the grids choice was manually selected in this study. However, the algorithm is fast enough due to the fact that it uses very simple addition and subtraction operation to reconstruct a rain field.

5. Conclusions

The objective of this paper was to demonstrate the feasibility of rainfall mapping by means of tomographic reconstruction applied to simulated signal attenuation from HF links. Initially obtained results lead to further works in the reconstruction algorithm development part: improvement on a grid selection in step 1, modifying the way of taking projection in step 2, test of other interpolation methods in step 3. Further, the definition of a priori knowledge about the state of the problem needs to be addressed since the problem to be solved is highly under-determined in tomography context. A sensitivity analysis to the application conditions, associated error sources in both measurement and reconstruction, spatial and temporal rainfall field structure.

References