Spatialization of precipitation data for flood forecasting applied to the Upper Rhone River basin

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Introduction

Alpine regions are particularly exposed to extreme precipitations and the complex topography of these regions increases their vulnerability to floods. In Switzerland, severe flooding events in recent decades have increased the need for reliable forecasting systems to mitigate flood effects. In 1999, the research project MINERVE was initiated with the objective of developing a flood forecasting and management system for the Upper Rhone River basin (MINERVE basin) upstream of Lake Geneva (Bérod, 2013). Since 2013, a forecasting system is operational for the entire basin and used as a tool for decision-making tasks.

Since the very beginning of the forecasting system development, enhancing the estimation of spatial precipitation patterns has been identified as one of the major sources of forecast improvement (Tobin et al., 2011). Indeed, the quality of the input precipitation data directly impacts the performance of the hydrological model because precipitations generally represent the main contribution to flow generation. Two main sources of precipitation data are generally considered, rain-gauges (point observations) and weather radars (yielding spatial information). On the one hand, rain-gauges provide direct precipitation measurements but often cover only part of the domain and are heterogeneously distributed. On the other hand, weather radars provide a better spatial coverage but require a relatively sophisticated post-treatment of the observations and are subject to significant bias. Combining both sources of data has been shown in previous studies to benefit from the strengths of both data types and to produce improved precipitation estimates (Haberlandt, 2007).

Based on a literature review of precipitation interpolation methods, the well-known kriging approach has been selected for an optimal combination of all available precipitation data over the MINERVE basin. Multivariate kriging methods such as kriging with external drift, hereafter referred to as KED (Goovaerts, 1997) allow the combination of point data with additional spatial information from either static (e.g. elevation) or dynamic (e.g. weather radar) covariates to improve the interpolation performance.

For the complete study over the MINERVE basin, precipitation data from 82 meteorological stations within the basin and 87 meteorological stations in the surrounding regions are considered. Preliminary results over the Grande-Eau River basin (see Case Study Section), located in the MINERVE basin, are presented hereafter. The analysis is composed of two parts. First, differences in terms of spatial precipitation intensity estimates are discussed for two interpolation methods. Second, precipitation spatial intensities estimated with the two methods are used as input for a hydrological model to analyse the sensitivity of the simulated flood hydrographs to input variations.

1. Case study

The MINERVE Project (*Modélisation des Intempéries de Nature Extrême dans le Rhône Valaisan et de leur Effets)* is part of the Third Rhone Correction Project in the Canton of Valais, Switzerland (Bérod, 2013; García Hernández, 2011; García Hernández et al., 2009, 2014; Jordan, 2007; Jordan et al., 2008). It aims to achieve a better flow control during flooding in the Upper Rhone River basin, which has the particularity of showing a very high number of water regulation works and accumulation reservoirs for hydropower production (Jordan, 2007). The MINERVE flood forecast system has been operational since May 2013 and provides an updated hydrological forecast every two hours. The hydrological simulations are computed with the hydrological-hydraulic modelling software RS MINERVE (Foehn et al., 2016; García Hernández et al., 2016), which is a freeware that allows rainfall-runoff calculations based on a semi-distributed concept and downstream propagation of discharges. Simulated natural processes include surface and subsurface flow, snow accumulation and melting as well as glacier melting. Several conceptual models are available, including, among others, GSM-Socont (Schaefli et al., 2005), HBV (Bergström, 1992) or SAC-SMA. The GSM-Socont model is used within the MINERVE project and the work presented here.

Currently, in the MINERVE flood forecast system, precipitations are interpolated with the Inverse Distance Weighting method (IDW), in which the inverse of the squared horizontal distance from the point of interpolation to the nearest stations is used as the unique weighting criteria. Ly et al. (2014) proposes a review of precipitation interpolation methods in the frame of hydrological modelling. Discussed methods include deterministic and geostatistical methods, in particular the group of methods known as kriging in which the statistical relationship between measured points is used, in addition to the distance, for the computation of the weighting scheme (Goovaerts, 1997; Webster, 2007). In their conclusion, Ly et al. (2014) clearly mention the need for further research in the field of precipitation interpolation for hydrological modelling.

In Switzerland, the Swiss Federal Office of Meteorology and Climatology *MeteoSwiss* has developed over the last years a solution combining data from the network of automatic meteorological stations *SwissMetNet* and the information from the five national radars. The methodology used to produce this *CombiPrecip* product has been presented by Sideris et al. (2014a and 2014b) and is based on the so called co-kriging with external drift method. The external drift terms refer to the usage of radar information as a covariate whereas the co-kriging term refers to the combination of two time steps (the one of computation as well as the preceding time step), which increases the robustness of the computation. The objective behind developing a precipitation interpolation scheme specific to the Upper Rhone River basin is double. First, the *CombiPrecip* product only integrates stations from the *SwissMetNet* network, whereas other station networks exist in the basin. Integrating this information is expected to improve locally the quality of the precipitation estimates. Second, kriging methods rely on the computation of a mathematical function called the semi-variogram, which describes the degree of spatial dependence of the observed spatial variable. Computing the semi-variogram at the scale of the Upper Rhone River basin rather than for entire Switzerland is also expected to locally improve the performance of the precipitation estimates.

The results presented in this paper are based on the Grande-Eau River basin, a MINERVE sub-basin of 132 km^2 with undisturbed discharge and located upstream of the locality Aigle (Figure 1). The analysis is based on the four first days of the heavy rain event that occurred in early May 2015, with a national average of 100 mm of rain over 6 days (MeteoSwiss, 2016). Data from stations of several precipitation observation networks are used here. This includes the *SwissMetnet* network from MeteoSwiss as well as the networks of the private company MeteoGroup Schweiz AG, the Canton of Bern, MeteoFrance, the Regione Autonoma Valle d'Aosta and the Regione Piemonte. Only one meteorological station with a rain gauge is located within the Grande Eau River basin (in the locality of Leysin, Figure 1).

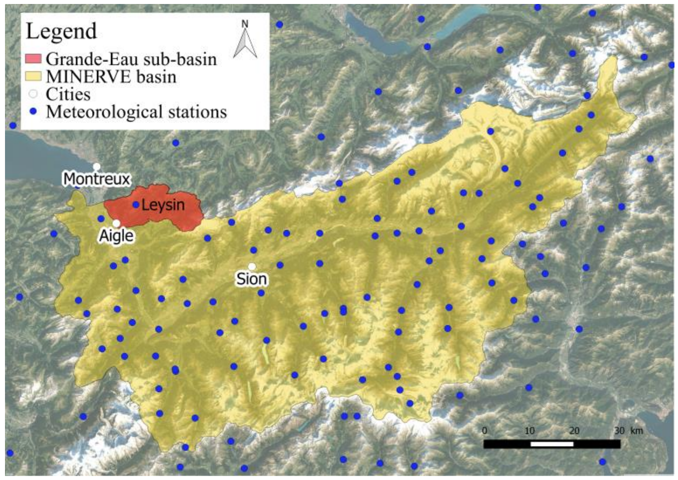

Fig. 1. The MINERVE study area: the complete Upper Rhone River basin and the Grande-Eau River sub-basin

2. Methodology

2.1. Spatialization of precipitation data

The major issue of working exclusively with ground station data is that no information is observed between the points of measurement. If the precipitation observed at the stations is not representative of the entire basin, which is often the case, this will lead to over- or underestimation of the precipitation estimates over the surface. In the context of the present paper, the main focus is on assessing the added value of a spatialization method based on external drift kriging (KED) over the much simpler IDW method. In a next step, the obtained precipitation estimates will be compared to the *CompiPrecip* product. Ultimately, the objective of the project will be to implement a specific interpolation method focussed on the MINERVE basin (not presented here).

For both methods, interpolation of precipitation amounts has been carried out over a grid of 1 km by 1 km, corresponding to the spatial resolution of the radar product of *MeteoSwiss*. The IDW method will not be further discussed here, see e.g. Shepard (1968) for more information. Radar observations over the study basin are used as an external covariate for the KED method, shortly discussed hereafter. Kriging is a geostatistical method in which the variance of the prediction error is minimized and the estimator unbiased. In all kriging approaches, the basic idea is to predict the value of a function at a given point using a weighted average of the nearby observations. Kriging approaches differ in their way of computing the weights. KED is one of the kriging approaches in which auxiliary information is used to remove the underlying trend before applying kriging to the residuals. For a more detailed description, see Chilès and Delfiner (1999, p. 355).

For the computational implementation of the methods, the *gstat* package (Pebesma, 2014) of the R coding language (R Development Core Team, 2015) has been used.

2.2. Hydrological modelling

For the hydrological model of the Grande Eau River, the basin has been divided into 6 sub-basins, which themselves are further subdivided into 25 elevation bands. A precipitation and a temperature time series is computed for the center of gravity of each elevation band by interpolation of the surrounding information (meteorological station data or estimated grid cell data). The temperature time series (not further discussed here) are interpolated from the surrounding meteorological stations with a temperature gradient of -0.0054 °C / m.

The hydrological model has been calibrated over a period of three hydrological years, from September 1st 2012 to September 1st 2015, using the discharge observations at the gauging station “Aigle - Grande Eau” from the Federal office for the environment, located at the outlet of the basin. The calibrated parameters for the Socont model were 1) the degree-day snow melt coefficient, 2) the maximum storage capacity of the slow soil reservoir, 3) the release coefficient of slow soil reservoir and 4) the surface runoff Strickler coefficient. For the glacier part, which accounts only for 0.6 % of the catchment area, calibrated parameters were 1) the degree-day snow melt coefficient and 2) the degree-day ice melt coefficient. The calibration has been performed using the automatic calibration module of the RS MINERVE software (García Hernández et al., 2016), which uses a single objective function composed of the five performance indicators listed in Table 1. For further details, refer to García Hernández et al. (2016).

For the simulation of the flood occurred in Mai 2015, initial conditions of the model state variables were initialized on May 1st 2015 00:00 (UTC+1) by running the model from September 1st 2012 to May 1st 2015.

Table 1: Name of the performance indicators combined into the single calibration objective function, their weights and the model performance obtained after calibration.

Indicator	Weight	Obtained value
Nash	1	0.63
Nash-ln	0.5	0.51
Person correlation coefficient	1	0.80
Relative root mean squared error	0.5	0.45
Relative volume bias	1	-0.08

3. Results

3.1. Precipitation interpolation with IDW and KED

As mentioned earlier, the results of the two different precipitation spatialization schemes is discussed here based on a single event from the year 2015. The main focus is hereby on the comparison of the estimated precipitation amounts at the Grande-Eau river basin scale. Large differences between the two methods might point towards situations where the areal precipitation estimates are subject to strong biases, which typically result from a poor spatial coverage by the available point observations. The comparison of hourly areal average precipitation over the basin for IDW and KED shows three distinct precipitation fronts over the studied period (May 1st 00:00 to May 5th 00:00, UTC +1) (Figure 2a). Over the first two fronts, IDW and KED produce only small differences in the areal precipitation amounts for the Grande-Eau River basin. During the third front, this difference becomes large, with the KED amounts exceeding the IDW amounts by more than 50% for several time steps. This difference in the precipitation intensities becomes particularly visible in the cumulative plots (showing the average areal accumulation for all the precipitations fronts (Figure 2b).

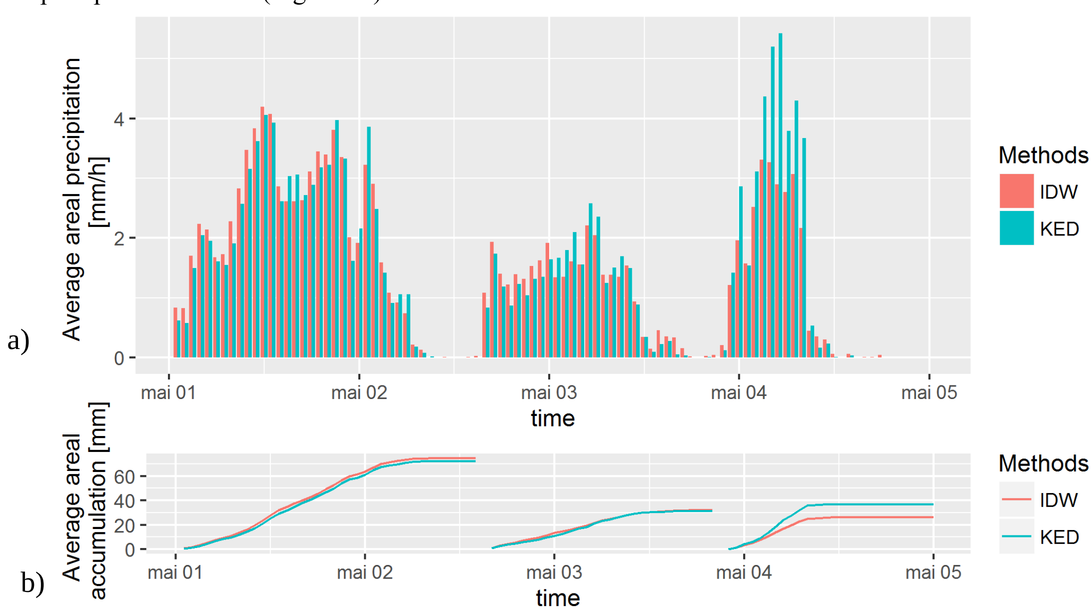

Fig. 2. a) Average areal precipitation over the Grande-Eau River basin in [mm/h] - May 1st 00:00 to May 5th 2015 00:00; b) Average areal accumulation of precipitation in [mm] over the Grande-Eau River basin for all three fronts.

Over the first front, IDW generates slightly more precipitation; over the second, the amounts for both methods are very similar. During the third front, the KED method exceeds the IDW method by about 10 mm, which corresponds to 10 more liters per square meter or about 2 million additional cubic meters over 12 hours for the entire basin.

To understand the origin of this difference, the spatial patterns of the cumulative precipitation estimates for the 4-days period are analysed (Figure 3). A considerable difference of intensity appears in the upper part of the basin (eastern part), with the KED method generating higher precipitation intensities.

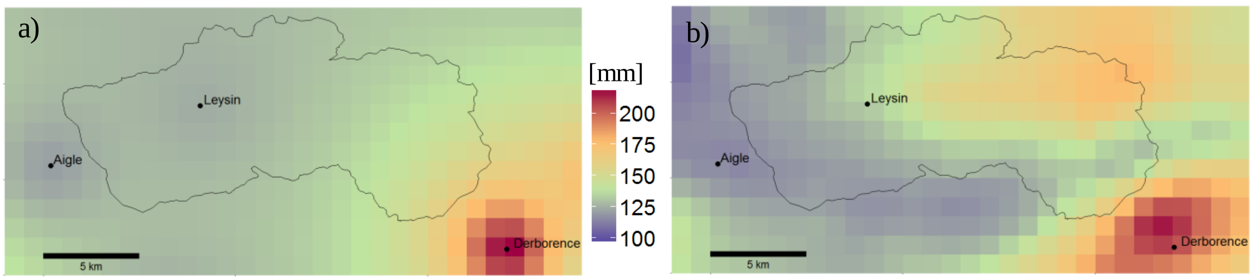

Fig. 3. Cumulative precipitation in mm over the 4 days (May 1st 2015 from 00:00 to May 5th 2015 00:00) estimated with a) IDW and b) KED methods for the Grande-Eau River; the same colour scale is used for both images.

A plot of the differences between the IDW and KED amounts for each grid cell highlight these spatial intensity differences (Figure 4a). To analyse more in detail the behaviour of the precipitation fields, Figure 4b provides the difference of intensity estimates from both methods over a single time step during the third precipitation front; the selected time step (May 4th 04:00 to 05:00) is the one with the highest local difference, with a difference exceeding 5 mm/h for some grid cells.

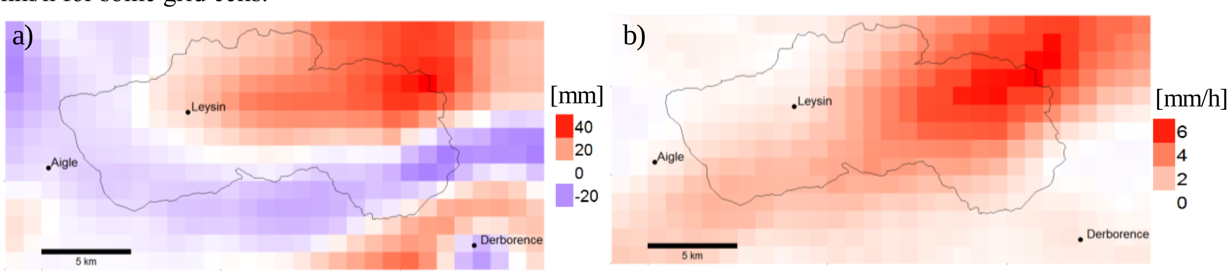

Fig.4. Difference between IDW and KED estimates at the grid cell-scale: shown is the KED amount minus the IDW amount in mm a) over the 4 days (May 1st 2015 from 00:00 to May 5th 2015 00:00); b) for the 1 hour period from May 4th 2015 04:00 to 05:00.

The differences observed in Figure 4 can be explained with the hourly precipitation estimates from both methods (Figure 5). The IDW method generates a very smooth surface as it only considers data at ground stations. The KED method reproduces the heavy precipitation occurring in the upper part of the basin thanks to the radar observations.

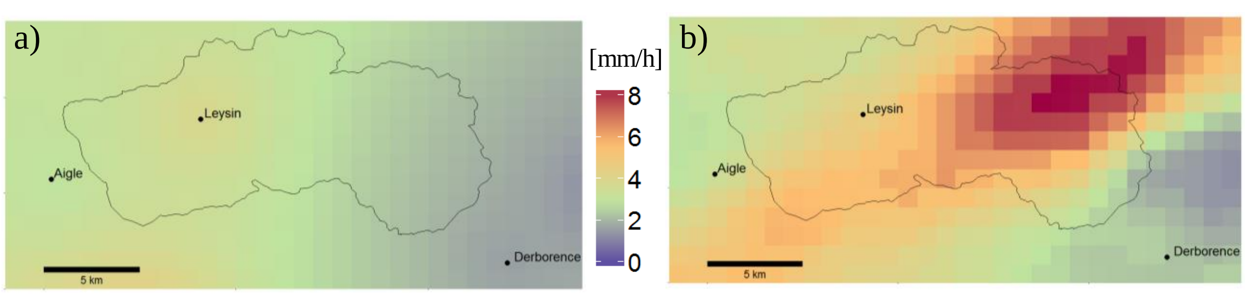

Fig. 5. Hourly precipitation in mm estimated with a) IDW and b) KED methods for the Grande-Eau River for May 4th 2015 from 04:00 and 05:00; the same colour scale is used for both images.

The presented event analysis shows the significant difference obtained when using the radar information as an external covariate to improve the spatialization of precipitations. To validate the higher performance of the KED method, a measurement station with a rain gauge in the upper part of the basin would be desirable. Thereby, interpolated estimates from both methods at the location of the additional station (without using its data) could be compared to observed data, which would further strengthen the analysis. Since such data are not available for this case study, this analysis cannot be achieved here. The precipitation estimates of both methods are therefore only assessed via the aforementioned discharge simulations.

3.2 Hydrological response analysis

The simulated hydrographs obtained with the two different precipitation inputs over the selected 4-days period reproduce the three successive precipitation fronts discussed earlier (Figure 6). For the first two fronts, only small differences are obtained between the discharges simulated with the two interpolation methods (IDW vs. KED). As expected, much larger differences arise for the third front. Indeed, the discharge increase over the third front is about twice more important with the precipitation integrating the radar information compared to the one based only on ground stations. This results from the much higher precipitation intensities in the upper part of the basin highlighted in Figures 3 and 4.

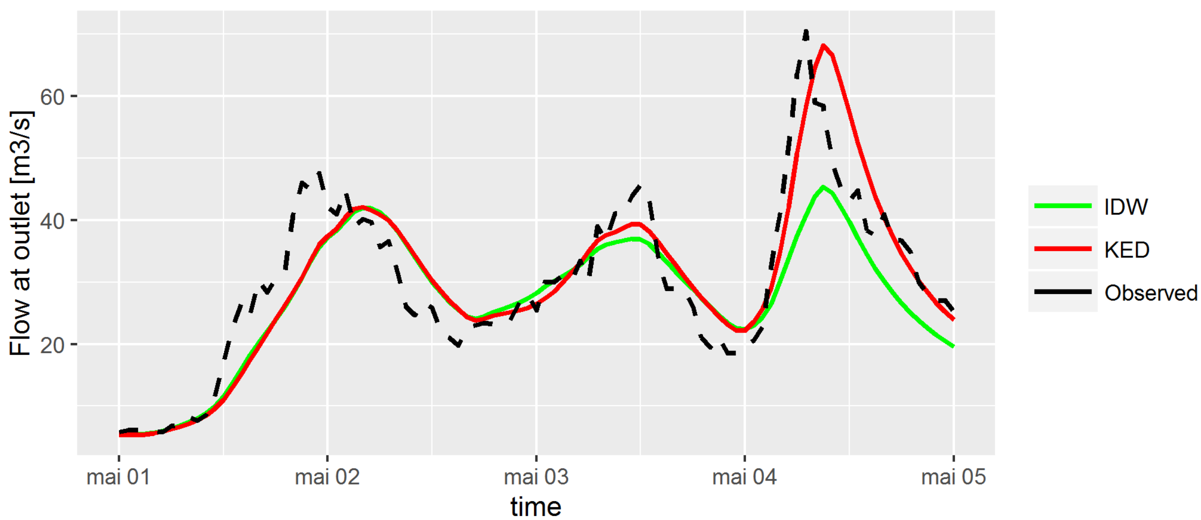

Fig. 6. Discharges obtained with the meteorological inputs based on IDW and KED estimates and discharge observed at the Aigle gauging station over the 4-days period from May 1st 2015 00:00 to May 5th 2015 00:00.

The results obtained for this case study confirm the importance of the quality of precipitation input to the hydrological model. Using an improved precipitation input for the calibration therefore opens new perspectives for improving the performance of the forecasting system and will be explored in the near future. It is noteworthy that different hydrological initial conditions or different model calibrations could also modify somewhat the hydrographs. How the overall conclusions might rely on initialization and calibration is part of the planned future work.

4. Conclusion

This paper presents the first results and findings to increase the reliability of the flood forecasting system of the Upper Rhone River basin (Switzerland) with the help of improved spatial precipitation estimates. The focus here was on the comparison of a simple spatial interpolation scheme with a new scheme that uses information from weather radar as external drift in a kriging approach.

Results have shown a significant difference when using the radar information as an external covariate, both from a meteorological and a hydrological point of view. With heterogeneous precipitation fields, using only ground stations data can lead to considerable estimation errors. If those precipitation estimates are then used as input data to a hydrological model, hydrological performance will be affected because the input data does not properly correspond to the real input generating the observed flow. Future work will show whether the new spatialization scheme, using different station networks and local variogram estimates, outperforms existing Swiss-wide spatialization products. Once a spatialization method set up, improved interpolated data will be used to improve the calibration of the hydrological model used within the MINERVE system and, thus, to improve the hydrological forecasts.

Acknowledgments

The research project from which this article results is realized at the Ecole Polytéchnique Fédérale de Lausanne (EPFL) in Switzerland, and is funded by the Centre de Recherche sur l'Environnement Alpin (CREALP), located in Sion, Switzerland. The authors express their gratitude to all involved stakeholders: the Canton of Valais, the Swiss Federal Office for Meteorology and Climatology, the Universitat Politècnica de València and the engineering office HydroCosmos SA. The meteorological data used within the projects come from the SwissMetnet network from MeteoSwiss, as well as the networks of the private company MeteoGroup Schweiz AG, the Canton of Bern, MeteoFrance, the Regione Autonoma Valle d'Aosta and the Regione Piemonte. The radar data have been provided by MeteoSwiss and the hydrometric data delivered by the Swiss Federal Office for the environment. We thank all the different data providers. Acknowledgments also go to the collaborators of the CREALP who collaborate on the MINERVE system and on the set-up of the hydrometeorological database used for the study.

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