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LETTER

Potential of commercial microwave link network derived rainfall for river runoff simulations

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Abstract

Commercial microwave link networks allow for the quantification of path integrated precipitation because the attenuation by hydrometeors correlates with rainfall between transmitter and receiver stations. The networks, operated and maintained by cellphone companies, thereby provide completely new and country wide precipitation measurements. As the density of traditional precipitation station networks worldwide is significantly decreasing, microwave link derived precipitation estimates receive increasing attention not only by hydrologists but also by meteorological and hydrological services. We investigate the potential of microwave derived precipitation estimates for streamflow prediction and water balance analyses, exemplarily shown for an orographically complex region in the German Alps (River Ammer). We investigate the additional value of link derived rainfall estimations combined with station observations compared to station and weather radar derived values. Our river runoff simulation system employs a distributed hydrological model at 100 × 100 m grid resolution. We analyze the potential of microwave link derived precipitation estimates for two episodes of 30 days with typically moderate river flow and an episode of extreme flooding. The simulation results indicate the potential of this novel precipitation monitoring method: a significant improvement in hydrograph reproduction has been achieved in the extreme flooding period that was characterized by a large number of local strong precipitation events. The present rainfall monitoring gauges alone were not able to correctly capture these events.

1. Introduction

Past large flood events in the Alpine region have emphasized the need for reliable flood prediction and warning systems with different lead times. Nowcast and forecast systems apply hydrological models (HMs) driven by precipitation data derived from observations and the forecasts of numerical weather prediction models (NWPs). Recent floods resulting from local strong precipitation events which allowed only very little lead time for a warning have especially stressed the importance of nowcasting tools. The performance of both relies on the correct description of the initial state of HMs, the actual precipitation estimates, and in the case of NWP-based systems, which provide longer lead times, on the quality of the precipitation forecast. Several statistical procedures have been developed to cope with the phase and amplitude errors present in precipitation forecasts from NWP models. They rely on past precipitation measurements. Also, the initial state of the considered system depends to a large extent on the data of the precipitation history in the considered region. As the number of precipitation monitoring gauges is continually decreasing (Lorenz and Kunstmann 2012), novel techniques for precipitation monitoring are receiving increasing attention.

The present article examines the application of precipitation data derived from attenuation measurements provided by commercial microwave links (CMLs), which are operated as backhaul on a cellular phone network. This technique, introduced by Messer *et al* (2006), has the great advantage that it relies on the existing infrastructure of cellular phone networks. Hence, it is applicable in most inhabited areas around the globe (Overeem *et al* 2013). Furthermore, the required CML data can be made available in real time Chwala *et al* (2016), allowing the application of this technique with operational tools for warning of precipitation and floods. It can advantageously complement the existing networks of rain gauges and radar, but it can also be used in areas where station networks are very coarse or non-existent. Thus, the derivation of precipitation information from CML data was and is the subject of intensive research.

Zinevich *et al* (2008) showed that this techniques is suitable for measuring the near-ground rainfall over large areas in Israel with biases smaller than 10%. In experiments in the Alpine and pre-Alpine regions in southern Germany, Chwala *et al* (2012) obtained correlations of 0.81 for the CML–rain gauge comparison and 0.85 for the CML–rain radar comparison. Doumounia *et al* (2014) tested the CML method during the monsoon season in West Africa, where 95% of the rainy days were detected with a correlation of 0.8 in the daily precipitation amounts compared to rain gauge measurements. Overeem *et al* (2013) demonstrated that processing algorithms are capable of providing real-time rainfall maps for an entire country, in this case the Netherlands. Chwala *et al* (2016) implemented a system to acquire and distribute the required CML data in real time. From a case study in Prague, Czech Republic, Fencl *et al* (2015) concluded that the CLM captures the spatio-temporal rainfall variability with a positive bias and emphasized its potential to improve runoff predictions. Besides rainfall measurement, CLM data can also be applied to the calibration of rain radar and increase the accuracy of the precipitation rates derived from stationary dual polarization radar (Trömel *et al* 2014). Recently, Brauer *et al* (2016) studied the effects of differences in rainfall measurement techniques including CML on discharge simulations in a small (6.5 km^2) low land catchment. The authors found seasonally varying errors with CML derived precipitation and conclude that for the assessment of the novel rainfall observation technique longer simulation periods are required.

In contrast to previous CLM studies the present investigation applies the CML derived rainfall in a distributed hydrological model. Its scientific aim is to investigate the ability of CML derived precipitation data to extend the observational data input and to improve the initial state of the river discharge simulation and forecasting system applied in the complex terrain of the Alpine Ammer River catchment. Smiatek *et al* (2012) described the NWP/HM-based flood forecasting system in detail. In order to avoid errors which might result from the NWP simulated precipitation amount, the initial state of the hydrology model is obtained from a continuous hindcast simulation with observed meteorology data input. The subject of the present study is restricted to the application of the CML derived precipitation data in this hindcast simulation. All conclusions, however, apply also to a nowcast application. Compared to the study of Brauer *et al* (2016) the present investigation considers a much larger catchment in complex terrain with links within the considered area and alternative methods of the rain rate estimation.

The outline of this paper is as follows: in section 2, the CML-based precipitation estimation, the applied hydrology model, and the investigation area are described. The application of the investigated system is presented and evaluated in section 3. Finally, some conclusions are drawn in section 4.

2. Materials and methods

2.1. CML

A mobile phone communication network is composed of a set of cells. The base stations of these cells are radio towers, which are typically interconnected via radio links operating in the microwave frequency domain between 10 and 40 GHz. Rain between two towers attenuates the microwave radiation along the radio paths. This causes power fluctuations, which are closely correlated with the line integrated rain intensity. The specific attenuation A in dB km^{-1} can be captured and allows the approximation of the rain rate R in mmh^{-1} via the power law relation (Olsen *et al* 1978)

$$A = aR^b \tag{1}$$

where a and b are parameters depending to a large extent on the frequency of the propagating wave but also on the polarization, rain drop size distribution (DSD), and temperature (Chwala *et al* 2012).

Although the attenuation of microwave radiation strongly depends on the amount of precipitation along its path of propagation, hydrometeors are not the only source of disturbance. There are other influences on the signal transmission, such as anomalies of the link electronics or small variations of the atmospheric conditions that result in power fluctuations even during clear sky conditions. In order to derive reasonable precipitation information, it is therefore necessary to identify the disturbances caused by rain events. In the simulation studies presented in this article, two approaches are applied to the time series of transmitted and received signal levels (TRSL) acquired with the method described by Chwala *et al* (2016). The first procedure *stdev* after Schleiss and Berne (2010) calculates the standard deviation σ within a moving time window along the TRSL. When the standard deviation exceeds a certain threshold, the period is classified as rainy. Chwala *et al* (2012) described in detail the second procedure, denoted by *stft*. It is based on a short-time Fourier transform (STFT) and operated with a moving Hamming window of length 256 minutes. By calculating the Fourier transform of each windowed TRSL data, it is possible to derive

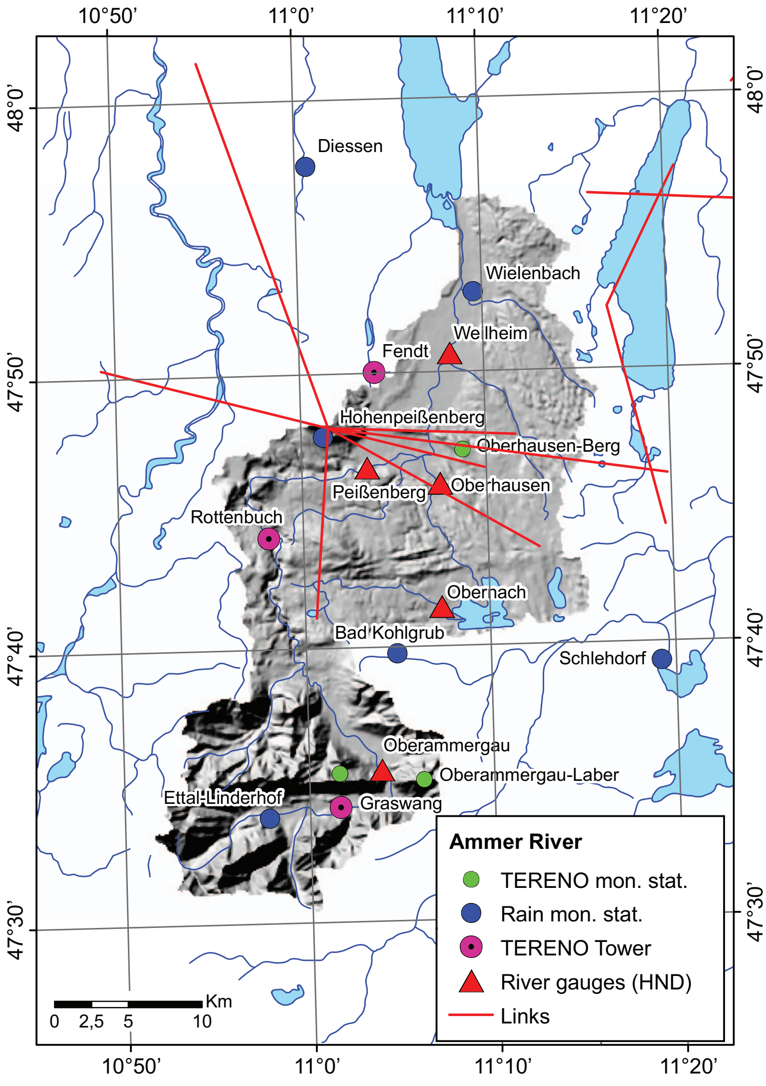

Figure 1. Ammer River catchment. Location of the monitoring stations and the applied links.

normalized power spectra. The spectra of the wet and dry periods differ considerably, especially at low frequencies. If the difference P_{diff} between the sums of low and high frequency amplitudes exceeds a certain threshold, the period is classified as rainy. Then for each rainy period, the line integrated rain rate R is finally derived using equation 1 with the parameters a and b provided by the International Telecommunication Union (ITU 2003). No further adjustment, e.g. considering the wet antenna effect, are applied. This would require an additional calibration of the processing procedure and introduce further uncertainties. Our experience indicates that the most crucial processing step is the robust identification of rain events in the raw TRSL time series.

2.2. Model and application area

The AM-POE simulations and forecasting system is implemented for the Ammer catchment located in the Bavarian Ammergau Alps and Alpine forelands, Germany (figure 1). AM denotes the Ammer River and POE the Perl Object Environment (Caputo 2003) which is used in the system integration together with SOAP (Simple Object Access Protocol)-based Web services, as discussed by Smiatek (2005), for input data provision. The catchment is 609 km^2 in size. In its southern part, the elevations reach 2185 m a.s.l. The northern part at the outflow to the Lake Ammersee has elevations about 500 m a.s.l., and is rather flat. The long term mean annual precipitation ranges from 1100 mm a^{-1} in the northern part to 2000 mm a^{-1} in the mountainous southern part, with a maximum in the summer.

AM-POE employs the hydrological water balance model WaSiM-ETH (Schulla 2015) run at 100 m × 100 m grid resolution. It uses both physically-based algorithms and conceptual approaches. A detailed description of the model setup and its adaptation to the limestone Alpine zone of the Ammer catchment is given in Kunstmann *et al* (2004). Kunstmann *et al* (2006) describe the model calibrations in which 37 parameters were calibrated applying the Gauss–Marquardt–Levenberg algorithm for nonlinear parameter estimation. For the hydrologic year 1997, simulated and observed runoff was compared at eight gauges. The calibrated parameters were: the recession constants of direct runoff and interflow, the drainage density, the hydraulic conductivity of the uppermost aquifer in each subcatchment and five snowmelt specific parameters in the entire area. In total, data from 14 meteorological stations within a radius of 50 km were used. The model validation for the hydrologic year 1993 yielded NS efficiency values up to 0.7, suffered, however, from the fact that only one monitoring station was located within the catchment.

The Ammer River is subject to intensive monitoring and research by the TERENO (TERrestrial ENvironmental Observatories) Longterm Observatory preAlpine (www.tereno.net) (Zacharias *et al* 2011). In the present article, we apply the measurement data of temperature, precipitation, wind speed, solar radiation and air humidity obtained from the TERENO infrastructure (six stations). In addition, five river gauges and three rain gauges (Ettal–Linderhof, Diessen and Schlehdorf) operated by the *Hochwasser Nachrichtendienst* (HND) and *Wasserwirtschaftsamt* (WWA), Weilheim, as well as three rain gauges (Bad Kohlgrub, Hohenpeißenberg and Wielenbach) operated by the *Deutscher Wetterdienst* (DWD), Offenbach, are used. Figure 1 depicts the location of the monitoring stations. Beside the gauge measurements, we also apply gridded precipitation data from the RADOLAN data product provided by DWD at a resolution of 1 km × 1 km. The RADOLAN method combines precipitation derived from weather radar and measured gauge precipitation (Winterrath *et al* 2012).

Presently, data from 10 CML are applicable within the Ammer catchment. They are operated by Ericsson GmbH for the German cellular phone provider T-Mobile. The technical details of the data acquisition are presented by Chwala *et al* (2016). Each CML is considered as an indirect monitoring station with a location in the middle of each CML. Finally, the precipitation estimates are interpolated together with the rain gauge observations on to the 100 m × 100 m WaSiM grid applying the Inverse Distance Weighting (IDW) method. Because the available CML links do not cover an entire subcatchment of the Ammer River the combined CLM and rain gauges precipitation data is yet the only available option for CLM application. The number of usable CMLs is, however, supposed to grow in the near future as the data acquisition system will be further extended. Up to now, only CMLs from the T-Mobile provider and only the newest generation of Ericsson hardware is included. Older hardware is currently being replaced step by step all over Germany.

2.3. The model runs

The AM-POE system has been applied in hindcast mode for the period from 1 June 2015 to 30 June 2015 with moderate river flow and the period from 14 May 2016 to 14 June 2016 with a larger number of intensive convective events and a maximum discharge at the Weilheim gauge of 184 $m^3 s^{-1}$, which is well above the mean high water flow (MHQ) of 165 $m^3 s^{-1}$. Table 1 shows the details of the model runs. Simulation SIM_1 employs gauge precipitation data from HND, DWD and TEREMO. It is the standard in AM-POE. Simulation SIM_2 employs the gauge precipitation and, in addition, CML derived precipitation calculated with the *stdev* method. SIM_3 uses gauge precipitation and CML derived precipitation calculated with the *stft* method. Simulation SIM_4 uses only precipitation from RADOLAN radar data which already include an adjustment according to the DWD rain gauges. The efficiency of the model runs has been measured by applying the Nash–Sucliffe coefficient (Nash and Sutcliffe 1970), which compares observed and simulated discharge values.

Table 1. Matrix of performed simulations. The simulations were carried out with precipitation data from DWD, HND and TERENO, with additional precipitation data from CML with processing procedures *stdev* and *stft* as described in chapter 2.1 and with precipitation from RADOLAN rain radar.

Acronym	Observed			CML		Radar
	DWD	HND	TERENO	*stdev*	*stft*	RADOLAN
SIM_1	•	•	•			
SIM_2	•	•	•	•		
SIM_3	•	•	•		•	
SIM_4						•

3. Application of the CML data

3.1. An example of processing the CML data

The principle of the data processing is exemplified in figure 2 for an 11 day time series of TRSL data from an Ericsson CML in southern Germany. Figure 2(*a*) shows the minute resolution raw TRSL data of one CML channel directed from Hohenpeißenberg to Huglfing. In figure 2(*b*) the rolling standard deviation of the procedure *stdev* including the customized threshold is plotted. Figure 2(*c*) shows P_{diff} of procedure *stft* and its optimized threshold. The rainy periods, where the rolling standard deviation and P_{diff} respectively exceed the particular threshold, are shaded gray in figures 2(*b*)–(*c*). The thresholds and further processing parameters for both methods have been optimized for the period of August and September 2015 using RADOLAN data as reference for the start and end of rain events along the CMLs. In figure 2(*d*), the resulting rain rates and the accumulated sums of rain are plotted for both approaches. Although both methods yield similar results, in general there are classification differences, especially in identifying short and weak rain events.

3.2. Application in the AM-POE system

Figure 3 shows the hydrograph of the simulation SIM_1 at the Weilheim river gauge obtained for the

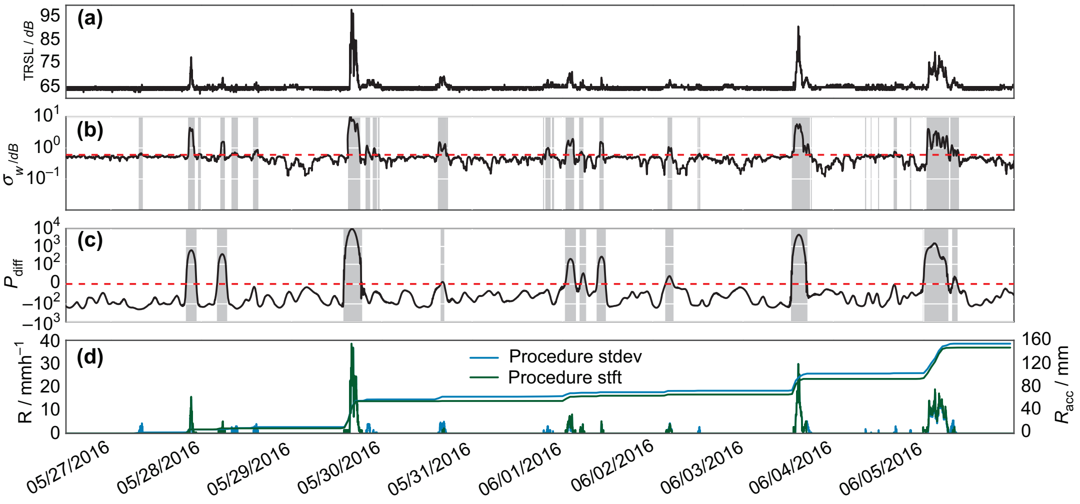

Figure 2. Illustration of both CML processing procedures for an 11 day time series. (*a*) The raw *RSL* data of one CNL channel, (b) its rolling standard deviation, (*c*) P_{diff} as explained in section 2.1 and (*d*) the resulting rain rates and the accumulated sums of rain respectively. The gray shaded areas in (*b*) and (*c*) indicate the periods where the threshold (red dashed line) is exceeded. These are the periods which are classified as rain events.

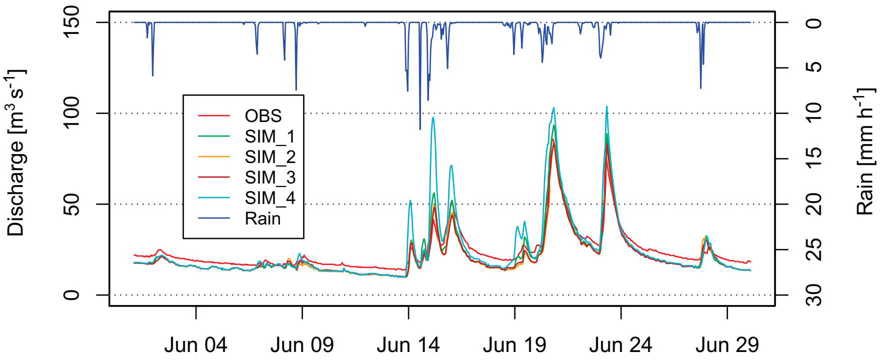

Figure 3. Observed (OBS) and simulated discharge at gauge Weilheim and basin mean rainfall (Rain) as interpolated by the WaSiM model in the simulation SIM_1 1 June 2015–30 June 2015.

first simulation period from 01.06.2015 to 30.06.2015. The corresponding Nash–Sucliffe (NS) efficiency values are presented in figure 4. In this period, of comparatively low flow, where the highest discharge, of roughly 80 m^3 s^{-1} at June 20th, was caused by precipitation of 30–50 mm d^{-1}, the amounts of precipitation monitored at the available rain gauges are very similar. Thus, additional precipitation data from CML, which for example, reduces the precipitation in the northern part of the catchment on 21 June by roughly 10 mm d^{-1}, does not alter the efficiency of the model in the entire considered period. A small efficiency increase can be seen in the period from June 19 to June 24. There are only minor differences between the values of the NS for the Weilheim and Peißenberg river gauges obtained by the performed runs. In the complex terrain of the Oberammergau subcatchment, the performance of the AM-POE system is unsatisfactory in a low flow period. However, it has to be stated that the system was calibrated for better reproduction of high flow events. Also, in order to obtain the system performance without potential upstream errors, the Peißenberg and Weilheim subcatchments were simulated with observed inflow, neglecting the uncertainties from the mountainous upper parts of the catchment. Simulation SIM_4 with RADOLAN precipitation performs best at the gauges Oberammergau and Peißenberg. In Weilheim, however, a substantial overestimation of the precipitation amount leads to an overestimation of the peak flow values and to a NS efficiency of 0.5.

The situation in the second simulation period is very different. Several strong convective precipitation events caused severe flooding in the region, which are also visible in the discharge measurements. Figure 5 depicts the obtained hydrograph for the period from 15 May 2016 to 15 June 2016. It shows a significant improvement in the simulation of high flow values with the CML assisted model runs. The run based on the less dense monitoring network tends to overestimate the amount of rain within the catchment, and produces an overestimation of the discharge values. As a result, the NS coefficient at the Weilheim gauge obtains a value of only 0.45 (figure 4) while the CML assisted runs reduce the precipitation amount and yield an NS of 0.9. The reason is a significant change in

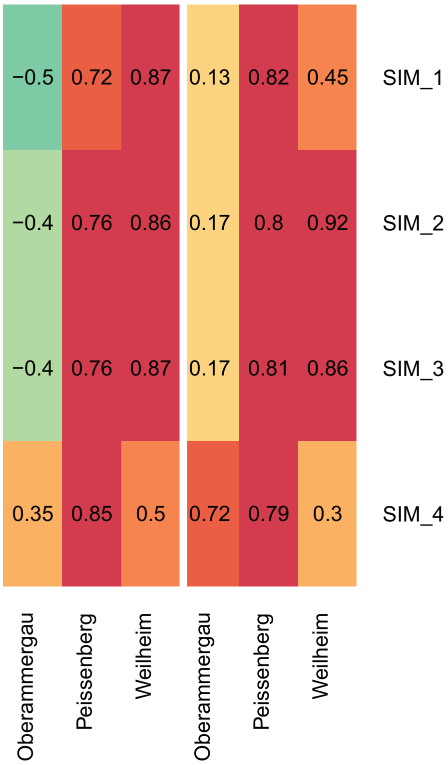

Figure 4. NS values obtained for the period 1 June 2015–30 June 2015 (left panel) and the period 15 May 2016–15 June 2016 (right panel).

the spatially interpolated precipitation patterns, shown in figure 6, which depicts the precipitation map for 8 June, interpolated by the WaSiM model applying the IDW method. With the CML added data, the influence of the strong local precipitation event observed at the Oberhausen-Berg rain gauge is reduced, and the reproduction of the observed discharge is improved. It should be noted that compared to the first investigation period, the precipitation amounts and the discharges are much higher. Errors in high discharge rates stronger impact the NS efficiency. Therefore, the additional CML rainfall data influences the NS of the entire period. This effect is not visible in the considered episode in 2015. Similar to SIM_1 simulation, SIM_4 suffers from an overestimation of the precipitation amount. For example, on 9 June 2016, the WASiM interpolated area mean daily precipitation sum was 40.8 mm d^{-1} in SIM_1, 44.4 mm in in SIM_4 but only 25.8 mm d^{-1} in SIM_2.

NS efficiencies obtained for the Peißenberg catchment are similar in all runs (figure 4) since there is currently only data for one CML available in this area. In the complex terrain of the Oberammergau subcatchment only simulation SIM_4 reaches reasonable NS efficiency of 0.72. In general, the RADOLAN precipitation improves the discharge simulation in the Ammer area. It should, however, be noted that the TERENO observations are not included in the RADOLAN weather radar adjustment. These results show that improvements in flood simulations can only be obtained with a denser rainfall monitoring.

The urgent need for a denser monitoring network can be clearly identified at the Obernach gauge (see figure 7), where a local very strong convective event caused an excess of the decadal high water flow (HQ10) in this relatively small subcatchment. No model run captured this event. Flooding events in this comparatively flat terrain strongly depend on the soil water saturation, and thus to a large extent on the precipitation history. This history is a key point in the initialization of any hydrological simulation and forecast system. The present precipitation monitoring network is obviously insufficient for deriving the real precipitation in the region. A denser precipitation monitoring network with a large number of CMLsis therefore certainly a possible way to significantly improve the discharge forecast. This is especially relevant in the context of the expected increase of intense rain events under climate change for this region (e.g. Wagner *et al* 2013).

CMLs provide a cheap and extremely fast method of precipitation monitoring. There are, however, still scientific and technical challenges to be solved. CMLs fail with snow and with extreme rain events, which can cause a total signal loss. Furthermore, the method delivers a line integrated signal. Its transformation into a precipitation intensity faces, beside the nontrivial solution of equation 1, also the problem of the location of the rainfall event. In the present study, it has been located as a measurement of an artificial rain gauge in the middle of each CML. A denser system of links will allow additional options in the future. An additional improvement in the simulation results can also be expected from the model recalibration when sufficiently long periods of observations of both gauges and CLM will become available.

4. Conclusions

Precipitation data derived from the attenuation in microwave transmission between data links of a cellular network system has been applied as an additional input to a river discharge modelling system of the Ammer River, located in the Ammergau Alps and the Alpine forelands. The results obtained in two episodes with different meteorological characteristics indicate the great potential of this novel precipitation monitoring procedure. A significant improvement in the reproduction of the observed discharge values has been obtained for the episode with a large number of local strong precipitation events in May–June 2016, which were not captured by the present rain fall monitoring gauges and gridded precipitation from gauge adjusted weather radar data. Such events require an extremely dense monitoring network. It is an obvious fact that a denser precipitation monitoring network improves river discharge simulations. However, in view of the generally decreasing trend in the number of traditional rain monitoring stations, CMLs

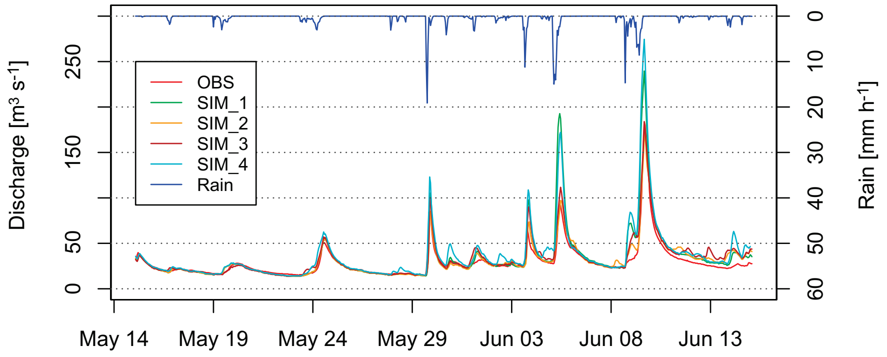

Figure 5. Observed (OBS) and simulated discharge at gauge Weilheim and basin mean rainfall (Rain) as interpolated by the WaSiM model in the simulation SIM_1 15.05.2016–15.06.2016.

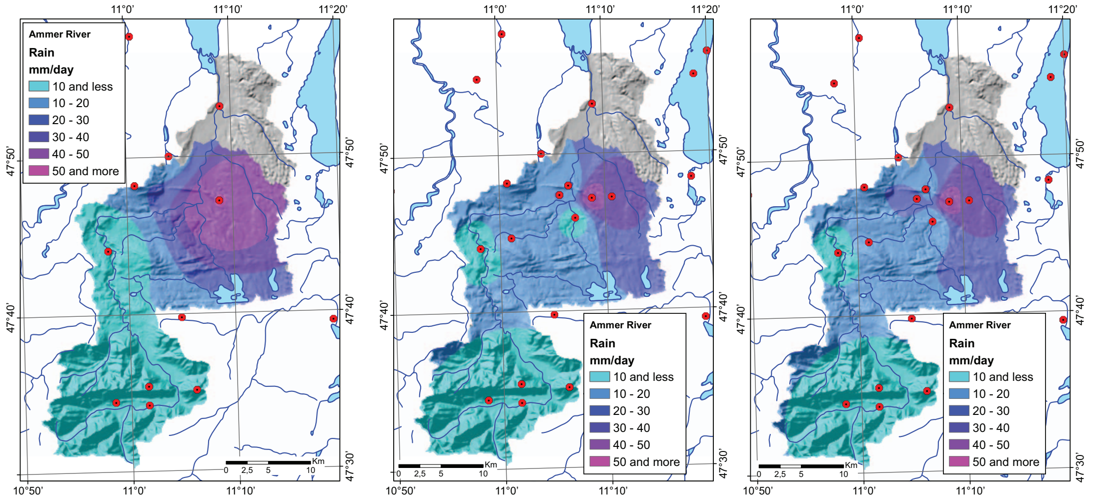

Figure 6. Daily sum of precipitation for the 8 June 2016 as interpolated by the WaSiM model. Gauge precipitation only (left), gauge and CML processed rain with the *stdev* method (middle) and gauge and CML processed rain with the *stft* method (right). Red dots indicate the location of the monitoring stations and rainfall events derived from the CML network.

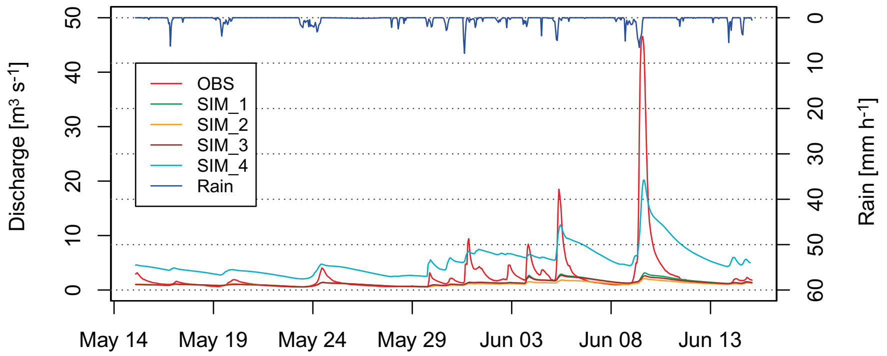

Figure 7. Observed (OBS) and simulated discharge at gauge Obernach and basin mean rainfall (Rain) as interpolated by the WaSiM model in the simulation SIM_1 15 May 2016–15 June 2016.

open a perspective not only for filling the gaps, but also for extending the quantitative precipitation monitoring and thus helping to improve the initialization of hydrology models in forecast systems. This technique is world-wide applicable with particularly great potential in areas where traditional rainfall measurement infrastructure such as rain gauges and weather radar is generally not available. The CML rainfall has also good potential for large scale applications, e.g., to complement or enhance satellite rainfall in areas lacking of ground adjustment information and thus improve real time flood nowcasting and prediction capability, currently suffering from errors in the satellite precipitation input as pointed out by Wu *et al* (2014). Large scale investigations in many sectors such as numerical weather prediction, agricultural monitoring, public health or disaster monitoring as discussed by

Kirschbaum *et al* (2017) could also benefit from additional precipitation input from CML. The initialization of this technique in Africa has already started (Gosset *et al* 2016).

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