On the use of a weather radar for flood forecasting in the Centre of Portugal

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Abstract

There has been an increase in the frequency and severity of floods. Accurate forecasting tools and early warning systems are needed to increase preparedness, to reduce vulnerability, and to potentially save lives. A judicious combination of real-time analysis of udometer data and hydrological and hydraulic modelling lies at the heart of most flood warning systems. Estimations of precipitation obtained with meteorological radar have been increasingly used to provide complementary precipitation data. The aim of this master thesis is to evaluate the contribution of the weather radar to flood forecasting systems in flood-prone watersheds, like the catchment of Águeda. Two flood events, with different precipitation regimes (stratified and convective), that took place in 2016 and 2019, in Águeda, were studied. To understand if the weather radar offers relevant data for flood modelling and forecasting, the two events were simulated with the hydrological model HEC-HMS, using as input, modified radar and udometer precipitation data. The modified radar estimates were the result of a correlation analysis between precipitation measurements obtained at udometric stations and radar estimates in the near vicinity of those stations. The adjusted radar, along with raw data and udometer data, were then used as input of HEC-HMS. The resulting computed discharges were compared with observed ones, at river gauges. This comparison allows to understand how radar data impacts the computed discharges. The two events presented very dissimilar results. The simulation of the event of 2016 suggests that the weather radar may suffer from errors that render problematic its use in operational context. The event of 2019, however, is an interesting example of the usefulness of the weather radar to provide redundancy to operational forecasting systems. In conclusion, the contribution of the meteorological radar for modelling and subsequent forecast of floods is valuable but only within systems with redundancy. For ungauged basins, the relevance of the weather radar is not firmly proved.

Key words: Weather radar, Udometric station, Precipitation, Discharge, Flood.

1. Introduction

There has been an increase of flood events in Portugal, (Cunha et al., 2017), even if the mean annual rainfall has been decreasing, (Soares et al., 2014). Floods have major negative impacts on the communities affected, potentially causing asset damage and even human losses, as was the case of the 1967 Lisbon, flash floods that caused major socio-economic impacts. The lack of a proper warning system contributed to the death of almost 700 people and nearly 900 became homeless, (Trigo et al., 2016).

Flood early warning systems are designated to effectively disseminate alerts and warnings and to ensure preparedness, (Kundzewicz, 2013). They comprise monitoring, event forecasting and characterization and decision making subsystems. Flood forecasting systems provide consistent information on the evolution of an event, by estimating when and where the flood is expected to happen and with which severity. An alert or early warning contributes to the reduction of the damages caused to people and property, by enabling emergency actions, such as evacuation of people, and protection of goods, (Kundzewicz, 2013).

Meteorological and hydrological monitoring systems are a fundamental component. Their data may be directly interpreted or fed to mathematical models to forecast water levels, river discharges and inundated areas for a future time horizon, (Kundzewicz, 2013).

Generally, the rainfall data is measured by rain gauges, but these instruments have the disadvantage of only executing point measurements, ignoring the spatial variability of rainfall phenomena. Thus, the use of complementary devices, such as the weather radar can help to reduce this limitation. Additionally, weather radar can be used to forecast precipitation in the very short term, also known as nowcasting, by projecting the movement of rainfall areas.

The radar is an instrument that indirectly measures precipitation. It measures reflectivity that can be transformed into rainfall by the application of Z-R equations (Wilson & Brandes, 1979). When compared with the udometers, the weather radar has the benefit of providing precipitation estimates for an area, which is crucial for the study and understanding of the precipitation conditions that can cause a flood. However, raw radar data is affected by errors, such as ground clutter, beam blockage, anomalous propagation, radome attenuation and the variability of reflectivity-rainfall equations (Wilson & Brandes, 1979), (Raghavan, 2003). Taking into consideration the advantages and disadvantages of this device, a question arises: is the use of radar in hydrology an unfulfilled promise or an unknown potential, (Berne & Krajewski, 2013) ?

In Portugal, the weather radar is commonly used on the detection and monitorization of meteorological events, such as heavy precipitation and strong wind, as well as on functioning as a warning tool for severe weather events, (Barbosa, 2006; Prior et al.,2008).

Due to the uncertainty regarding the quantitative precipitation estimates executed by the weather radar, the rain gauge is the most common instrument used to provide precipitation data for the modelling and forecasting of hydrological events, like floods, at least on an operational level. However, there are already some studies that have explored the application of the radar in these circumstances. Macedo & Hipólito (1997) and Brandão(2018) allied the meteorological radar estimates with the precipitation measurements of the udometric stations, getting successful results on the forecast of flood events.

This work addresses the feasibility and added value of using rainfall data estimated by the Portuguese weather radar to improve flood forecasting, by analysing how it functions on an hindcast situation. To achieve this goal, the flood events of February 2016 and December 2019 that occurred in the city of Águeda were simulated. Using a gauge adjustment technique, the rainfall measured by the weather radar of Arouca was corrected, resorting to the relevant udometers from APA and IPMA. The precipitation data, radar corrected and udometric, were then used as input on the hydrological modelling program HEC-HMS, to transform it into discharge. The resulting discharges were then compared with the discharges measured by the APA river gauges: Ponte Águeda, Ponte Redonda and Ribeiro.

2. Methodology

2.1. Case Studies

The events under study occurred in the city of Águeda, located in the centre of Continental Portugal (Figure 1), more specifically in the sub-region of Aveiro.

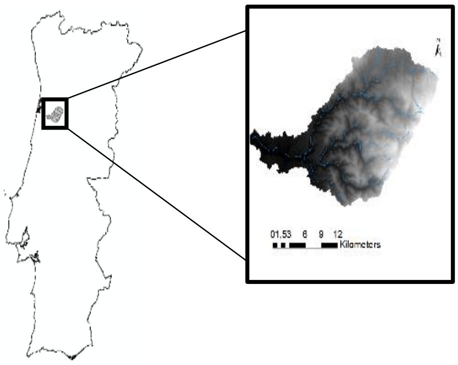


Figure 1. Location of the study area

The city is located by the Águeda river that originates at Serra do Caramulo, in the parish of Varzielas (Oliveira de Frades), and converges into the Vouga river, downstream of the city. The watershed under study is therefore a sub catchment of the Vouga river basin and belongs to the Hydrographical Region 4, managed by the Centre River Basin Authority, from APA.

The watershed boundaries and the drainage paths were determined using the tools available at ArcGIS, namely the ArcHydro and the HEC-GeoHMS extensions, using the digital terrain model (DTM), from nasa.gov, with a resolution of 30m, as an input.

The watershed was divided in subcatchments according with the river gauges operating in on the area, Ponte Águeda, Ponte Redonda and Ribeiro. The subcatchments that generate the discharge measured by the stations of Ponte Redonda and Ribeiro were divided in three subbasins, named after the original subbasin with the addition of the number from 1 to 3, according to the proximity of the subbasin to the station, being 1 the closest and 3 the furthest, (Figure 2, Table 1).

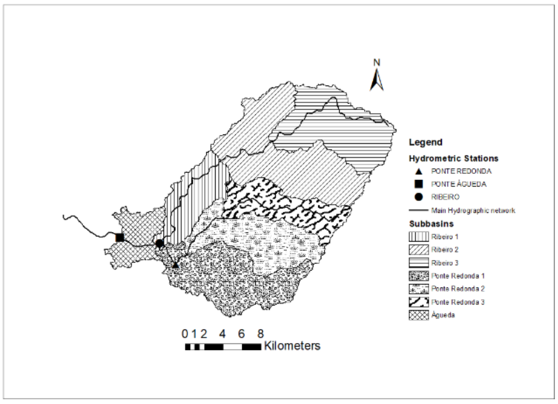


Figure 2. Subbasins and river gauges considered.

Two flood events were analysed. The first event considered took place from the 9th to the 13th of February 2016. This event was characterized by the passage of a frontal perturbation that presented a stratiform precipitation regime. The second event occurred between the 16th and the 23rd of December 2019, it was also characterized by the passage of a frontal perturbation, however in this case the regime was identified as convective.

2.2. Data Analysis

2.2.1. Udometric Data

Due to the complexity of the hydrological phenomena, monitorization systems have been implemented, such as the extensive network of udometric stations that exists on national territory. In this work, the precipitation data collected by the rain gauges that surround the basin were considered. These stations are managed by two entities: Agência Portuguesa do Ambiente (APA) and Instituto Português do Mar e da Atmosfera (IPMA). Both collect information at a sub hourly scale, but for this thesis, the hourly accumulated rainfall measurements were considered. As some stations were inactive or simply did not collect information from 2016 to 2019, the analysis of the 2019 event considers a smaller number of rain gauge records.

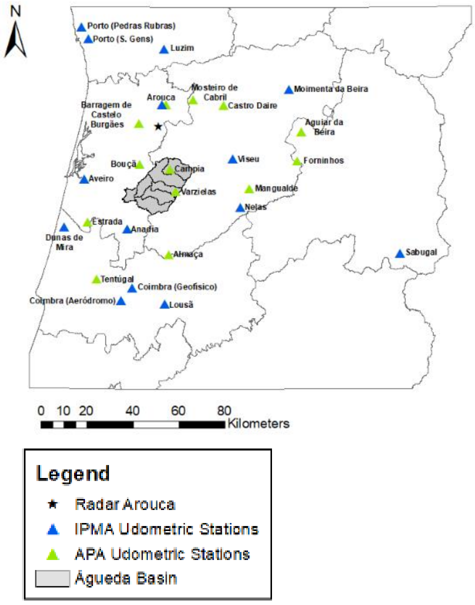


Figure 3 . Location of the udometers.

2.2.2. Weather Radar Data

The radar data used in this work was collected by the weather radar of Arouca, (Geographical coordinates WGS 1984 40,844923 °N, -8,279637°W). This device is a WRM 200 doppler weather radar with a dual polarization C-band magnetron, that provides data about wind and reflectivity.

The precipitation intensity estimates are RAIN 1 products, indicating that the precipitation was hourly integrated by each pixel (1000x1000 m^2), and the visualization maps are P-CAPPIs. Due to an anomaly on the data archive that occurred in the event of February 2016, the periodicity of information collection was variable between events. In 2016, the periodicity was of 10 minutes, while in 2019 the accumulated precipitation data was acquired with a periodicity of 5 minutes. Additionally, there was a failure on the data collection between 13h10 and 14h55, on the 21st of December 2019.

Radar estimates, and therefore the radar rainfall maps, are prone to the influence of external sources, such as surrounding environment, data acquisition devices and transmission devices, that generate random errors/clutter

Table 1. Main characteristics of the subbasins

Basin	Basin Area (km^2)	Slope	River	River Length (km)
Águeda	25,24	0,0024	Águeda	4,45
Ponte Redonda 1	63,47	0,0058	Águeda	5,47
Ponte Redonda 2	51,79	0,011	Águeda	6,28
Ponte Redonda 3	36,31	0,0138	Águeda	15,82
Ribeiro 1	38,56	0,0052	Alfusqueiro	13,35
Ribeiro 2	96,38	0,016	Alfusqueiro	7,27
Ribeiro 3	70,93	0,023	Alfusqueiro	16,92

incorrigible by rain gauge calibration, (Giuli, Baldini & Facheris, 1994). Therefore, the application of the median filter, on a 3x3 window, was used on the processing of the RAIN1 product. This low pass filter is very effective in the reduction of random noise and suppression of impulse noise, also known as, salt and pepper, while retaining the image details since they don't depend on values that ate significantly different from the typical values of the neighbourhood, (Tan & Jiang, 2019; (Xumin & Xue,2011; Rinollo et al., n.d.).

2.3. Precipitation Correction

Raw radar data is usually corrected to increase the accuracy of the radar estimated values of precipitation and to assure that they can be used as a reliable input in hydrological modelling systems, (Ochoa-Rodriguez et al., 2019).

To correct the radar precipitation estimates, a process called gauge adjustments is used. Its goal is to increase the accuracy of the radar precipitation estimates, using mathematical equations that approximate the radar rainfall estimates to the precipitation measurements executed by the udometers. Gjertsen et .al, (2004), recommends this method even though it cannot assure an acceptable result in the whole radar domain.

Considering this technique, two different methods that involve the application of corrective equations were considered: the Single Equation Method and the Multiple Equations Method

The first method considers the precipitation information collected on all rain gauges to determine the corrective equation, which is assumed to be linear. The equation is obtained from the scatter plot of udometric precipitation measurements and measured values by the weather radar at the pixels where the udometers are located. The pixel value was determined by using QGIS to read the precipitation maps provided by IPMA. The resulting equation is then used as a filter for all the raster files that contain the precipitation estimates, and the value of each pixel is changed according to the equation. In this work, the corrective equation used was:

$$P_{corr} = 2.0431 * Pr \qquad (1)$$

where P_{corr} is the corrected precipitation and Pr is the original radar precipitation.

The corrected raster files are then intersected with the basin under study and the new average values of precipitation per subcatchment are calculated. These corrected values per subcatchment are then used as an input on the modelling program HEC-HMS.

The second method, the multiple Curves method, uses distinct corrective equations to adjust the radar files, assuming a different relation between the radar and each rain gauge considered. Similarly, to the previous method, the radar values used to calculate the relationship were withdrawn from the radar precipitation maps, at the exact location of the udometers, resorting to the QGIS program. The measurements are used to create a scatter plot for each udometer and respective radar estimate, and the corrective equations are assumed to be linear, (Table 2).

Table 2. Corrective equations per udometer for multiple equations method

	Corrective Equations
Anadia	$P_{ME} = 2.3093\ P_r$
Aveiro	$P_{ME} = 1.9103\ P_r$
Bouçã	$P_{ME} = 2.2874 P_r$
Campia	$P_{ME} = 1.9406\ P_r$
Varzielas	$P_{ME} = 0.8358\ P_r$

These equations were then separately applied to each radar raster file, and the weight that each udometer corrective equation had on each pixel was calculated using the squared inverse distance factor. Lastly, the corrected precipitation for each pixel was calculated by summing the corrected precipitation per udometer:

$$Pcorr = \sum_{j=0}^{n} wj.P_{ME} \qquad (2)$$

where P_{corr} is the corrected precipitation, P_{ME} is the equation corrected precipitation and wj is the weight of the udometer on the pixel.

The corrected raster files are then intersected with the watershed understudy and the new average values of precipitation per subbasin are calculated. These corrected values per subbasin can then be used as an input on the modelling program HEC-HMS or other hydrological models.

2.3.1. Considerations about the radar data

Impacts on the quality of the Single Equation method

When considering only the data from 2016, a significant variation of the udometer specific correction factors is observed. This variation may be due to the stratiform precipitation regime, characterised by the widespread coverage and the weak reflectivity gradients. The corrective equations obtained with the data from the 2019 event were more homogeneous, with the exception of Varzielas. The limited variability may be related with the regime, since a convective regime is associated with higher reflectivity values, therefore, less probability of the radar missing the precipitation.

The coefficients in 2016 are generally higher than in 2019, so when joining the data there is a middle ground corrective factor. This means that there might be some underestimation on the event of 2016 and some overestimation on the event of 2019.

Impacts on the quantification of udometer factors for the Multiple Equation method

The consideration of the total precipitation affects the factors used. As was the case in the previous situation, when considering the individual equations from each event separately, the factor reduces from 2016 to 2019, in most of the cases. This decrease leads to an insufficient correction of the radar precipitation for the first event, that is especially felt due to Varzielas. Since it is one of the stations with the largest weight within the basin, a final factor under 1, can have a great impact on the results. It was observed that the pixel where this udometer is located was affected by different phenomena in both events. In 2016 (Figure 4), an anomaly was detected that caused attenuation of the precipitation is exhibited. For the event of 2019 (Figure 5), the opposite was detected. It was found that during some periods of time, there were interferences or maybe even clutter on the basin that caused the radar to detect excessive precipitation on the basin when the udometers wither have no collection of these precipitation or the precipitation measured by this device is quite lower.

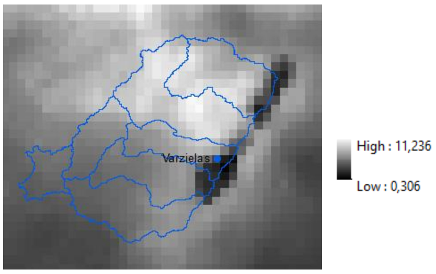


Figure 4.Accumulated Precipitation map on the 9th of Feb 2016

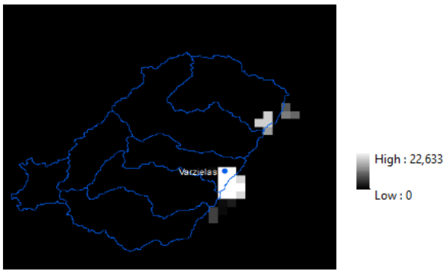


Figure 5.Accumulated Precipitation map on the 17th of Dec 2019.

2.3.2. Hydrometric Data

The hydrometric data is used to compare the simulated discharges with the discharge measured at three river gauges: Ponte Águeda, Ponte Redonda and Ribeiro. The conversion from water height into discharge is executed through the application of the rating curves available at snirh.pt.

The hydrometric records from both events are not complete. Failures occurred during short periods of the 2016 event and during a long period of time for the most recent flood, in Ponte Redonda and Ribeiro stations.

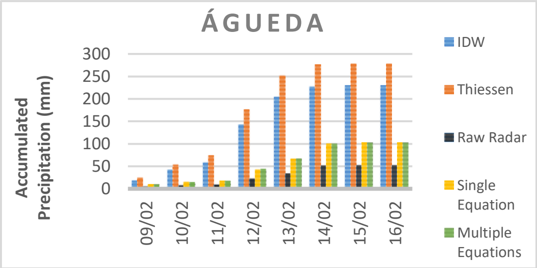
Additionally, there were also several circumstances where the hydrometric level measured was outside of the curve validity range. Without an alternative curve for high level measurements, the existing curves were still used, recognizing that there might be an error associated with these values. Furthermore, the rating curve available for the station of Ponte Águeda expired in 2014. Lacking an actualized rating curve, this equation will still be used, acknowledging that errors may rise from its use.

3. Results and Discussion

3.1. Precipitation

When comparing the original weather radar estimates with the measurements at udometric stations, it is clear that the weather radar underestimates the total volume of precipitation for both events. This underestimation occurs during periods of higher precipitation intensity and is almost non-existent towards the end of the event. This is in accordance with what authors such as (Gjertsen, Šálek & Michelson, 2004; Wilson & Brandes, 1979), had already noted, the radar tends to underestimate heavy precipitation and sometimes overestimate light precipitation.

When considering both events, it was observed that the degree of underestimation of the precipitation by the weather radar was very different, (Figure 6). The difference between the precipitation the udometers measurements and the weather radar estimates is much larger in the 2016 event. These dissimilarities were attributed to the type of precipitation regime that characterizes each event. A stratiform regime, in 2016, which indicates widespread coverage and weak reflectivity gradients, increasing the susceptibility to error and underestimation, a convective regime, in 2019, associated with higher reflectivity values, vertical movements and more prone to the overestimation of precipitation, (Šálek et al., 2004).


ÁGUEDA
Accumulated Precipitation (mm)
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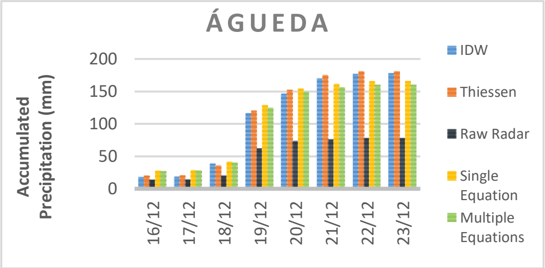
Thiessen
Raw Radar
Single Equation
Multiple Equations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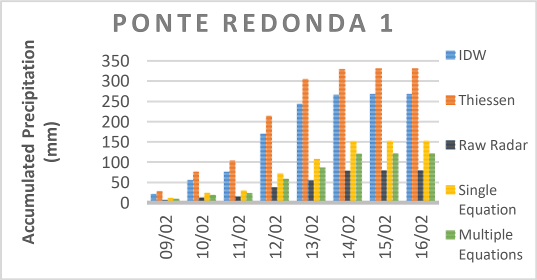
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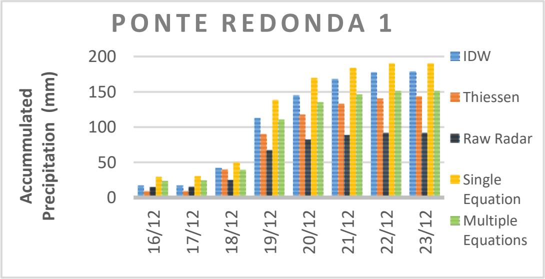
Multiple Equations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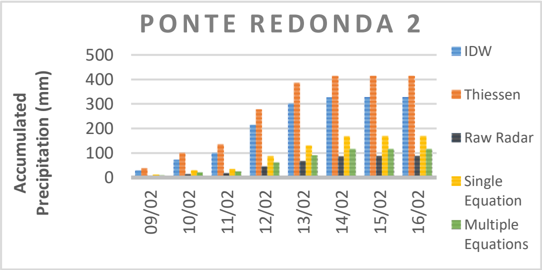
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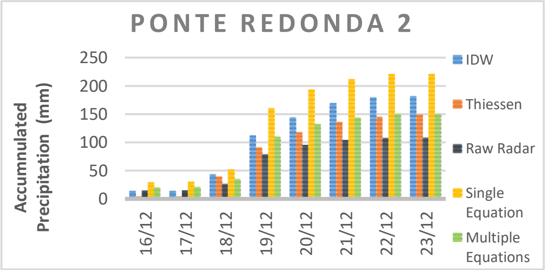
Thiessen
Raw Radar
Single Equation
Multiple Equations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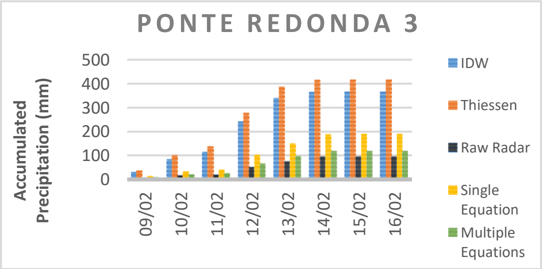
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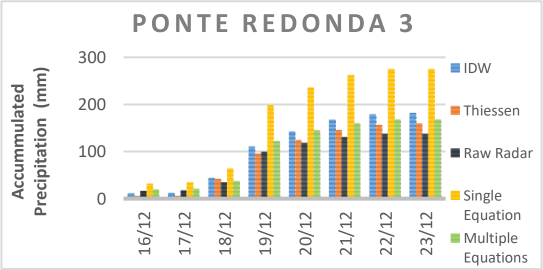
PONTE REDONDA 3
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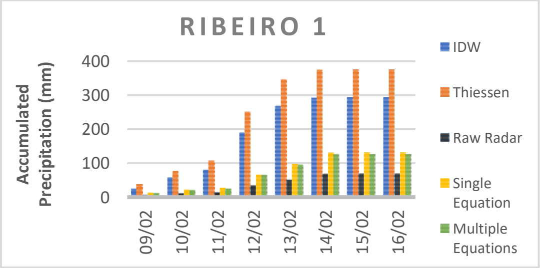
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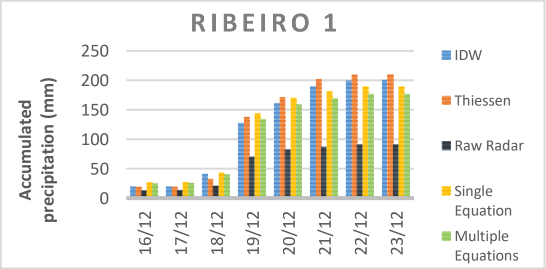
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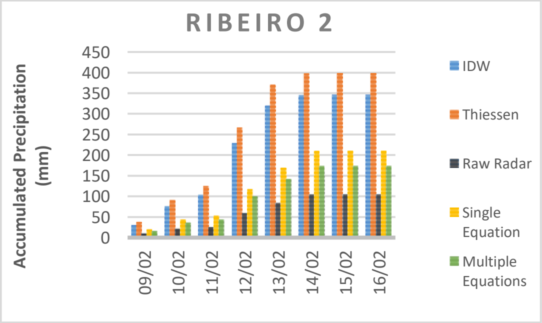
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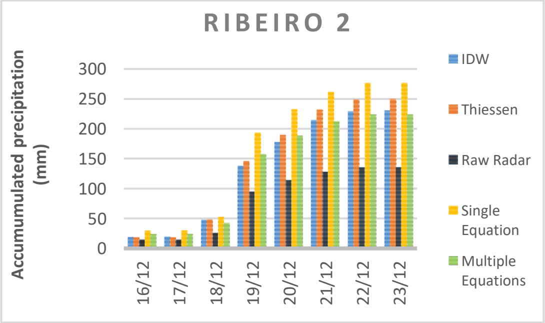
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Accumumulated precipitation (mm)
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Thiessen
Raw Radar
Single Equation
Multiple Equations

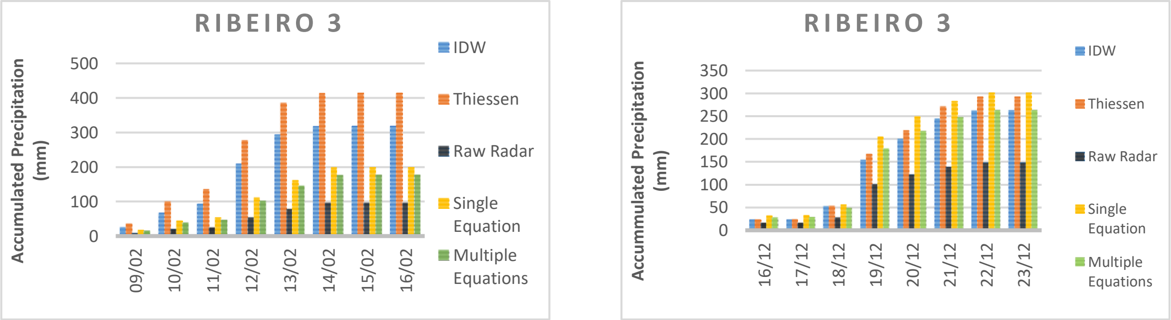

Figure 6. Accumulated Precipitation per subcatchment.

For the single equation method, a single equation that doubled the amount of precipitation estimated by the weather radar was used. For 2016, this increase of precipitation values was insufficient to achieve precipitation results close to the ground truth, due to the low original radar values and to the application of a lower corrective equation than the one needed. For 2019, this method proved to be mostly successful in approximating the estimates to the precipitation measurements executed by the udometers. A significant part of the improvement on the corrected estimations is due to the original estimates performed by the weather radar already being closer to the ground truth values, since this tool performs better in convective events, according to IPMA. The precipitation of this event is also overestimated which was attributed to the fact that the original weather radar estimates are already close to the ones measured by the udometers, for most of the event. In particular, there is an evident overestimation of the corrected values in the Ponte Redonda 3 subcatchment. This problem was recurrent throughout the event and is especially noticeable when considering the total volume of precipitation measured. Another reason for this overestimation, is that the use of a single corrective equation leads to an increase of the factor that would be used if only the data from this event was considered, due to the difference between measurements on the previous event.

For the multiple equations method, the precipitation results were similar to the ones portrayed in the previous method. In 2016, there was an underestimation of the precipitation, that may be attributed to the use of a general corrective factor per udometers. Another aspect that influenced the corrected values, and even the corrective factor used, was the existence of an attenuated region that crosses over the pixel where the udometric station of Varzielas is located. This station is one of the most important sources of information, since is the only one that is located within the studied watershed, in this event, the loss of this data can give origin to an unrepresentative corrective factor, which impacts the whole corrected data, especially when considering that the station of Varzielas is the one that has higher weight overall the watershed. As previously discussed, the station of Varzielas also overestimates the event of 2019, which implies a corrective factor under one. When combining the events data, the final factor is also under one, resulting an underestimation of an already underestimated event. For the event of 2019, it is possible to ascertain that the main goal of approximating the radar and udometric values is generally fruitful and more homogeneously observed. However, and taking into consideration the critics previously made concerning the use of a combined corrective factor, the good results from this event are actually linked with this factor. As aforementioned, on the event of 2019 the calculated corrective expression for Varzielas would be $Pcorr = 0{,}3957Pr$, when in reality the factor used was 0,8358, if the first equation was to be used, it would probably be detected an underestimation of this corrected precipitation for the most of the subcatchments of Ribeiro and Ponte Redonda. This would happen because these are the subcatchments where the Varzielas station has more weight, and the precipitation measured at this station pixel is frequently higher than on the rest of the watershed.

3.2. Discharge

HEC-HMS was used to determine the discharge record from precipitation records. Four sets of discharge records were generated: two computed from udometric data, using the most common spatial interpolation methods, IDW and Thiessen and two radar precipitation estimates corrected using a single equation or multiple equations, (Figure 7).

For the event of 2016, the discharge estimates obtained from udometric records present a good simulation of the event, even displaying some minor discharge variations not presented on other results and reaching the peak discharge. The discharges obtained using the

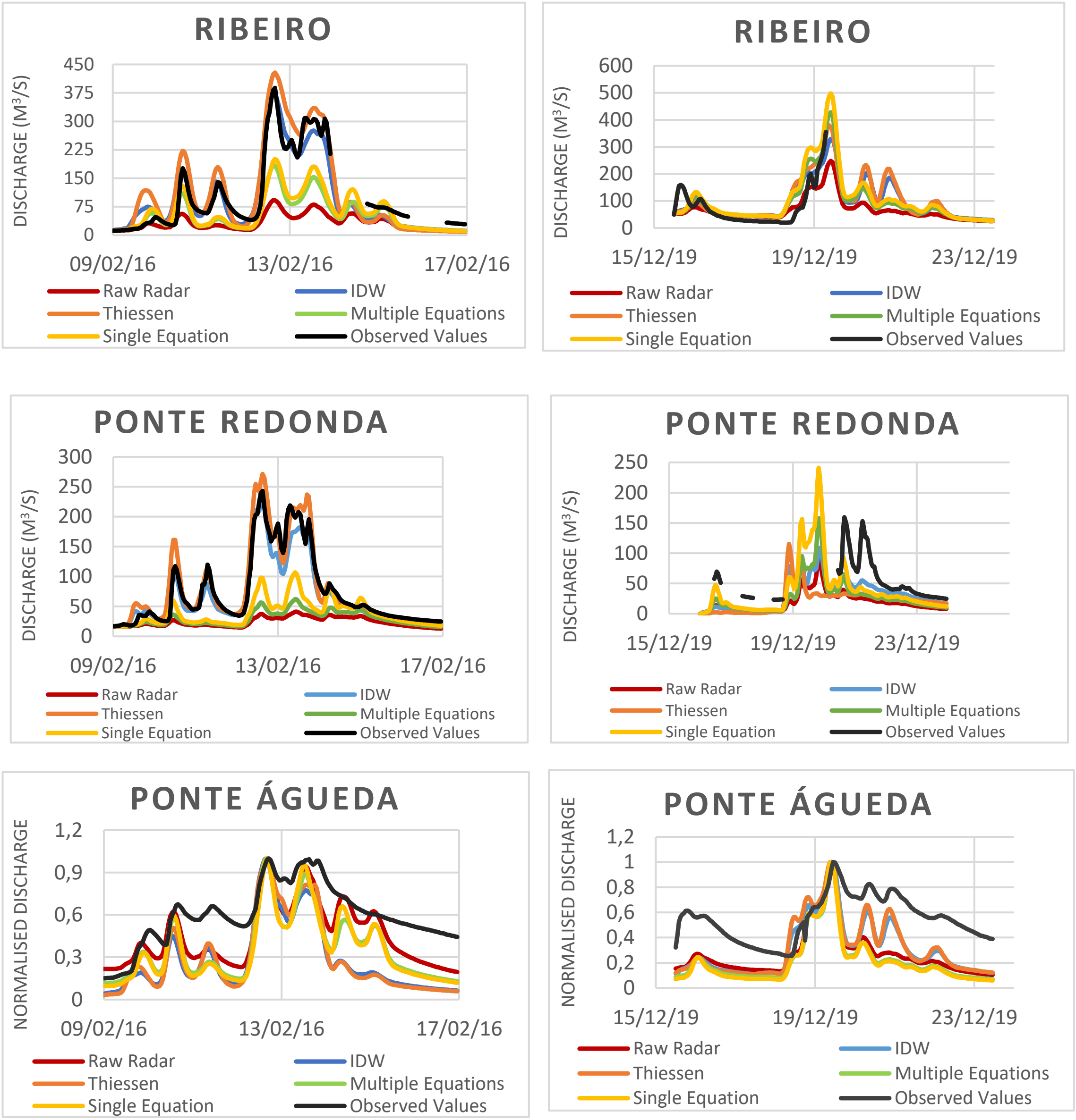

Figure 7. Simulated and Observed Discharges.

IDW estimates follow the recorded discharge accurately until the peak discharge is reached, slightly underestimating the subsequent minor peaks after that moment. The discharges obtained using the Thiessen method overestimate most of the discharge peaks but provides accurate results for other instances of the event. Some of this overestimation may be associated with the use of a single set of values for the HEC-HMS parameters for all precipitation records. The weather radar methods results were consistent with the results obtained on the precipitation correction section, which means that a severe underestimation of the whole event was generated using the single and multiple equations method. The single equation discharges are slightly higher than the multiple equations method, associated with the higher corrected precipitation estimates, however it is still insufficient to be considered a good simulation of the event. Considering Ponte Águeda, the udometric methods were able to simulate the small fluctuations of discharge values. The weather radar methods presented some difficulty on displaying the same fluctuations and smoothens the discharge peak on the descending limb.

The event of 2019 offered different results. The udometric stations offered a good performance, although the IDW method was unable to reach the assumed peak discharge of the event, unlike the Thiessen method. In this event, the udometric methods displayed a lack of sensibility on the small but abrupt discharge variations that occurred on the 19th of December. The radar methods offer a better performance than on the previous event, since they simulate the discharge abrupt variation, however these results are characterized by a possible overestimation of the discharge values. This overestimation is more evident on the single curve method, which is consistent with the precipitation correction results. Although unexpected, due to the similar precipitation results with the IDW method, the overestimation of the multiple equations method could probably be controlled if a personalized set of parameters was used. For Ponte Águeda, the udometric discharges (IDW and Thiessen) offered a good performance, especially the Thiessen method, which was the only method that simulated the discharge variation that occurred on the 19th of December. After the peak discharge, the simulated discharge by the radars smoothens the discharge variations measured at this station, while the udometric discharges, especially the Thiessen, heightens it.

While for the event of 2016 the radar discharges were not successful on simulating the event, the performance for 2019, is assumed to be very good, although the incomplete hydrometric information for the duration of the event, hinders the absolute definition of a very good performance.

4. Conclusions

The application of adjustment techniques to correct radar measurements, on the form of the single equation and multiple equations method, were partially successful. It was concluded that the application of these corrective equations had the ability to close the difference between the original radar estimates to the ground truth values, as measured by the udometers, but not always achieving acceptable corrected precipitation records. The results are extremely dependent on the pre-existent difference between the original estimates and the udometric measurements, highlighting the importance of udometric information to describe the ground truth and the need to use effective corrective methods that are able to correct precipitation events with different characteristics.

The discharge results presented in this study also demonstrate that the weather radar performance is quite variable along different events. For the event of 2016, neither methods presented a reasonable improvement on the discharge estimates. This case study is the perfect example of a situation where the weather radar would have been useful in an operational context. This was mainly due to radar measurement errors, the nature of which was impossible to establish beyond doubt. However, it has been observed that the weather radar had exhibited difficulties in capturing accurate reflectivity information in the precipitation conditions that occurred, the fact that the corrective equations were insufficient to correct the data. There was also pixel corruption, as it occurred in Varzielas, that had a great negative impact on the multiple equation method.

In the 2019 case study, both (single and multiple equation) methods offered better estimates of discharges in River Águeda. The event of 2019 had different characteristics, including a different precipitation regime. In this event there was also a catastrophic failure of river gauges, destroyed by the flood itself. The fact that the discharge results were good, and coherent with registered data before river gauges malfunctioned, allowed to verify the operational potential of the radar, as a redundancy operational alternative. The fact that the correlation between the udometers and the radar were less variable in this event, also indicates that these methods would work better in 2019.

The evaluation of the performance of the weather radar for each case-study led to different but complementary conclusions. The event of 2016 lays the argument for the need to carefully analyse the precipitation maps generated by the weather radar, since they may induce the operator in error. To avoid major forecasting errors, it is advisable to use the weather radar within a framework of redundancy, complementary to with other precipitation gauges, namely udometers.

The event of 2019, suggests that even a simplistic methodology, as that adopted in this dissertation, may be sufficient to correct the estimates of weather radar and render them useful at operational context, as a redundancy alternative, when there is lack of hydrometric data and in the event of failure of udometric stations.

5. Recommendations

Although the case studies used in this thesis suggest that the weather radar does not consistently provides extra relevant information for flood modelling and forecast, it must be recognised that there is still a significant room for improving the methods to validate and correct the weather radar precipitation measurements.

The precipitation correction results indicate a need to find a methodology that analyses the precipitation maps and detects corrupted pixels, minimizing the impacts that these can have on the results, for instance by replacing the pixel measurement from the radar surface by a statistic of the pixels within a window. The use of additional precipitation data, both from udometers and radar, would increase the statistical confidence of the correlation models.

For the hydrological model, using a set of parameters that are adequate for the method considered may also increase the performance of the method, the calculation of a rating curve for the station of Ponte Águeda would allow for a more accurate calibration of the methods and analysis of the event results.

Beyond data treatment, the application of these methods to other basins with different size and orography may also allow to understand what other factors can affect the final results.

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