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**NOVOS
DESAFIOS**

NOMOGRAPHS IN FLOOD FORECASTING

Application to Portuguese catchments

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Abstract

Flood forecasts may have a major role in flood warning systems, namely in regions prone to flash floods. The work presented is focused on a data-driven model for flood forecasting, whose performance is analysed for mainland Portugal. The model uses statistical relationships derived from rainfall and discharge data, in the form of nomographs, to generate flood discharge forecasts. Importantly, this is the first time that such a model is applied in Portugal.

A nomograph is a graphical representation of an equation of several variables consisting of as many graphical elements as variables has the equation. These elements are points or lines, straight or curved, as appropriate. A nomograph based on an equation of three variables, as considered in the present work, provides the flood event in instant i as a function of the discharges in instants i and $i + 1$, and of the rainfall in instant i . The moderate computing time and the limited data input requirements of such model make its application very advantageous. However, the suitability of the nomographs for each specific application relies on factors such as data availability, complexity of the rainfall-runoff processes, and temporal and spatial scales.

The case studies were three Portuguese river gage stations, namely Monte dos Pachecos, Castro Daire and Ponte Águeda. The nomographs were applied at a daily level aiming at producing forecasts one day ahead. For Ponte de Águeda the model was also used at an hourly level, with very promising results regarding its capability to provide forecasts for the next 4 and 12 h.

The calibration processes demonstrated that the model is efficient and easy to establish, provided that the proper input data set is identified. The model also proved to be robust with outputs from the validation phase consistent with those from the calibration phase.

Keywords: Flood forecast, discharge forecast, nomographs.

Topic: *Gestão de recursos hídricos e bacias hidrográficas.*

1. INTRODUCTION. MODEL FRAMEWORK

Flood damages have been increasing all around the world in the last decades (WMO, 2017) due to factors such as the increasing frequency of heavy rainfall, the changes in the upstream land-use and, especially, the growing concentration of population in areas prone to floods (Collier, 2007) which makes flood forecasting still a relevant issue. In recent years, the incorporation of flood forecasts in flood warning systems received much attention aiming at improving the performance of those systems and at implementing flood control measures (Toth *et al.*, 2000). For that purpose, conceptual models, such as the one proposed in this paper, can be advantageous and easily operated with fewer data resources. Furthermore, these models provide additional information for developing temporary defences, operating flood alleviation schemes and other critical assets. However, questions such as how accurate the models are when applied to daily and hourly data and how robust are their discharge forecasts still need to be addressed.

A hydrological forecast is an estimate of the future state of a hydrological phenomenon (WMO, 2011). Since floods are rare and unpredictable events, anticipating them with enough warning time is one of the main objectives of research (Estupina-Borrell *et al.*, 2006). The time factor is very important when addressing the floods. In fact, the usefulness of a flood forecasting system depends largely on the time gap between the issuing of a warning and the water arrival, sometimes a matter of a few hours (Richards & Clark, 1974).

Flood forecasting models are based on the study of local weather and seasonal variations in river flow and their ability to respond to extreme rainfalls (WMO, 2011). The specific role of flood forecasting is different depending on the circumstances dictated by the local hydrometeorological and built environments (Moore *et al.*, 2005), obviously, besides the catchment morphology. The nature of a flood event is also important, especially when floods occur regularly. Thus, there is no specific fixed design for a flood forecasting system. The balance among different components (e.g. meteorological and hydrological forecasts, scale and timing) must be adjusted to the circumstances (Moore *et al.*, 2006). In some cases, mathematical models for flood forecast can use statistical relationships to predict floods, e.g. data-driven models (Hapuarachchi *et al.*, 2011). Often, the models based on less input data have a better performance than more complex ones when the physical processes and their interactions are poorly understood or known. The main disadvantage of those simpler models is that they are often based on site specific relationships hard to generalize. However, the relatively moderate computing time and input data they require make their application very advantageous in the context of rainfall-flood discharge forecasting.

The suitability of a model when operated under extreme conditions is a key factor to consider in model generation, since there can be a high risk of poor results in using purely data based methods. In each specific application that suitability relies on factors such as input data availability, process complexity, temporal and spatial scales and the envisaged outputs. Most hydrological models perform well in humid zones, however, not in arid and semi-arid zones,

often characterized by more complex hydrometeorological processes (Collier, 2007) and greater spatial and temporal variability of the hydrological variables.

In Portugal, dams and lateral dykes, among other structures, have been built to prevent flooding in cities and industrial areas. However, those structures do not provide a full protection against flood, which still makes flood forecasting a useful tool for flood management. Additionally, due to the specific features of the relief and of the extreme rainfall regime, the country is particularly prone to flash floods that affects small to medium natural catchments and that last for only a few hours to a few days (Ramos & Reis, 2001).

Within the previous framework, this work analyses the possibility of building a simple, yet accurate, conceptual approach for short term flood forecast based on daily and sub-daily data, and that could be operated without requiring specific skills. For these purposes nomographs were developed due to their practicality and availability. It is important to mention that the proposed approach was applied in other countries with good results (Espinosa, 2016) but never to Portuguese catchments.

To test the use of nomographs in flood forecasting, rainfall and discharge data from three catchments with different hydrological constraints (from semi-arid conditions, in the south, to humid conditions, in the north), but with areas of similar magnitude, were adopted as case studies. Aiming at identifying the optimum model structure, different conditions were considered regarding the time interval used to compute rainfall before each flood and the threshold for flood recognition.

The mathematical representation of the flood forecasting model can be expressed as:

$$f(Q_{i+1}) = f(Q_i, P_i^x, P_i, \dots) \quad (1)$$

where the initial state is given by the current discharge, Q_i , and the pressure is the (cumulative) rainfall in the previous x hours, P_i^x , or the current rainfall at day/instant i , P_i , and the response of the system is the discharge in the next time step, Q_{i+1} , i.e., the forecasting target. In order to account for the effect of the time step in the forecasting capability of the nomographs, applications based on daily and sub daily data were carried out for one of the studied catchments. However, it is important to stress that, regardless of the approach, the forecasted discharge will always have a certain error and uncertainty, because the relationship between the rainfall and the discharge is necessarily affected by randomness of the phenomena (Toth et al., 2000).

2. STUDY AREA

The case studies refer to three river gage stations, under natural conditions, with catchments areas with similar magnitude (in order make the results more comparable) and located, one in the south of Portugal, and two in north, respectively: Monte dos Pachecos (Faro district; Odelouca stream, 386 km^2), Castro Daire (Viseu district; Paiva River, 288 km^2) and Ponte Águeda (Aveiro district; Águeda River, 404 km^2). The area of the catchments were obtained from the hydrological database *Sistema Nacional de Informação de Recursos Hídricos*

(SNIRH - <http://snirh.pt>), and confirmed by generating the catchments using a Geographic Information System.

3. MATERIAL AND METHODS

The rainfall and discharge data necessary to forecast the discharges were obtained from the SNIRH. Daily rainfalls and mean daily discharges are available for the three catchments from 1962-1993 with a few rainfall gaps that were easily filled by weighting the records at nearby rain gages. For Ponte Águeda hourly rainfall and discharge data were also available, although only from 2000-2012.

3.1 Threshold set-up

The establishment of a flood threshold, R_T , is a critical decision when issuing warnings. A low threshold would lead to numerous false alarms while a relatively high one would increase the number of unannounced flooding events (Siccardi *et al.*, 2005). The selection of the suitable threshold is subjective and requires a comprehensive practical experience.

Keeping in mind that seven times the long term mean daily flow, Q_{mod} , can be considered a lower limit to identify the flood occurrences (Quintela, 1984), thresholds from two to five times Q_{mod} were adopted and tested when applying the model based on daily data. Accordingly, all the discharges above R_T were considered floods events. At each iteration, the same R_T selection criterion and, for each R_T , the same period of analysis were used in the three catchments in order to evaluate the relative improvements of the model.

However, when considering the hourly data at Ponte Águeda, because floods are reported to occur for discharges above $Q = 400\text{m}^3/\text{s}$, thresholds around this value were analysed. It is important to mention that, due to input data availability constraints at this river gage station, it was not possible to compare the results from daily and hourly data based on a same period.

Having a number of suitable extreme events, three variables were used to generate nomographs: the dependent variable Q_{i+1} (discharge in the next day or instant $i + 1$), and two explanatory or independent variables, namely, Q_i (discharge at current day or instant i) and P_i or P_i^x (rainfall at the same day or instant i or rainfall in the previous x hours). Since in Portugal there are not extreme floods during the dry season, only the wet one, from October to September, was analysed.

3.2 Nomographs generation

Nomographs generation has been used in other science fields besides engineering (Timmons *et al.*, 1984) because of its suitability for representing the interaction among several physical properties. A nomograph is a graph to solve an equation using a representation that allows fast numerical calculations. In its most general concept, the nomograph simultaneously represents the set of equations that define a given problem and

the full range of their solutions (Wischmeier *et al.*, 1971). A nomograph must consist of as many graphic elements as variables an equation has. These elements are points or lines, straight or curved, as appropriate. In other words, a nomograph of an equation of three variables (e.g. $Q_{i+1} = f(P_i, Q_i)$) typically consist of three scales which is the case of the applications carried out (Figure 1).

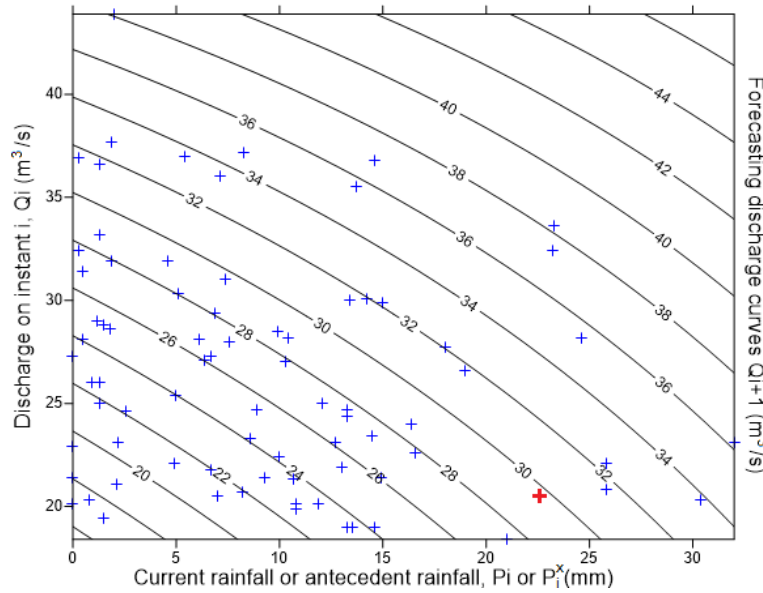


Figure 1. Example of a nomograph, based on daily data. The blue crosses (P_i, Q_i, Q_{i+1}) are observed extreme events for Q_i above an adopted threshold. The measured data that to which the red cross refers is $P_i = 22.6\text{mm}$, $Q_i = 20.5\text{m}^3/\text{s}$, $Q_{i+1} = 29.54\text{m}^3/\text{s}$. For this point, the solution of the problem, given by interpolation between the two black curves for 28 and $32\text{m}^3/\text{s}$, is $Q_{i+1} \approx 29.36\text{m}^3/\text{s}$.

Each point represented in Figure 1 by a blue cross refers to measured conditions, namely: (i) the current discharge (above the adopted threshold), Q_i (given by the vertical axis); (ii) the pressure, i.e., the current rainfall or the antecedent cumulative rainfall, P_i or P_i^x (given by the horizontal axis); (iii) and the discharge in the next instant, Q_{i+1} (that would appear in a third axis, not included). The lines are the 2D solution of the three dimensional problem (De-Lima, 1990), i.e., the forecasting discharge curves. The nomographs with three variables applied to the case studies were developed using the software *Surfer Ver.9*. The gridding method, described in detail in the user's manual (Golden Software, 2014), should be tested because the shape of those curves depends on its selection. Since one of the advantages of using nomographs is to have a helpful visual representation, we opted for a polynomial regression (bi-linear) as gridding method because it produces forecasting discharge curves easier to read by the users.

The regression coefficients generated by the gridding method were identified by A_{00} , A_{01} , A_{10} , A_{11} according to:

$$\text{Forecasted } Q_{i+1}(P_i \text{ or } P_i^x, Q_i) = A_{00} + A_{01}Q_i + A_{10}P_i + A_{11}P_iQ_i \quad (2)$$

The advantage of a graphical representation is obvious, since in a single chart several elements can be found almost simultaneously. Additionally, the shape of the curves of the nomographs can be related to the behaviour of the catchments under flood conditions. In fact, previous applications (Espinosa, 2016) suggest that the curves with upward concavity can be interpreted as floods requiring large amounts of rainfall to happen. Furthermore, curves with downward concavity, as those of Figure 1, can mean that floods are “pressure oriented”, or rainfall-triggered, and that even low rainfalls could lead to marked changes in the discharges.

Different statistical indicators can be used to assess the quality of the model. The Pearson’s correlation coefficient, r , was used to judge if the model represents correctly the data (Vujica, 1972), implying that the if the correlation coefficient between measured and calculated Q_{i+1} is not significantly different from 1 then the model is accurate enough. Finding the appropriate model is a heuristic trial-and-error process done by combining different thresholds, reference periods, gridding methods, etc. If high correlations are obtained from an exploratory analysis, then the model must be calibrated and validated before being adopted in a flood forecasting system.

3.3 Rainfall in the last seventy-two hours (P_i^{72h}) criterion

In some applications, the actual rainfall, P_i , was replaced by the rainfall in a longer period, namely in the last 72 h, P_i^{72h} , in order to take into account for the antecedent rainfall conditions and for the time required by the propagation until the outlet of the catchment of the flood thus originated. Despite the arbitrary nature of this time interval, 72 h is a commonly used value in rainfall analyses (Schröter *et al.*, 2015). The results obtained by considering P_i^{72h} , for Castro Daire, were compared with those from P_i .

3.4 Weighting factors for antecedent rainfall

The P_i^{72h} criterion considers that the influence on the actual flood event of the rainfalls in the previous three days does not depend on the temporal pattern of those rainfalls. To improve the mathematical formulation of the model based on such criterion, larger time windows of several days were adopted. When computing the cumulative rainfall, weighting factors were assigned to the rainfalls in the days that preceded each flood event. The values of the weighting factors, WF , took into account the correlation (according to the available data) between daily discharges, Q_i , and antecedent rainfalls with different time intervals, from P_i to five days before P_i , i.e., P_{i-5} . This approach was applied to the three studied catchments.

3.5 Sub-daily data approach

The analysis of the performance of the model at a sub-daily scale utilised the only river gage station with compatible data, namely Ponte Águeda (data from Nov. 2000 to Jul. 2012).

When applying the model at a daily scale we always considered that one day-ahead forecasts were envisaged and that P_i and Q_i referred to the same day and Q_{i+1} to the discharge in the next day. However, these variables are not directly adaptable to an hourly scale, by replacing days per hours, because, in one hand, it is meaningless to issue warnings only one hour in advance, and in the other hand, the dependency between rainfall and discharge at such scale is much more complex. Having this in mind, when using hourly data we considered that we could assign to P_i^x either the actual discharge, Q_i , or the discharge before the actual time, Q_{i+j} , with $j = \pm 1, 2, \dots, 24 h$. Furthermore, the discharge to be forecasted was defined as Q_{i+ct} , being ct the forecasting capability in h .

In order to identify the number of hours of x and ct that should be considered when computing P_i^x , Q_{i+j} , Q_{i+ct} , a correlation analysis was performed, based on hourly rainfall and discharge data, between P_i^x and the changes of the discharges ΔQ_k , for different time frames, i.e., $\Delta Q_k = Q_{i+ct} - Q_{i+j}$, with $k = 3, 6, 9, \dots, 20, 24 h$, and $j = ct - k$. If such correlation exists it would mean that the cumulative rainfall has a significant influence on the discharge changes, making possible to identify not only the forecasting capability of the model (ct) but also the input data for the nomographs establishment (P_i^x , Q_{i+j} , Q_{i+ct}). In this case Equation 2 becomes:

$$\text{Forecasted } Q_{i+ct}(P_i^x, Q_{i+j}) = A_{00} + A_{01}Q_{i+j} + A_{10}P_i^x + A_{11}P_i^x Q_{i+j} \quad (3)$$

Figure 2a), exemplifies how P_i^{6h} , cumulative rainfall for $x = 6h$, is correlated to the changes of the discharge ΔQ_{3h} . This rainfall was obtained from the runtime correlation curves shown in Figure 2b), since P_i^{6h} (highlighted with a yellow point at $ct = 2h$) exhibits the highest correlation coefficient in comparison to six other cumulative rainfalls. If the discharge are forecasted using input values for a ΔQ_k or a ct with lower correlation, a lower r between measured and forecasted discharges Q_{i+ct} is expected.

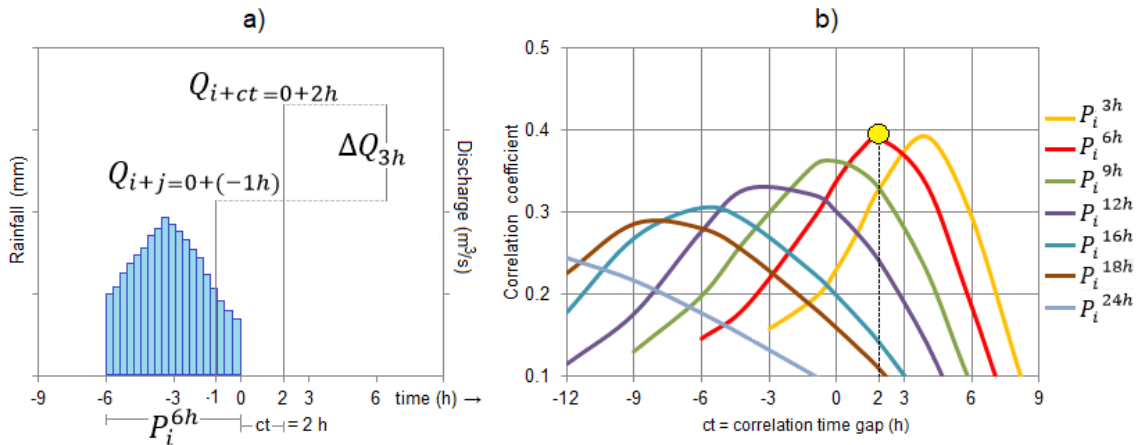


Figure 2. a) Rainfall P_i^{6h} and ΔQ_{3h} for $i = 0h$, $j = 2 - 3h = -1h$. b) Runtime correlation curves of different rainfalls $P_i^{3h \text{ to } 24h}$ with ΔQ_{3h} and different ct (from -12 to $9h$).

4. RESULTS AND DISCUSSION

4.1 Monte dos Pachecos for P_i

The model was firstly applied to Monte dos Pachecos river gage aiming at producing one day-ahead forecasts.

Based on the period from 1962 to 1993, 490 events were identified as extreme events for the threshold of $4 Q_{mod}$. The nomographs thus obtained are shown in Figure 3 for different gridding (polynomial and Shepard's) and regression methods. For the sake of the readability of the figure, the vertical axis was limited to $Q_i = 250 \text{ m}^3/\text{s}$ (the 10 events with higher discharges are not represented). The correlation between measured and forecasted Q_{i+1} for a polynomial regression and bi-linear saddle was $r = 0.41$ (Figure 3a). The correlation coefficient also for a polynomial regression, but combined with a cubic surface (Figure 3b) was $r = 0.43$, meaning that more complex solutions (as denoted by comparing the shapes of the two first nomographs), did not improve the performance of the model. Shepard's method was also used, but with absurd results, resulting in null or even negative forecasted Q_{i+1} (Figure 3c). Accordingly, Figure 3 shows that the method, with its current structure, is definitely not suitable for Monte dos Pachecos catchment.

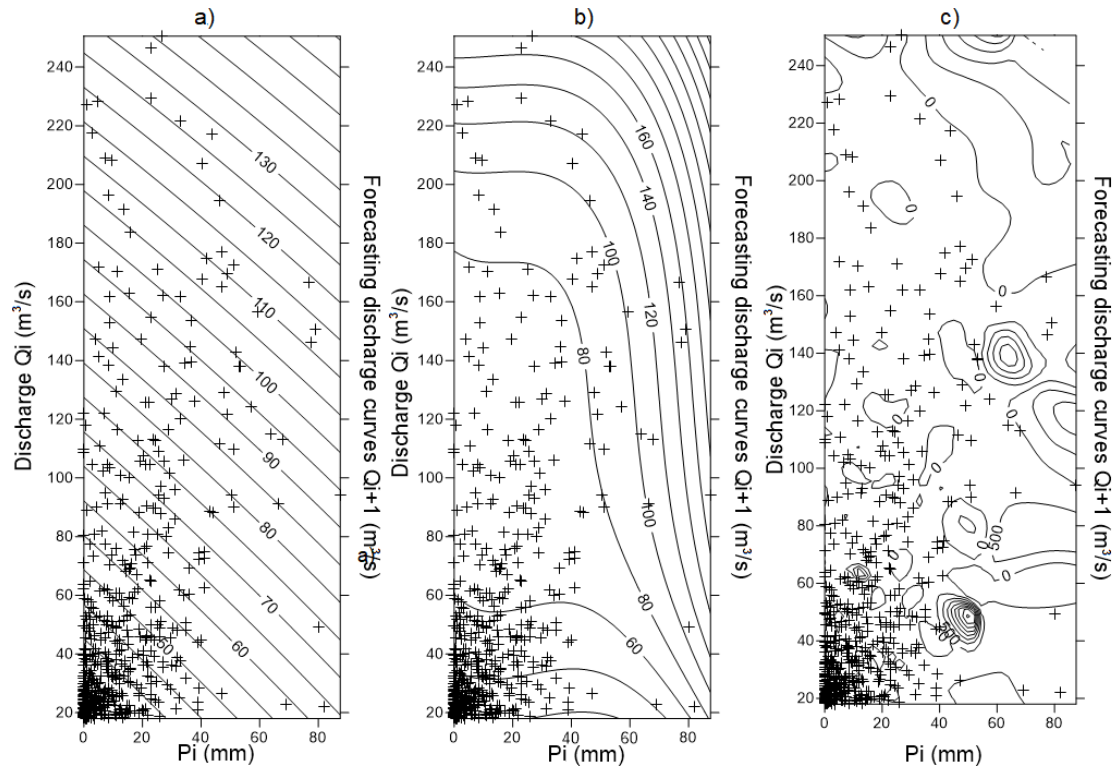


Figure 3. Nomographs from 1962 to 1993 in Monte dos Pachecos catchment to forecast Q_{i+1} :
 a) Polynomial-bi-linear gridding; b) Polynomial-cubic gridding; and c) Shepard's method.

4.2 Antecedent rainfall for Castro Daire (P_i^{72h})

The data at Castro Daire river gage station were divided into two data sets: the calibration period, from Oct. 1950 to Sep. 1975, and the validation period, from Oct. 1975 to Sep. 1987. The threshold adopted was $5 Q_{mod}$ ($32.8 m^3/s$) and the nomographs were generated with polynomial-bilinear-gridding using as inputs (P_i^{72h}, Q_i, Q_{i+1}) for $Q_i > R_T$. The number of flood events and the correlation between measured and forecasted events, Q_{i+1} , were 339 events and $r = 0.53$, for the calibration period, and 176 events and $r = 0.65$, for the validation period.

The correlations when considering only P_i , were slightly smaller than those now achieved ($r = 0.50$, for the calibration period, and $r = 0.61$, for the validation period), meaning that it is relevant to take into account the rainfall before the actual day. Because of this, the model based on weighted antecedent rainfalls was also analysed, as mentioned in the next section.

4.3 Weighting factors criteria applied in the three catchments

In order to address the performance of the model when considering longer antecedent rainfalls with different temporal patterns, the data from the three catchments was also split into a calibration period (Oct. 1970 to Sep. 1990) and a validation period (from Oct. 1960 to Sep. 1970). The flood threshold adopted was $2 Q_{mod}$ resulting in $9.62 m^3/s$, in Monte dos Pachecos, $13.52 m^3/s$, in Castro Daire, and $18.41 m^3/s$, in Ponte Águeda. The forecasting solutions for the three catchments were calculated with a polynomial-bi-linear gridding, as in the previous section, but based on the actual rainfall plus the cumulative rainfalls in the 5 previous days affected by weighting factors, namely, $P_i + (\sum_{i-1}^{i-5} P_i * WF)$.

Table 1 summarises the correlations between measured and calculated discharges, Q_{i+1} . Castro Daire and Ponte Águeda had acceptable performances while Monte dos Pachecos had a poor performance. It is worth mentioning that this last catchment has the highest observed discharges, but the lowest antecedent rainfall in comparison to the other two catchments. The results from the calibration and validation period did not show big differences, which suggests that the model is a robust tool, with similar results regardless the period used to establish its framework.

Table 1. Number of floods and correlation coefficient, r , between calculated and measured discharge for weighted antecedent rainfalls.

Catchment	Calibration 1970-1990	Validation 1960-1970
Monte Dos Pachecos	491 floods, $r = 0.50$	404 floods, $r = 0.59$
Castro Daire	661 floods, $r = 0.70$	451 floods, $r = 0.66$
Ponte Águeda	813 floods, $r = 0.72$	508 floods, $r = 0.84$

4.4 Sub-daily flood forecasting at Ponte Águeda river gauge station

Rainfall and discharge data at sub-daily scale from SNIRH at Ponte Águeda river gage station were analysed for the period from Nov. 2000 to Jul. 2012. As described in 3.5, the first step was to identify the relevant values of P_i^x and ΔQ_k .

Two runtime correlation analyses of ΔQ_k , and rainfall P_i^x (for values of x of 3, 6, 9, 12, 18, 24 h), at different time gaps (ct) are exemplified in Figure 4. P_i^x is correlated to ΔQ_k only for a certain period, for instance, according to Figure 4a), P_i^{12h} is positively correlated at different levels with ΔQ_{20h} over a period of 27 h, P_i^{9h} over 25.5 h, P_i^{6h} over 24h and so on. The curves with highest correlations can be found around $ct = 4h$ for both runtime analyses. This helped us to identify the data structure, however keeping in mind that ΔQ_k should be equal or higher than the forecasting capability, ct . We stress that moving forward ΔQ_k is always possible, but not the opposite way, which would mean that we would be relating the influence of discharge on future rainfall.

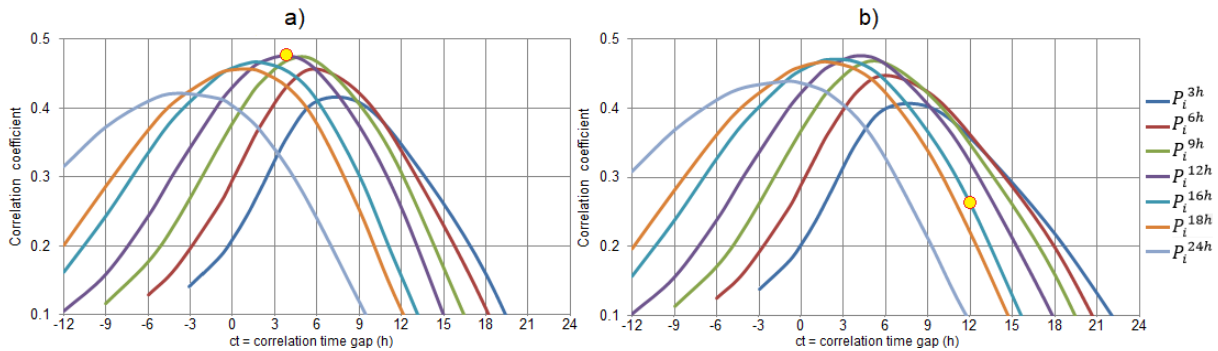


Figure 4. Runtime correlation curves for: a) ΔQ_{20h} ; and b) ΔQ_{24h} : The yellow circles highlight the chosen P_i^{12h} and P_i^{16h} and the corresponding correlation time gaps, ct , of 4 h and 12 h, respectively. Each paired P_i^x and ct was adopted to identify the input data sets for flood forecast.

Once the runtime correlation curves for different parameters (ΔQ_k , P_i^x , and ct) were obtained and the data structure identified (based on the highest correlation coefficient criterion), two input data sets were formed, aiming at comparing results: one based on P_i^{12h} , $ct=4h$ and $\Delta Q_{20h} = Q_{i+ct=i+4h} - Q_{i+j=i-16h}$ and with the highest runtime correlation coefficient (Figure 4a, $r = 0.48$) and another based on P_i^{16h} , $ct=12h$, and a $\Delta Q_{24h} = Q_{i+ct=i+12h} - Q_{i+j=i-12h}$, with a very small runtime correlation coefficient (Figure 4b, $r = 0.27$). The following three thresholds were considered (the number of floods for each threshold is specified between brackets): $R_{T1} = 100m^3/s$ (3504 floods), $R_{T2} = 200m^3/s$ (1775 floods), and $R_{T3} = 400m^3/s$ (238 floods).

The nomographs for the first input data set, ΔQ_{20h} , and for each one of the previous thresholds are shown in Figure 5. The similar shape of the nomographs of Figure 5, regardless the threshold, R_T , suggests that the model is stable even when a considerable small number of floods is used to establish it.

For the two input data sets considered, the overall performance of the model, expressed by the correlation coefficient, r , for any of the adopted thresholds, was 0.90 and 0.64 for the forecasting capabilities of $ct = 4h$ and for $ct = 12h$, respectively. The smaller r achieved for $ct = 12h$ is justifiable, since the corresponding input data set has a lower runtime correlation coefficient, as previously shown (Figure 4).

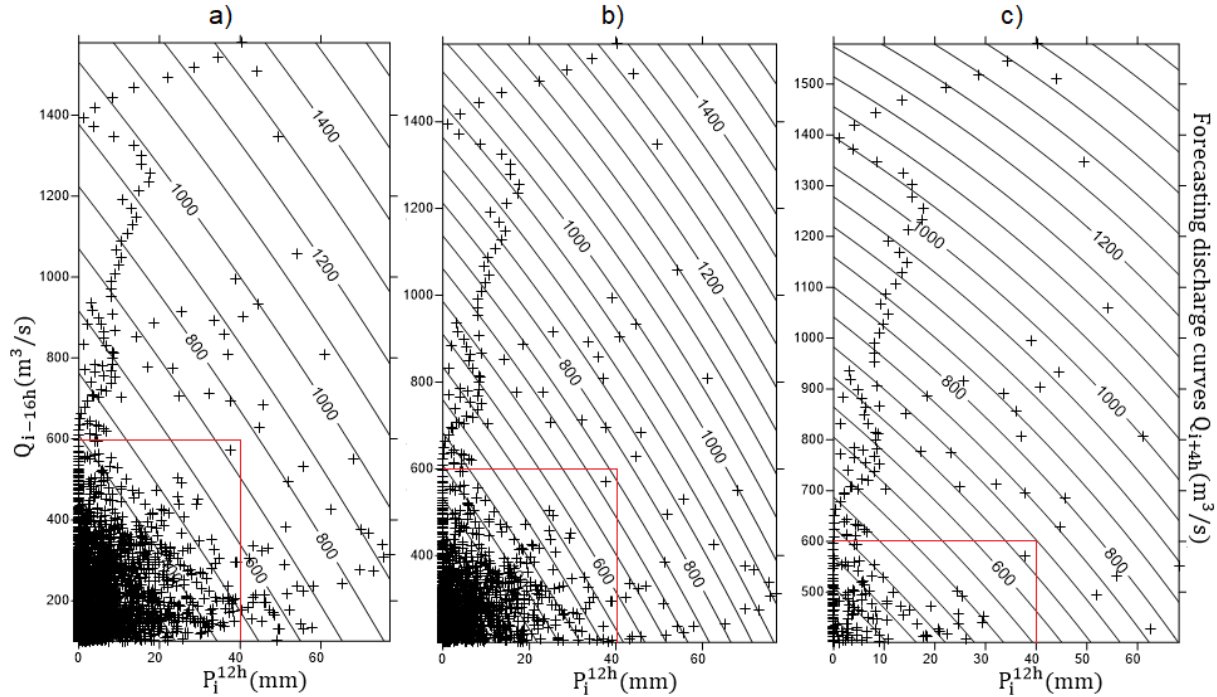


Figure 5. Hourly data nomographs generated with a polynomial-bi-linear gridding for Ponte Águeda for P_i^{12h} , $ct=4h$ and ΔQ_{20h} . The marks $(P_i^x, Q_{i+j}, Q_{i+ct})$ are observed extreme events for Q_{i-16h} above the threshold, R_T , of: a) $100m^3/s$; b) $200m^3/s$; and c) $400m^3/s$. An interpolated forecasted, Q_{i+4t} , of 700 to $750m^3/s$ is achieved for $P_i^{12h} = 40mm$ and $Q_{i-16h} = 600m^3/s$.

5. CONCLUSIONS

The objective of the research discussed in this paper was to make an exploratory analysis, for mainland Portugal, on the use of nomographs for flood forecast at different time scales, based solely on measured rainfall and discharge. The performance of the model was tested for the three Portuguese river gage stations of Monte dos Pachecos, Castro Daire and Ponte Águeda. Different time scales (daily and hourly) and different criteria to identify the input data were considered and the results achieved briefly presented and, whenever possible, compared.

The model proved not to be suitable to forecast floods in Monte dos Pachecos whereas for Castro Daire and Ponte Águeda the one day-ahead forecasts were quite acceptable. Based on Ponte de Águeda, the only catchment with hourly data, an improved formulation was achieved, able to provide forecasts with a few hours ahead.

However, only three case studies were analysed. Additional case studies and different frameworks (involving different time steps, input data sets, and gridding methods) need to be considered before concluding if nomographs are a suitable tool for flood forecast in mainland Portugal.

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