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Runoff analysis of the Couto de Andreiros hydrometric station watershed using geographic information systems

Extended Abstract

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Scope

The present study's objective was to analyze the creation of flood hydrographs as a consequence of precipitation events in the watershed of the hydrometric station of Couto de Andreiros, localized in the Raia or Seda stream (river Tejo watershed) through the combination of hydrological models and geographical information system tools.

Flood analysis has always been of the outmost importance, due to its application in the design of infra-structures, such as hydroelectric plants, bridges, or in the scope of riverine rehabilitation and flood mitigation studies. The Human and financial cost that is dependent on these structures can be very high so we can't stress enough the importance of these studies at the early design stage.

In effect, this work uses geographical and hydrological information and programs available to the engineering community, in combination with GIS software to export the gathered information to a hydrological model on the HEC-HMS. This model was used to calibrate several parameters and finally as a validation tool. During these steps, namely the calibration phase, the HEC-HMS model's parameters used a selection of hydrographs recorded in the Couto de Andreiros hydrometric station and establishing hietograms derived from those hydrographs at points with influence at that station. The optimized parameters were then used in multiple simulations with precipitation events differing from the initially used to calibrate the model's parameters, and with validation through comparison with the hydrograph recorded at the station.

Watershed Characterization

The Couto de Andreiros Hydrometric station, and was selected because of its particular location, enabling the correlation between models and the precipitation records and the actual drainage runoff recorded at the Couto de Andreiros hydrometric station. You can find the main operational characteristics of the station on Table 1.

This study provided a climatic, geographical and morphological characterization of the watershed. The morphological characteristics of the area allow us to better understand the watershed's response to precipitation stimuli so that we may predict its future behavior. Several parameters were computed; parameters like Gravelius compactness index, k_c, the equivalent rectangle and the elongation index. With these metrics we can conclude that the watershed is elongated similar to a rectangle, e.g. the runoff is further distributed in time when it reaches the downstream section, and this can lead us to conclude that the basin will be less susceptible to flash floods – Lencastre e Franco (2010).

Table 1 – Couto de Andreiros hidrometric station characteristics (source: SNIRH).

Code	8L/01H	Responsible Department (conv)	CCDR Alentejo
Name	Couto de Andreiros	**Type of station (auto)**	Level sensor
Altitude (m)	208	**Start of operation (auto)**	10-07-2001
Watershed	Tejo river	**Closed (auto)**	-
River	Ribeira da Raia ou de Seda	**Telemetry**	yes
District	Portalegre	**Status**	Active
County	Crato	**M coordinate**	245622,239 m
Head Department (auto)	INAG, I.P.	**P coordinate**	255789,902

Notes:
auto – automatic station; conv – conventional station

The stream network was then analyzed with the Horton and Strahler methods. Through the Horton method we were also able to determine the river's main stream – Strahler (1957) & Horton (1945). The basin's discharge can be considered and intermittent, in that there is only measurable runoff during the rainy season. During the dry season the runoff drops to near zero levels.

Applied Models

The basin model used in this study takes the precipitation input, extracts the effective precipitation loss and thus calculates the effective precipitation for the given storm event. The effective precipitation is processed and results in surface flow that is transported through to the final downstream section by the stream network.

Using ArcGIS it is possible distribute the precipitation in a expedite fashion. This was done with the use of the Thiessen polygon command, which is a well-known method precipitation distribution method. Of a total of 8 udometric stations in the area, 4 were chosen, because of several factors such as, data availability, active status and location. The chosen stations are described in detail on Table 2 as well as their weight over the watershed. The application of the Thiessen polygon method resulted in: Cabeço de Vide is the most influential of all the chosen stations with an area of 124 km^2, followed by Castelo de Vide with 65 km^2 and finally Vale do Peso and Alter do Chão (36 and 20 km^2, respectively)

Table 2 – Summary of the udometric station characteristics.

Code	Name	Basin	Distrit	County	Municipality	Weight %
18L/01UG	Alter do Chão	Tejo	Portalegre	Alter do Chão	Alter do Chão	8,16
19L/01UG	Cabeço de Vide	Tejo	Portalegre	Fronteira	Cabeço de Vide	26,53
17M/01G	Castelo de Vide	Tejo	Portalegre	Castelo de Vide	S. João Baptista	50,61
17L/02UG	Vale do Peso	Tejo	Portalegre	Crato	Vale do Peso	14,69

Loss model

The curve number is widely used method of precipitation loss estimation by computing the effective precipitation and direct runoff, taking into account the type and soil usage. The method includes a parameter for the initial precipitation loss, resulting from the initial basin retention capacity. From then on the precipitation loss is distributed in time and is considered to be a result of soil infiltration. This infiltration is naturally proportional to the type of soil and its permeability.

Through the use of the SCS experimental methodology developed in the USA, the many different components considered are reduced to only one, the curve number. The curve number will consequently vary from 0 to 100. When the value is 0 the effective precipitation will also be zero. When the value reaches 100 the effective precipitation will be equal to the recorded precipitation – Hipólito e Vaz (2011). The curve number is a consequence of the watershed characteristics, by the soil conditions and the antecedent moisture conditions prior to the storm event. The curve number in average conditions (AMC II) for Portugal is available at the Atlas da Água (http://geo.snirh.pt/AtlasAgua/; visited on 19/09/2013). The curve number layer was intercepted with each sub-basin, and average curve number was then computed based on the area of each curve number for that sub-basin.

Runoff models

The SCS unit hydrograph developed by Mockus in 1957 (Viessman and Lewis, 1995), resulted from the analysis of a great number or watersheds to obtain several parameters. The HUS parameters are, the discharge, q, and time, t, and are represented as fractions of the hydrograph peak discharge, q_p, and the time to peak runoff, t_p – Portela (2005).

Table 3 – The average CN(II) and CN(III) values for each sub-basin created.

Sub-bacias	CN(II)	CN(III)	Sub-bacias	CN(II)	CN(III)
W580	64.65	80.79	**W840**	61.25	78.42
W590	64.37	80.60	**W850**	60.00	77.53
W610	61.95	78.93	**W860**	66.13	81.78
W620	61.47	78.58	**W890**	69.25	83.82
W630	64.33	80.58	**W900**	63.30	79.87
W640	75.46	87.61	**W910**	63.98	80.34
W650	73.81	86.63	**W930**	60.00	77.53
W660	72.59	85.89	**W940**	66.60	82.10
W670	61.47	78.59	**W950**	64.18	80.47
W680	60.06	77.57	**W970**	71.83	85.43
W690	61.36	78.51	**W980**	62.84	79.55
W700	75.77	87.79	**W1000**	71.40	85.17
W710	71.89	85.47	**W1030**	76.52	88.23
W720	73.34	86.35	**W1040**	77.82	88.98
W730	60.00	77.53	**W1050**	82.28	91.44
W750	60.22	77.69	**W1060**	78.85	89.55
W760	62.41	79.25	**W1070**	70.35	84.51
W770	76.12	87.99	**W1080**	76.17	88.02
W780	60.00	77.53	**W1110**	76.62	88.29
W790	69.01	83.66	**W1120**	78.11	89.14
W800	75.10	87.40	**W1130**	77.61	88.86
W820	60.14	77.63	**W1140**	77.77	88.95
W830	60.03	77.55			

Possibly one of the most important parameters is the analysis of storm events and subsequent floods is the time of concentration. For the Couto de Andreiros basin the time of concentration was calculated through the equation (1) were; t_c is the time of concentration (minutes), L the main stream length (m), Sm the average basin slope (%) and CN the basin curve number – SCS (1972) e Viessman e Lewis (1996):

$$t_c = \frac{100}{0{,}3048^{0,8}} * \frac{L^{0,8} * (\frac{1000}{CN} - 9)^{0,7}}{1900 * Sm^{0,5}} \quad (1)$$

Exponential regression model

In general, not all the runoff recorded at any given section of a watershed originates from the storm event taking place at that moment, part of that runoff was already present in the watershed, stored underground. Multiple hydrographs recorded at the Couto de Andreiros hydrometric station were used to assist in the estimation of the components of the surface runoff. Separating the two surface runoff components can be a difficult task, nonetheless some empirical rules have been developed to separate the discharge in simple hydrographs, but that can be extrapolated to more complex applications, as long as the resulting hydrographs are considered to be a product overlapping simple hydrographs – Lencastre e Franco (2010).

To separate the two previously mentioned surface runoff components, we employed the regression curve, a negative exponential equation described by Horton in Chow, Maidment e Mays (1988). The implementation of the said exponential regression equation on HEC-HMS is very straightforward; the user has only to choose the desired baseflow estimation model, in this case the model's equation is (3) – HEC (2000).

$$Q(t) = Q_0 {k_{HEC}}^{t} \quad (2)$$

In the equation, Q_0, represents the discharge after which the recession starts and, $Q(t)$, the baseflow in the instant, t and k_{HEC} the exponential decay constant, the varies from 0 to 1.

The recession model is applied by HEC-HMS at the start of the simulation and at its terminal phase when the underground discharge reaches the surface stream network – HEC (2000). Using the said model, the program will automatically subtract the baseflow from the total basin discharge, and subsequently obtain the event flow.

Muskingum model

The Muskingum model is first mentioned, according to Viessman e Lewis (1995), by Graeff in 1883, and it is the most widely used model in flood propagation computations. It roughly considers the stream storage as the sum of two storages, one prismatic and an edged one – Hipólito e Vaz (2011).

Geographical information systems

The software program ArcGIS version 10, as well as the freely available tool from the U.S. Army Corps of Engineers, HEC-HMS were employed to create the Couto de Andreiros basin model. To enhance its features, ArcGIS is coupled with additional software, namely Arc Hydro and HEC-GeoHMS customized for special purposes by the Hydrologic Engineering Center of the

United States Army Corp of Engineers (USACE). These tools were also used to compute the watershed at a chosen point in the stream network, generate stream networks, compute hydrological parameters and prepare the hydrological model to be exported to specific and independent standalone hydraulic and hydrologic analysis software HEC-HMS.

The quality of the work produced, be it in positional accuracy, thematic exactness or completeness, depends only on the initial dada from which the GIS conversion is made – Matos et al. (2001). The digital terrain model and the watershed area were computed in the International 1924 Transverse Mercator coordinate system, while the curve number chart was available only in the Hayford Gauss IGeoE, datum Lisboa system. Consequently, a coordinate transformation was required to overlap the data; this operation is susceptible of creating distortions and overlapping errors. Other sources of imprecisions identified, could be the relatively old curve number chart, produced in 1973. Due to the length of time between the publication of this chart and the time span of the present work, several changes could have occurred on the study area resulting in erroneous conclusions.

The digital elevation model (DEM) is a 50 by 50 m grid of Portugal. After obtaining the watershed area a sequence of commands is applied the DEM. These commands include filling and smoothing the DEM’s surface in preparation for the coming work – Illustration 1.

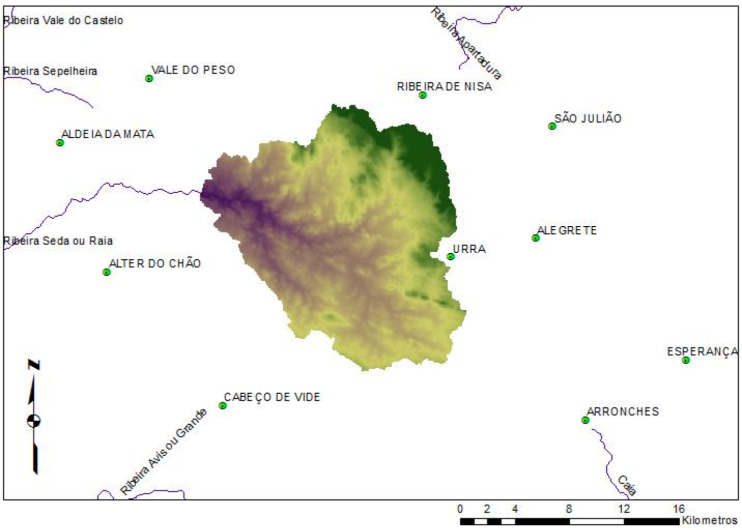

Illustration 1 – DEM model of the Couto de Andreiros watershed.

The result of the complete process can be seen in Illustration 2, the watershed is divided into multiple sub-basins that are ready to be processed into the final HEC-HMS export model. After this it is necessary to obtain the necessary basin hydrological parameters, they are: the stream length, stream slope, longest path, sub-basin centroid, centroid elevation and the centroidal flow path. These parameters can later be edited on HEC-HMS.

The final step in the process has no hydrological significance and is conducted to make sure the exported model has no inconsistencies or errors that will undermine its use in HEC-HMS.

ARC HYDRO

This tool has two main components and was created to work within ArcGIS and aid its users to quickly and surely create watershed models. The tool creates various layers that can be edited, such as HydroID, DrainID, NextDownID or Length Down. The components are: Arc Hydro Data Model and the Arc Hydro Tools.

HEC-GeoHMS

This tool also functions in ArcGIS environment; it generates data parameters to be used in HEC-HMS and also readies the hydrological model for export. The interaction between the two programs is implemented with clearly defined protocols, allowing for the automatic creation of stream networks, watersheds and sub-basins, hydrological parameters, curve numbers as well as the use of recorded precipitation to estimate flood hydrographs.

HEC-HMS

The program used in the present study was the HEC-HMS 3.5, and it is organized in three main components; the basin model, the meteorological model and the control specifications. The control or represent the physical parameters, the precipitation and its transformation and simulation parameters. With these components the user can simulate a wide range of hydrological behavior, especially because the program includes multiple mathematical models to describe the physical processes occurring in the watershed.

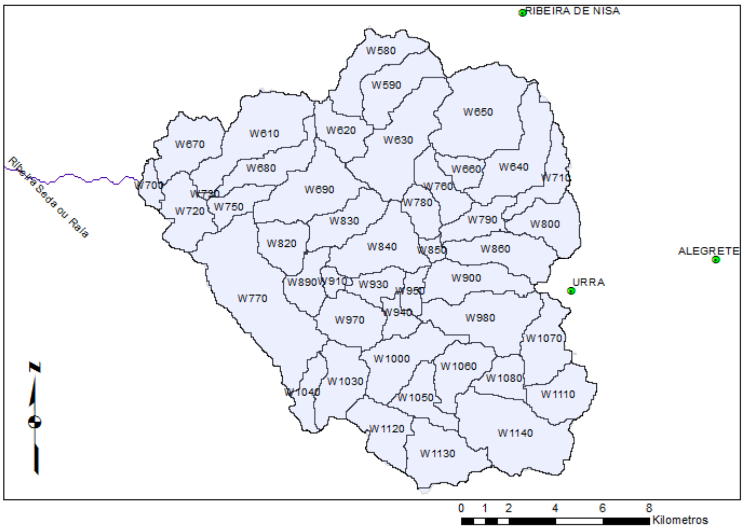

Illustration 2 – Final physical representation of the Couto de Andreiros watershed.

After importing the model into HEC-HMS, the calibration and final simulation can begin. The model is comprised of 45 sub-basins, with areas ranging from 1 to 18km^2. There are also 25 river reaches and 25 joints created automatically by HEC-GeoHMS and numbered according to HEC-HMS standards – Illustration 3.

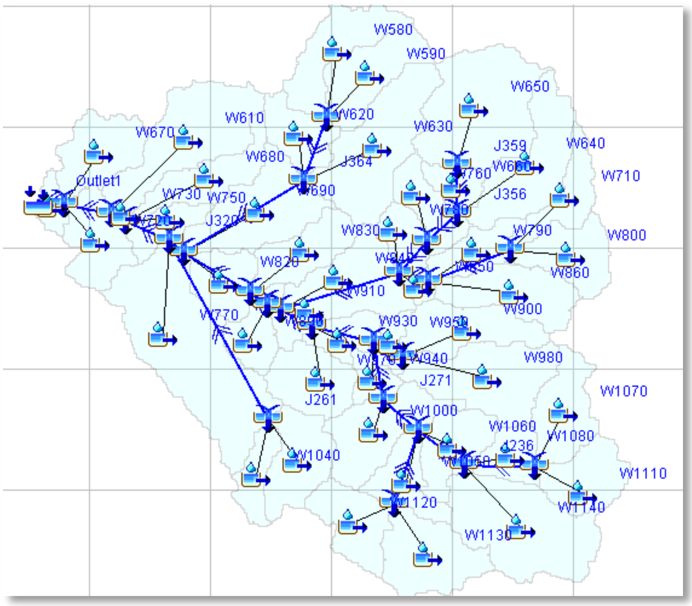

Illustration 3 – Representation of the Couto de Andreiros watershed in HEC-HMS environment.

Case Study: Sampling and results

The meteorological data can greatly influence the outcome of this study. The sample data ranges from 2002 to 2010 and due to station maintenance or malfunction is provided with several gaps and missing values that range from a few hours to several days. These gaps must be filled in, and to do so a suitable method from US Weather Bureau was found.

After analyzing and cross-referencing the peak discharge and the Couto de Andreiros hydrometric station with the multiple storm events recorded by the udometric stations of Alter do Chão, Cabeço de Vide, Castelo de Vide and Vale do Peso. This resulted in a total of 19 events to be used in calibration of the watershed model parameters and 25 to validation of those parameters.

The events used for calibration and validation can be found on Table 4, and although some of the events had data gaps, none of them were chosen for the calibration phase. The parameters subject to calibration are: the Muskingum K parameter, Muskingum X parameter, baseflow recession constant, initial component of the baseflow in m^3/s, and the curve number.

The calibration used in HEC-HMS is of the Univariate Gradient type, with a tolerance between 0.1 and a maximum of 500 iterations.

The calibration results show some approximation of the estimated discharge with the observed discharge, as well as the temporal interval of the peak discharge, especially when using CN(III) values. This conclusion is especially true on intense and uniform precipitation on all of the udometric stations. Note that HEC-HMS provided little calibration for the baseflow parameters, even when several different iterations of the calibration were experimented. During the validation phase the model parameters were updated with the newly calibrated parameters.

Table 4 – Storm events used in the calibration and validation phases.

Calibration Events			
Date	Date	Date	Date
18-12-2002	30-10-2005	23-02-2003	20-10-2006
26-12-2002	31-10-2005	29-03-2003	07-12-2006
19-01-2003	15-01-2006	09-12-2003	07-02-2007
21-01-2003	04-03-2006	27-01-2004	25-02-2008
19-02-2003	23-03-2006	22-10-2005	

Validation events			
Date	Date	Date	Date
30-12-2002	28-11-2006	**24-10-2006**	23-12-2009
07-01-2003	08-12-2006	**04-11-2006**	**25-12-2009**
22-01-2003	12-02-2007	**05-11-2006**	**28-12-2009**
24-02-2003	**19-11-2007**	**07-11-2006**	16-02-2010
24-01-2004	19-02-2008	16-11-2006	23-02-2010
15-03-2006	17-04-2008	25-11-2006	
22-10-2006	23-05-2008		

To fill the said gaps, an adaptation of the US Weather Bureau as described by Quintela (1996) was employed. The method consists of correlating data from various udometric stations in the surrounding area to fill the gaps in the need station or stations. The method uses the equation (4) and weights the values, P_1, P_2 and $P_3$of three nearby stations at the same temporal period of the gap to be filled with relation between the annual average precipitation in the problem udometric station, $\overline{P}$, and the annual average precipitation of the auxiliary stations, $\overline{P}_1$, $\overline{P}_2$ and $\overline{P}_3$: in which $\overline{P}$ is annual average daily precipitation on the problem station (mm), P_i the precipitation in three nearby stations (mm) and $\overline{P}_i$ the annual average daily precipitation in three nearby stations (mm).

$$P = {}^{1}/_{3}\left({}^{P}/_{\overline{P}_1}\,P_1 + {}^{P}/_{\overline{P}_2}\,P_2 + {}^{P}/_{\overline{P}_3}\,P_3\right) \quad (3)$$

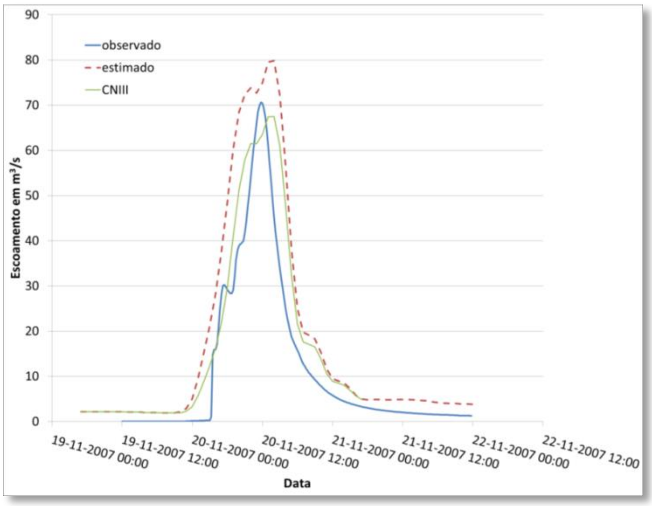

Illustration 4 – hydrograph for the storm event of 20-11-2007.

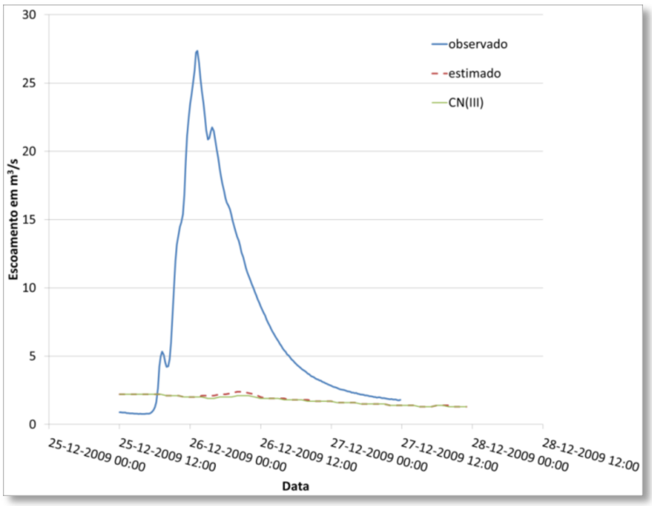

Illustration 5 – hydrograph for the storm event of 26-12-2009.

In the following previous it is possible to observe one of the hydrographs resulting from the HEC-HMS simulation. The simulation provides a good estimation in comparison with the observed discharge, although that isn't always the case, as can be seen in the Illustration 5. In this case, the precipitation was extremely lopsided across the udometric stations resulting in a poor hydrograph match.

Conclusion

The main objective of this project was to analyze the hydrological behavior of the Couto de Andreiros, namely in obtaining flood hydrographs through the use of geographical information systems.

Several software programs were used to achieve the objective, namely, ArcGIS, Arc Hydro or the series of programs provided by HEC: HEC-HMS, HEC-RAS, HEC-GeoHMS or HEC-FIA. These programs allow it's users to gather and store great amounts of information and their speed and ease of use is also an advantage, as they can produce a great number of estimates economically and with a great number of models and formulations.

The methodology used was consistent with a flood analysis of the watershed of the Couto de Andreiros hydrometric station and required the use of georeferenced data in digital form, from several sources and the processing of the data with ArcGIS for later export to HEC-HMS. The data used consisted in digital terrain model, soil classification, curve number, temperature and precipitation. ArcGIS enabled not just the creation of the watershed and sub-basins, the stream network, obtain geographical and hydrological parameters, but also to preprocess the information necessary to create precipitation loss model, the transport and routing models.

The estimated hydrographs for the ribeira da Raia or da Seda section display a broad degree of precision; some are notoriously bad match to the observed hydrographs. It is then safe to conclude that the created model is no the faithful hydrological representation of the Couto de Andreiros watershed. The main reason for this may be the fact that an accurate special distribution of the precipitation is extremely difficult to achieve with the limited number of udometric stations available.

Despite this fact, the tools used are immensely useful, by their ease of use, allowing the creation of very detailed models and whilst shortening the information processing time and estimation production. Such a combination has a clear effect on the cost of project design. Although they are very useful, we must always be critical of the estimates produced, with clear knowledge of the way they perform these estimates, and avoid using them as black boxes, for we know not the manner in which they perform their calculations and processes.

Through the present investigation we can conclude that a case can be made on improvements to the software tools used. Especially through improvements to the special distribution of precipitation, possibly using meteorological radar information, so that the precipitation could be more accurately modeled. Naturally similar studies must be undertaken so as to better judge its adequacy on such applications. If judge adequate and a suitable model is found, then it would be of interest to include such a model in real time flood prediction and monitoring systems.

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