Dear Reviewers and Editors,

We would like to thank three anonymous Reviewers for having handled and reviewed our manuscript. We really appreciate your comments to improve this manuscript. We would like to show you what we have revised following your comments. In this letter, in blue you can read our reply to your kind comments.

In the file “water-427845_marked_manuscript”, the corrections are in red.

In the file "water-427845_Clean_manuscript_Sami revised" in blue, the changes of the language revision are marked.

The final version with all the changes is in the file "water-427845_Clean_manuscript".

**Reviewer 2:**

Comments on “Assessment of snowmelt role for a flood event in a gauged catchment” by Mateo-Lazaro et al.

The paper presents the results of a theoretical application aimed at understanding the role of snowmelt in the interpretation of a flood event. The study has been carried out considering a well-monitored test case.

The findings are attractive even if they are presented unconvincingly. The English is of poor quality. The main problems are:

**Response**

Thank you for your comments. We have tried to improve English throughout the paper. In the marked manuscript, we have with red colour for substantial changes of content.

In the file “water-427845_Clean_manuscript_Sami revised” in blue colour are the language corrections.

1) Lack of a consolidated international literature

**Response:**

The authors appreciate the reviewer’s observation. We have made an important structural and background reform in the introduction, adding more than 40 new bibliographical references. Below are the new references that, in our opinion, are of international scope and cover several topics related to the snowmelt:


2) Poor quality of images that if printed in black and white are not clear

Response:

The authors appreciate the reviewer’s observation. Figures 1 and 3 are preserved in colour. Both figures can be visualized in grey scale as shown below. The other figures have been passed to different shades of grey scale to facilitate the reader to properly identify the content.

Figure 1 in grey scale:

Figure 3 in grey scale:
3) The introduction is a labyrinth of information that does not follow a common thread

Response:

Thank you for the comments. We have made an important structural and background reform in the introduction. The introductory framework and its references are carried out sequentially ordered by theme. The changes are the following:

"Hydrological processes related to snow (snowfall, snowpack, snowmelt) occur in large regions of the Earth. The snowmelt is one of the processes that intervene in the hydrological cycle interacting with many other processes. This article focuses on the phenomenon of melt-induced flooding and the changes it causes in the runoff regime, but this issue and its consequences has already been widely studied from a multitude of approaches [1, 2].

The tendency and the variability of the discharge in the rivers and their relation with the runoff coming from the snowmelt is a recurrent topic even in recent studies [3-6]. Sensitivity studies of the variables that intervene in the melting processes is another key issue, for example Reference [7] evaluates the sensitivity of a snowmelt runoff model with temperature input data, in a region with complex temperature elevation gradients.

Another phenomenon to be highlighted caused by the melting process is the time lag in the water balance, a lag that takes place between precipitation in the form of snow and runoff, which is another of the topics we quantify in this article. Recently other authors have contributed light on this topic [8, 9]. Other authors have developed rain-snow separation methods within time series and their lag with runoff [10-12]. Reference [13] uses data from the temporary estimate of the thickness of the snow cover to study the time lag. Reference [14] models the relationships of the depletion of the snow cover with the influence of
the heterogeneity of the accumulation of snow and with the melting energy. Reference [15] proposes calibration methods for the time lag snow-runoff.

In addition to the methods proposed in [23] there are recent publications that use models developed to implement the snow-runoff process. The well-known SWAT model is widely used also in recent publications [1, 16-31]. Reference [15] develops a progressive segmented optimization algorithm to calibrate the temporal variation parameters of the snowfall-runoff model. Reference [14] conducts simulations of snowfall-runoff in various environments of mountain basins. The most frequent parameters used in the models are analysed by reference [32] which concludes with the development of hydrological basin models with runoff from the thaw and shows that substantial progress has been made with models of different sophistication.

Other authors focus their research on the forecast of melting processes and their consequences. Reference [33] performs prediction studies with thaw in the Spanish Pyrenean chain, research location area of our article. In other cases, the studies focus on urbanized areas such as Reference [34] where the effect of snow melting on discharge forecasts is highlighted, carrying out a study in an urbanized basin with clear influence of snow processes on the increase of runoff.

Above we have referred to the relationship of the melting process with other processes. Erosion and sediment transport are processes that maintain a relationship. In many cases water melted by snow causes greater erosion of the soil than rainwater [35] so it is appropriate to investigate the differences in soil infiltration capacity during periods of rain or melting. Soil erosion in agricultural areas during winter and spring is a problem in many countries of the world such as Norway [36], USA [37], Belgium [38], United Kingdom [39], Germany [40] and Russia [41]. In these areas, soil erosion during winter and spring depletes the nutrient-rich top layer and contributes elements (phosphorus, nitrogen) to freshwater bodies [42].

The period of droughts is another process that may be related to the melting processes, in this case due to an absence or prolonged decrease in the contribution of snow [43].

Energy and thaw are also processes related to each other. Reference [44] shows how changes in the composition or structure of the soil in large areas influence the energy input of the soil and therefore the rate of thawing. Reference [14] demonstrates the influence of spatial distribution of snow cover thickness and heterogeneity in the distribution of fusion energy in extreme runoff production.

It can be said that the snow and thaw processes play an important role in the hydrological cycle, both in themselves and by the direct relationship with other processes, as well as by their regulatory role of water flow and volume of water reserve.”

Minor comments

Line 35-37: not use passive form (remember not article but paper)

Response: Thanks for the comment. We have changed the phrase as follows:
“The process of snowmelt has been considered in this paper within a flood model with hydro-meteorological methods or models of rainfall-runoff. We have introduced the melting process as an additional contribution that flows through the hydrological system of the basin.”

Line 40: there is a repetition of a sentence
Response: Thanks for the comment. This part of the text has been deleted when rewriting the Introduction section.

Line 67: reference for SHEE
Response: We have provided the link "http://www.unizar.es/hidrologia" where you can download an example. On the other hand, reference to papers is indicated below [45, 46, 53-61] where software parts are described. A more exhaustive description has also been added within the Methods section:

“The software SHEE has numerous applications for either DEM management or hydrological processes simulation [62]. Obtaining new cartographic coverage with the combination of DEM and simulated processes is also possible. The DEM management is achieved using the GDAL (Geospatial Data Abstraction Library), which permits to import and export different archive formats and to make new coverage from multiple archives. The program can combine coverage with different coordinate system thanks to the use of the PROJ4 library from the USGS. Thousands of terrestrial geodetic systems can be represented, transformed and converted between them. To do that, the program is able to obtain necessary Spatial Reference Organization parameters from the internet server transfer. Downloading information from WMS remote server is also possible. With regard to DEM characteristics, SHEE program can manage any format, size, accuracy and reference system. E.g., Global DEM has been used like SRTM30 (with file size 3.6 GB and grid size 30”, ≈900 m), MDT5 of Spanish territory (120 GB and 5 m) and Lidar. The use of PLR models (Parallel Linear Reservoir) as a hydrological model integrated within the sequential processing algorithm of the catchment is a special case of hydrological application where every cell of the DEM is considered as a reservoir combination in parallel [63].

Future developments of SHEE program are very promising. Recently we have incorporated a module for development and visualization of geological structures in three dimensions. In the near future, it will allow the development of combined hydrogeological models with complex subsurface structures. This implementation has resulted in the publication Reference [55]. Therein, we present an application that visualizes three-dimensional geological structures with digital terrain models. The three-dimensional structures are displayed as their intersection with two-dimensional surfaces that may be defined analytically (e.g., sections) or with grid meshes in the case of irregular surfaces such as the digital terrain models. Additionally, the process of generating new textures can be performed by a Graphics Processing Unit (GPU), thereby making real-time processing very effective and providing the possibility of displaying the simulation of geological structures in motion. Regarding the Graphics Processing Units, and since the DEM is becoming denser, we are currently completing the development of hydrological
models with this technique through the sequential processing algorithm, whose main advantage is the shortening of the computation time, which can be reduced 100 times. Due to parallel processing, it is necessary to reprogram the sequential algorithms for computing drainage networks."

Line 100: Where and not were
Response: Thank you, sorry for the error.

Line 138: check symbol of equation 7
Response: Thank you it’s about alpha (α).

Line 166: the experiment arrangement is not clear (number of gauges and pluviometer is confused)
Response: Thanks for the comment. We have tried to make it clearer with the following sentence:

"Altimetry representation of the Esca river basin with the rain gauges (A063, A268, A259 and P016) and the two stream gauges (A063, A268) that also have rain gauges."

Table 2 is not clear
Response: Thanks for the observation, we have changed table 2 as follows:

<table>
<thead>
<tr>
<th>Date</th>
<th>Rain duration</th>
<th>Time interval</th>
<th>Peak flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start time</td>
<td>End time</td>
<td>hours</td>
<td>15 minutes</td>
</tr>
<tr>
<td>January 18, 2009, 2:30 p.m.</td>
<td>January 28, 2009, 7:30 p.m.</td>
<td>245.25</td>
<td>981</td>
</tr>
</tbody>
</table>

Line 182: lack of references for RBF
Response: Thanks for the observation. We have added the following references of recent publication:

1. Tayyab, M.; Ahmad, I.; Sun, N.; Zhou, J.; Dong, X. Application of Integrated Artificial Neural Networks Based on Decomposition Methods to Predict Streamflow at Upper Indus Basin, Pakistan. *Atmosphere*. 2018, 9, 494; doi:10.3390/atmos9120494

Figure 5 not clear without coulors
Response: Thanks for the observation. Figure 5 has been converted to grey scale:
I suggest merging figure 7 and 8 to compare Temperature evolution with runoff from snowmelt.

Response: Thanks for the comment. We have put these two figures together in one:

Paragraph 4.3 has to be written completely as it is not clear (methodology, units of measures and which kind of data you used)

Response: Thank you for the comments. Section 4.3 has been rewritten, taking special care in the units and in the origin of the data used in the water balance:

"Table 4 contains the results of the water balance of the episode studied considering the temporal section between 0 and 200 hours. The balance is carried out in the two gauging stations (Isaba and Sigues), and the results are given in total units (hm³) for the entire basin corresponding to each gauging station. They are also given in specific units (mm), that is, total units dividing by the area of the"
corresponding basin. The last column represents a comparison between the results of the two gauging stations.

To elaborate the water balance, we start from the data and results of hyetographs and hydrographs that we have been using in modelling and that are summarized in three components:

(1) Total precipitation (Tp): It has been obtained from the model of distributed precipitation based on functions (RBF) shown in Figure 4, adding all the time intervals every 15 minutes from 0 to 200 hours. The results of this integration coincide with the term Total Rainfall of the average hyetograph of Figures 5 and 7.

(2) Snowmelt (Sm): it is determined in the distributed model calculated with the SHEE program, whose average representation coincides with the snowmelt fraction of the average hyetograph of Figure 7.

(3) Total runoff (Tr): it is also obtained from the distributed model, and the average value is represented in the hyetograph of Figure 7 as the sum of two terms: runoff from rainfall and runoff from snowmelt.

<table>
<thead>
<tr>
<th></th>
<th>Isaba</th>
<th>Sigues</th>
<th>Isaba</th>
<th>Sigues</th>
<th>Isaba / Sigues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tp</td>
<td>31.79</td>
<td>67.61</td>
<td>168</td>
<td>134</td>
<td>127%</td>
</tr>
<tr>
<td>Tr</td>
<td>17.90</td>
<td>42.06</td>
<td>95</td>
<td>83</td>
<td>90%</td>
</tr>
<tr>
<td>Ep</td>
<td>11.47</td>
<td>19.27</td>
<td>61</td>
<td>38</td>
<td>101%</td>
</tr>
<tr>
<td>Sm</td>
<td>6.43</td>
<td>22.79</td>
<td>34</td>
<td>45</td>
<td>76%</td>
</tr>
<tr>
<td>L</td>
<td>20.32</td>
<td>48.33</td>
<td>107</td>
<td>95</td>
<td>148%</td>
</tr>
<tr>
<td>Hv*</td>
<td>9.80</td>
<td>25.86</td>
<td>52</td>
<td>51</td>
<td>80%</td>
</tr>
</tbody>
</table>

(*)It is the volume measured between 0 and 200 hours. On the other hand, it remains to leave the basin (in Sigues stream gauge) 42.06-25.86 = 16.2 adding the volume prior to the start of the event.

In short, the terms Tp, Tr and Sm are obtained from data and direct results of the model. The terms Ep and L can be obtained from equations 11 and 12, which are partial water balance equations:

(1) Effective precipitation (Ep): in Figure 7 it comes as runoff from rain.

\[ Ep = Tr - Sm \] (11)

(2) Losses (L): It is the difference between the total precipitation and the effective precipitation.

\[ L = Tp - Ep \] (12)

The volume of the hydrograph (Hv) is obtained by integration of the actual hydrograph, in the 0-200 h range. The volume of water that remains in the basin just at the 200 h coordinate is the difference between total runoff (Tr) and volume of the hydrograph (Hv) adding the volume prior to the start of the episode. From the comparison of Table 4, analysing the specific values (mm), the following is deduced:

(1) Based on observed data: in Isaba there is a greater proportion of gross precipitation, although the output is similar (consider the volume of output = volume of the hydrographs).

(2) As data from the simulation: in Isaba (with a higher average altitude of the basin), there is less thaw and greater losses, part of which can be attributed to snow retention.”
Figure 11: legend in English

Response: Thanks for the comment. We have modified the figure that now has the number 10.

I suggest a deep revision and in some case a rewritten of many part to make the results fascinating.

Response: Thanks for the observation. We have made a substantial reform of the paper, especially in the Introduction, Methods, Data Source, Results and Discussion sections and in Bibliographic References.

We deeply appreciate the time spent by the Reviewer, who will undoubtedly contribute to the improvement of our manuscript.
Assessment of snowmelt role for a flood event in a gauged catchment

Jesús Mateo-Lázaro¹, Jorge Castillo-Mateo², José Ángel Sánchez-Navarro¹, Víctor Fuertes-Rodríguez³, Alejandro García-Gil⁴, Vanesa Edo-Romero¹

¹ Dept. of Earth Sciences, University of Zaragoza. Pedro Cerbuna, 12, 50009-Zaragoza, Spain; jesmateo@unizar.es; joseange@unizar.es; vanesa_edo@hotmail.com
² Dept. of Mathematics, University of Zaragoza. Pedro Cerbuna, 12, 50009-Zaragoza, Spain; 720193@unizar.es
³ Dept. of Geography and Territorial Planning, University of Zaragoza. Pedro Cerbuna, 12, 50009-Zaragoza, Spain; 696825@unizar.es
⁴ Geological Survey of Spain (IGME), C/ Manuel Lasala n° 44, 9º B, 50006 Zaragoza, Spain; a.garcia@igme.es

* Correspondence: jesmateo@unizar.es; (00) +34 (9) 690 609948

Abstract: An actual event that happened in the Roncal Valley (Spain) is investigated and the results are compared between models with and without snowmelt. A distributed rainfall model is generated with the specific data recorded in the rain gauges of the catchment during the episode. To describe the process of water routing in the hydrological cycle of the basin, a model is used based on combinations of Parallel Linear Reservoirs (PLR model), distributed by the basin and tip-out into its drainage network configured using a digital terrain model (DTM). This PLR model allows to simulate the different actual reservoirs of the basin, among them the snow and its contribution by melting that, in the model, depends on the temperature. The PLR model also allows for a water budget of the episode where, in addition to the effective rainfall contribution, the part that comes from the thaw is taken into account. The PLR model also allows determine the amount of water that exists in the basin before and after the episode, data of great interest. When comparing the simulations with and without thaw, it is evident that the intervention of the reservoir of snow has been decisive for a flood to have occurred.

Keywords: Availability of water resources; Snowmelt; Floods; Hydrological processes; PLR models; SHEE software

1. Introduction

There are numerous works that have been carried out in recent years in different lines of flood research, but there are few that include melting processes as a direct cause or added to the flood phenomenon. In this article, the process of snow melting is introduced in flood modelling with hydro-meteorological methods or rain runoff models as another contribution that flows through the hydrological system of the watershed. The process of snowmelt has been considered in this paper within a flood model with hydro-meteorological methods or models of rainfall-runoff. We have introduced the melting process as an additional contribution that flows through the hydrological system of the basin.

Floods are related to extreme and of little frequency events of intense rainfall, and generally occur in small ungauged basins, which are recognized as the most vulnerable to floods produced by storms. Snow-melt runoff models have been used for decades. Snow melt runoff models have been used for decades. The most frequent parameters used in this class of models are analysed by...
Hydrological processes related to snow (snowfall, snowpack, snowmelt) occur in large regions of the Earth. The snowmelt is one of the processes that intervene in the hydrological cycle interacting with many other processes. This article focuses on the phenomenon of melt-induced flooding and the changes it causes in the runoff regime, but this issue and its consequences has already been widely studied from a multitude of approaches [1, 2].

The tendency and the variability of the discharge in the rivers and their relation with the runoff coming from the snowmelt is a recurrent topic even in recent studies [3-6]. Sensitivity studies of the variables that intervene in the melting processes is another key issue, for example Reference [7] evaluates the sensitivity of a snowmelt runoff model with temperature input data, in a region with complex temperature elevation gradients.

Another phenomenon to be highlighted caused by the melting process is the time lag in the water balance, a lag that takes place between precipitation in the form of snow and runoff, which is another of the topics we quantify in this article. Recently other authors have contributed light on this topic [8, 9]. Other authors have developed rain-snow separation methods within time series and their lag with runoff [10-12]. Reference [13] uses data from the temporary estimate of the thickness of the snow cover to study the time lag. Reference [14] models the relationships of the depletion of the snow cover with the influence of the heterogeneity of the accumulation of snow and with the melting energy. Reference [15] proposes calibration methods for the time lag snow-runoff.

In addition to the methods proposed in [23] there are recent publications that use models developed to implement the snow-runoff process. The well-known SWAT model is widely used also in recent publications [1, 16-31]. Reference [15] develops a progressive segmented optimization algorithm to calibrate the temporal variation parameters of the snowfall-runoff model. Reference [14] conducts simulations of snowfall-runoff in various environments of mountain basins. The most frequent parameters used in the models are analysed by reference [32] which concludes with the development of hydrological basin models with runoff from the thaw and shows that substantial progress has been made with models of different sophistication.

Other authors focus their research on the forecast of melting processes and their consequences. Reference [33] performs prediction studies with thaw in the Spanish Pyrenean chain, research location area of our article. In other cases, the studies focus on urbanized areas such as Reference [34] where the effect of snow melting on discharge forecasts is highlighted, carrying out a study in an urbanized basin with clear influence of snow processes on the increase of runoff.

Above we have referred to the relationship of the melting process with other processes. Erosion and sediment transport are processes that maintain a relationship. In many cases water melted by snow causes greater erosion of the soil than rainwater [35] so it is appropriate to investigate the differences in soil infiltration capacity during periods of rain or melting. Soil erosion in agricultural areas during winter and spring is a problem in many countries of the world such as Norway [36], USA [37], Belgium [38], United Kingdom [39], Germany [40] and Russia [41]. In these areas, soil erosion during winter and spring depletes the nutrient-rich top layer and contributes elements (phosphorus, nitrogen) to freshwater bodies [42].

The period of droughts is another process that may be related to the melting processes, in this case due to an absence or prolonged decrease in the contribution of snow [43].

Energy and thaw are also processes related to each other. Reference [44] shows how changes in the composition or structure of the soil in large areas influence the energy input of the soil and therefore the rate of thawing. Reference [14] demonstrates the influence of spatial distribution of snow cover thickness and heterogeneity in the distribution of fusion energy in extreme runoff production.

It can be said that the snow and thaw processes play an important role in the hydrological cycle, both in themselves and by the direct relationship with other processes, as well as by their regulatory role of water flow and volume of water reserve.
To carry out this work, we start with a flow circulation model using a methodology based on a combination of Parallel Linear Reservoirs (PLR model) [45, 46]. It is fair in this model where the water contribution of the melting processes is introduced. In addition to the fusion of snow, there is a great variety of processes that depend on the generation of runoff, such as erosion and sedimentation [1-7]. In hydrological science, reservoir models have been widely used to represent different characteristics of river basins. References [47-49] synthesize several works in this area of research. Currently, reservoirs models are very widespread and are based on the concept that a watershed is like a set of interconnected deposits (rain, snow, aquifers, soil, biomass, etc.), each one with different characteristics in terms of recharge, storage and discharge [50]. The input hydrograph corresponds to the effective precipitation, also called effective rainfall, rainfall excess, or recharge. That is why this model has to be combined with another that performs the transformation of the gross precipitation into effective precipitation. It is very frequent, and it is going to be our case, to use the Curve Number method of the SCS (SCS-CN model) to carry out this transformation.

The models of reservoirs are traditionally used in hydrology to represent different characteristics of the basins, thus reference [49] they make a synthesis of different works in this line. Recently, a line of research has been established with models of reservoirs distributed according to geomorphological trajectories of flow within the basin, e.g., in reference [51] a conceptual model is developed based on the geomorphological properties of watersheds. Unitary hydrograph models applying linear reservoirs distributed in cascade according to the geomorphology of the basin are developed in reference [52].

This article investigates the cause of an actual flood event that occurred in the Roncal valley in January 2009, where everything seems to indicate that fusion processes in the basin’s snow reservoirs contributed decisively to the activation of the flood. The work is carried out following the methodology developed in reference [45], and for this the computer program SHEE (Simulation of Hydrological Extreme Events, please find http://www.unizar.es/hidrologia) is used and that allows to represent the basin through a distribution of reservoirs in parallel (PLR model) that take into account the contributions due to the snow melt.

In the investigation of the actual episode the following scheme is followed: (1) Creation of a distributed model of total rainfall. (2) Creation of a water circulation model for the basin. The parameters of a reservoir model \(Q_i\) and \(w_i\) are determined from the recession curves of the actual hydrograph. (3) Precipitation model, generation of hyetographs of total precipitation and, using the Curve Number model, another effective precipitation model. (4) Establishment of the water balance. Based on the results of the simulation, a water balance is determined that determines the origin of the water that causes the flood.

2. Methods

The PLR models are part of the computer program referred to above SHEE (Simulation of Hydrological Extreme Events), carried out in the Department of Earth Sciences of the University of Zaragoza for its application in hydrological events. In essence, the program is an adaptation of traditional hydrological models to new technologies and data sources and reproduces, through models, the different intervening processes that, in the general case, are: geometric model of the basin; Rain model that distributes it in space and time; rain-runoff transformation model that aims to differentiate (or separate) between losses and runoff (losses are also called abstractions, retentions and runoff deficit); and flow circulation models (also called transit, propagation, routing, runoff and discharge). Then, to this general scheme is added a new model that estimates the contribution of water from snow reservoirs.

Figure 1 shows the interface of the computer program which, in recent years, has been used in numerous professional works on risks, spatial planning, civil and architectural works, and in scientific publications [45, 46, 53-61]. The software SHEE has numerous applications for either DEM management or hydrological processes simulation [62]. Obtaining new cartographic coverage with the combination of DEM and simulated processes is also possible. The DEM management is achieved using the GDAL (Geospatial Data Abstraction Library), which permits to import and
export different archive formats and to make new coverage from multiple archives. The program can combine coverage with different coordinate system thanks to the use of the PROJ4 library from the USGS. Thousands of terrestrial geodetic systems can be represented, transformed and converted between them. To do that, the program is able to obtain necessary Spatial Reference Organization parameters from the internet server transfer. Downloading information from WMS remote server is also possible. With regard to DEM characteristics, SHEE program can manage any format, size, accuracy and reference system. E.g., Global DEM has been used like SRTM30 (with file size 3.6 GB and grid size 30", ~900 m), MDT5 of Spanish territory (120 GB and 5 m) and Lidar. The use of PLR models (Parallel Linear Reservoir) as a hydrological model integrated within the sequential processing algorithm of the catchment is a special case of hydrological application where every cell of the DEM is considered as a reservoir combination in parallel [63].

Figure 1. SHEE program interface. It uses digital terrain models and hydrological models, actual or simulated rain, soil moisture and circulation through the drainage network.

Future developments of SHEE program are very promising. Recently we have incorporated a module for development and visualization of geological structures in three dimensions. In the near future, it will allow the development of combined hydrogeological models with complex subsurface structures. This implementation has resulted in the publication Reference [55]. Therein, we present an application that visualizes three-dimensional geological structures with digital terrain models. The three-dimensional structures are displayed as their intersection with two-dimensional surfaces that may be defined analytically (e.g., sections) or with grid meshes in the case of irregular surfaces such as the digital terrain models. Additionally, the process of generating new textures can be performed by a Graphics Processing Unit (GPU), thereby making real-time processing very effective and providing the possibility of displaying the simulation of geological structures in motion. Regarding the Graphics Processing Units, and since the DEM is becoming denser, we are currently completing the development of hydrological models with this technique through the sequential processing algorithm, whose main advantage is the shortening of the computation time, which can be reduced 100 times. Due to parallel processing, it is necessary to reprogram the sequential algorithms for computing drainage networks.

2.1. PLR models: characterization of a single linear reservoir

The hydrological relationships of a linear reservoir are governed by two equations, the flow or storage equation (equation 1) and the continuity equation or water balance equation (equation 2).

\[ Q = \alpha \cdot S \]  

(1)
Where $Q$ is the discharge (m$^3$/sec), $S$ is the storage (m$^3$), $\alpha$ is the depletion coefficient (sec$^{-1}$), $R$ is the recharge that enters the reservoir, for example in the form of effective precipitation, and $t$ is the time (sec). From a Topology perspective, the depletion coefficient ($\alpha$) is the slope of the line that relates storage to discharge (Figure 2) and hence the name of linear reservoir. By combination of equations 1 and 2 results in the differential equation of runoff or discharge with the form of the equation 3.

$$Q_2 = Q_1 \cdot e^{-\alpha \Delta t} + R \cdot (1 - e^{-\alpha \Delta t})$$

Where $Q_1$ and $Q_2$ are values of $Q$ spaced apart in an elementary fraction of time ($\Delta t$) during which the recharge can be considered constant.

\[ R = Q + \frac{dS}{dt} \] (2)

\[ S = \sum_{i=1}^{n} S_i \] (5)

\[ Q_i = Q_{ai} \cdot e^{-\alpha \Delta t} \] (6)

\[ S_i = \frac{Q_i}{\alpha_i} \] (7)

**Figure 2.** Water routing for a linear reservoir.

### 2.2. PLR models: combination of linear reservoirs in parallel sets

A basin (or a cell if it is the areal division of the basin in cells of a grid) can be represented with a single reservoir or with a combination of reservoirs. The simplest model to represent a basin is with a single reservoir whose behaviour is representative of the basin’s response. Evidently, the model is not very descriptive and the results obtained show greater deviations. In addition, a basin can be represented by a set of deposits, each one representative of certain characteristics of the basin. And also, a basin can be divided into sub-basins or cells, each of which can be represented by a set of deposits. The possibilities of combinations of reservoirs to build a model are unlimited, although they are few and simple with which acceptable results are achieved. In this work we have used a combination of two reservoirs in parallel for each cell of the digital terrain model in which water enters according to a distributed model of effective precipitation. The combination of the two reservoirs pours water into the drainage network whose flow is modelled with a classical method. This scheme is used in the SHEE program for the following qualities:

1. The calibration of the model is based on actual recession curves that is, based on actual responses from the basin.
2. Each reservoir represents a set of characteristics of the basin whose response differs markedly from the response of the characteristics represented by the other reservoirs.
3. As a result of the latter, the total hydrograph can be decomposed into several partial hydrographs that can be mapped into parts of the hydrological system (direct runoff hydrograph, underground runoff hydrograph, etc.).
4. The PLR model allows to know the water stored in the reservoirs (i.e. in the basin) and to make a water balance of each episode.
5. Finally, for the circulation in channels, standard models (kinematic wave or Muskingum-Cunge) are widely contrasted.

For a combination of $n$ linear reservoirs in parallel, the resultant is the sum of the reservoirs as shown in equations 4 and 5, and for each reservoir, as equations 1 and 2 are fulfilled, without considering recharge equations 6 and 7 are result.
By combination of equations 4 and 6, we arrive at equation 8 where we see that, for an instant t, there is a mathematical relationship between the flows of each deposit.

\[
\left( \frac{Q_1}{Q_{01}} \right)^{\frac{1}{\alpha_1}} = \ldots = \left( \frac{Q_i}{Q_{0i}} \right)^{\frac{1}{\alpha_i}} = \ldots = \left( \frac{Q_{nr}}{Q_{0nr}} \right)^{\frac{1}{\alpha_{nr}}}
\]  

(8)

The recession curve of a hydrograph is a set of data flow vs time, \(Q_i-t_i\), for the system of equations 8, whose resolution allows to obtain a set of parameters, \(\alpha_i\), and with them to establish a PLR model. Once the model is established, with equations 3, 4 and 6, hydrographs can be generated according to the inputs (\(R_i\)) to the system. Also, with equations 5 and 7 we have the amount of water stored in each reservoir of the basin, which allows us to carry out the water balance.

2.3 PLR models: snowmelt

The thaw supposes a new contribution that has to be added to the entrances along with the effective precipitation, and whose origin has to be looked for in a previous episode of precipitation in the form of snow. For a process of snowmelt in short events of intense rain, the factors of precipitation and temperature are considered, as the most influential in the fusion process. A simple model is to consider that snow melting is linearly proportional to precipitation when it occurs at temperatures above 0ºC. Thus, for a certain part of the hydrograph that coincides with temperatures above 0ºC, effective precipitation as an input to the surface runoff system can be replaced by total precipitation by adding snow melting. In this way, the runoff equation (equation 3) is modified by adding a new recharge term from snow melting (\(R'\)), and by substituting in \(R\) the effective precipitation by total precipitation, as expressed in equation 9.

\[
Q_2 = Q_1 \cdot e^{-\alpha \Delta t} + (R + R') \cdot (1 - e^{-\alpha \Delta t})
\]  

(9)

The main advantage of the PLR model is that, by allowing a water budget of an event to be made, the amount of snowmelt recharge, \(R'\), can be estimated to equilibrate the water balance.

3. Data Source

3.1 Characterization of the basin

The catchment studied is that of the Esca river (Roncal valley) located in the Pyrenees ridge, between Aragon and Navarra, two regions of northeast Spain. The basin is preserved in a natural state, without reservoirs or significant alterations. Figure 3 shows an altimetry representation of the basin, the location of the gauging stations (two) and the pluviometry stations considered (four). Table 1 gives some of the most significant hydrological characteristics for this watershed.
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Figure 3. Altimetry representation of the Esca river basin with the rain gauges (A063, A268, A259 and P016) and the two stream gauges (A063, A268) that also have rain gauges.

Table 1. Hydrological characteristics of the Esca River basins in Sigues and Isaba.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>ud</th>
<th>Isaba (A268)</th>
<th>Sigues (A063)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catchment area</td>
<td>km²</td>
<td>189.06</td>
<td>506.26</td>
</tr>
<tr>
<td>Length of the main channel</td>
<td>km</td>
<td>24.01</td>
<td>51.70</td>
</tr>
<tr>
<td>Average slope of the main channel</td>
<td>%</td>
<td>6.44</td>
<td>3.45</td>
</tr>
<tr>
<td>Average slope of the digital surface of the catchment</td>
<td>%</td>
<td>36.85</td>
<td>34.88</td>
</tr>
<tr>
<td>Average Curve Number (AMC II)</td>
<td></td>
<td>63.08</td>
<td>61.22</td>
</tr>
</tbody>
</table>

3.2 Melting event setting

The event investigated corresponds to the flood occurred between January 18 and 28, 2009. Table 2 shows its main characteristics, such as duration, peak flow, and the number of intervals considered for the treatment of actual rain.

Table 2. Characteristics of the actual event investigated.

<table>
<thead>
<tr>
<th>Date</th>
<th>Rain duration</th>
<th>Time interval</th>
<th>Peak flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 18, 2009, 2:30 p.m.</td>
<td>245.25</td>
<td>981</td>
<td>201</td>
</tr>
</tbody>
</table>

3.3 Rainfall model

The rainfall has been obtained from the data of the Spanish SAIH network that records the value of the precipitation with intervals of 15 minutes. Figure 4 shows two isohyet maps of the event.
corresponding to coverages generated from the accumulated precipitation in two of these intervals (the event requires the use of 981 layers). Spatial interpolation is performed by applying a distributed precipitation model based on the use of Radial Basis Functions (RBF) [64-66]. From these precipitation coverages, the computer program can generate a different hyetograph for each point of the basin.

Figure 4. Isohyet maps of the event of January 2009 (equidistance 0.25 mm). A sequence of 2 coverage intervals of 15 minutes is presented. The whole event has 981 layers.

3.4 Reservoir model

From the actual hydrographs of the episode the reservoir model is established by adjusting the parameters \((q_{oi} \quad \text{and} \quad a_i)\). For this, to the specific recession curve \((q = Q/\text{catchment area})\) the least squares method is applied with the system of equations 10.

\[
q_i = \sum_{j=1}^{m} q_{oi} \cdot e^{-a_j \cdot t_i} \quad (10)
\]

where \(m\) is the number of reservoirs (two in our case), \(q_i\) are the \(n\) known values of flow of the recession curve at time \(t_i\), and \(q_{oi}\) and \(a_j\) are the unknowns. We have thus, an overdetermined system of \(n\) equations and \(2\cdot m\) unknowns where \(n \gg 2m\). Once stated and solved for the recession curve of the actual hydrograph, we arrive at the results of Table 3, for a model of two linear reservoirs in parallel, which will be used within the SHEE program to perform simulations, considering or not the process of snowmelt.

Table 3. Parameters of the parallel linear reservoirs for the event in the Esca River.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reservoir 1</th>
<th>Reservoir 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha)</td>
<td>1.43 E-06</td>
<td>1.67 E-05</td>
</tr>
<tr>
<td>(q_o)</td>
<td>2.96 E-07</td>
<td>1.00 E+00</td>
</tr>
</tbody>
</table>

4. Results and Discussion

4.1 Simulation without snowmelt

The simulation of the event with the SHEE program without considering snowmelt shows a notable disarrangement with reality. To achieve an adequate water balance, it is required to modify the standard conditions to other very wet conditions by means of the curve number model, as seen in the ratio of total and effective rainfall hyetographs (Figure 5). It is evident that the effective rain
obtained is unusually high. On the other hand, there is very little agreement between both hydrographs (Figure 6). In the actual hydrograph a peak occurs in 125 hours that does not occur in the simulation, while at 220 hours, the simulated values exceed the actual ones.

Figure 5. Average Hyetographs in the Esca River basin in January 2009. Total precipitation obtained directly by interpolation method (blue) and effective precipitation without considering snowmelt (red) and with high curve number.

Figure 6. Hydrographs of the January 2009 event of the Esca River in Sigues (A063 stream gauge), actual and simulated without considering snowmelt.

4.2 Simulation with snowmelt

In the model with snowmelt, the average altitude of each of the two basins was taken into account, as well as the discharge contributions in each stream gauge. It has been seen that there is no proportional relationship between the area of each basin and its discharge contribution, as expected, because in winter the melting is greater at lower altitude, a circumstance that tends to be reversed towards spring as there is more snow in the high areas.

The ratio of the peak-flow with a rapid melting of snow would be supported by the evolution of temperatures, which can be seen in Figure 7, in the station of Arangoiti are located at 1,350 meters with a cold period between 45 and 90 hours, while between 90 and 140 hours exceed 0°C reaching up to 8°C.
With the model it has been estimated which should be the recharge by melting snow in the interval between 80 and 120 hours to be able to fit the hydric balance of the episode in less humid previous hydrological conditions than in the case of no snowmelt model. The optimal results are obtained with a melting equivalent to 90% of the gross precipitation that occurred in that interval, that is, $R' = 0.9 \cdot R$. In this way we obtain the hyetograph of Figure 7 and the hydrograph of Figure 8, where previous dry hydrological conditions have been considered. Thus, in the simulation a hydrograph very similar to the actual one is obtained.

![Temperature graph at the Arangoiti station during the episode of January 2009 and Hyetographs of total and effective precipitation with snowmelt in Esca River.](image1)

**Figure 7.** Temperature graph at the Arangoiti station during the episode of January 2009 and Hyetographs of total and effective precipitation with snowmelt in Esca River.

![Simulated hydrograph considering snowmelt. In fragmented lines are the partial hydrographs of each reservoir.](image2)

**Figure 8.** Simulated hydrograph considering snowmelt. In fragmented lines are the partial hydrographs of each reservoir.
Figure 9 shows the observed hydrograph in Isaba stream gauge (A268) located in the interior of the basin, which can be compared with that observed at the exit, at the Sigues stream gauge (A063). In Figure 10 is the simulated hydrograph at the point corresponding to the Isaba station.

![Figure 9](image1.png)

**Figure 9.** Actual hydrographs in Isaba (A268) and Sigues (A063).

![Figure 10](image2.png)

**Figure 10.** Hydrographs observed and simulated at Isaba stream gauge (A268).

4.3 Water budget

Table 4 calculates the water balance of the event considering the stretch from 0 to 200 hours. In this table, starting data of the water balance are the following:

1. Total precipitation (Tp): measured in the distributed precipitation model or in the average hyetograph of the episode (figures 5 and 8).
2. Snowmelt (Sm): it is determined in the modelling and can also be measured in the middle hyetograph of the event (in figure 8 it comes as runoff from snow melting).
3. Total runoff (Tr): it is also obtained with the modelling (in figure 8 it is the sum of the rainfall and snow runoff).
Table 4. Benchmarking of the water budget (in the range 0-200 hours) in the stations of Isaba and Sigues.

<table>
<thead>
<tr>
<th></th>
<th>Isaba</th>
<th>Sigues</th>
<th>Isaba</th>
<th>Sigues</th>
<th>Isaba / Sigues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total precipitation</td>
<td>31.79</td>
<td>67.61</td>
<td>168</td>
<td>134</td>
<td>127%</td>
</tr>
<tr>
<td>(Tp)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total runoff (Tr)</td>
<td>17.90</td>
<td>42.06</td>
<td>95</td>
<td>83</td>
<td>90%</td>
</tr>
<tr>
<td>Effective precipitation (Ep)</td>
<td>11.47</td>
<td>19.27</td>
<td>34</td>
<td>45</td>
<td>101%</td>
</tr>
<tr>
<td>Snowmelt (Sm)</td>
<td>6.43</td>
<td>22.79</td>
<td>52</td>
<td>51</td>
<td>76%</td>
</tr>
<tr>
<td>Losses (L)</td>
<td>20.32</td>
<td>48.33</td>
<td>107</td>
<td>95</td>
<td>148%</td>
</tr>
<tr>
<td>Hydrograph volume (Hv) *</td>
<td>9.80</td>
<td>25.86</td>
<td>52</td>
<td>51</td>
<td>80%</td>
</tr>
</tbody>
</table>

(*) It is the volume measured between 0 and 200 hours. On the other hand, it remains to leave the basin (in Sigues stream gauge) 42.06-25.86 = 16.2 adding the volume prior to the start of the event.

The terms to calculate using water balance equations are:

1. Effective precipitation (Ep): in Figure 8 it comes as runoff from rain.
   \[ Ep = Tr - Sm \]  
2. Losses (L): It is the difference between the total precipitation and the effective precipitation.
   \[ L = Tp - Ep \]

The volume of the hydrograph (Hv) is obtained by integration of the actual hydrograph, in the 0-200 h range. The volume of water that remains in the basin just at the 200 h coordinate is the difference between total runoff (Tr) and volume of the hydrograph (Hv) adding the volume prior to the start of the episode. From the comparison of Table 4, analysing the specific values (mm), the following is deduced:

1. Based on observed data: in Isaba there is a greater proportion of gross precipitation, although the output is similar (consider the volume of output = volume of the hydrographs).
2. As data from the simulation: in Isaba (with a higher average altitude of the basin), there is less thaw and greater losses, part of which can be attributed to snow retention.

5. Conclusions

The hydrological modelling of watersheds by combination of deposits is a classic method, but it is in recent years that it reaches a great diffusion with the development of computers. A new model is presented that combines linear deposits in parallel that represent the circulation of water through the reservoirs of the basin, and that has given excellent results in simulations of actual events. A quality that stands out in this model is its calibration, based on actual recession curves that are the response of the discharge of all the reservoirs of the basin. In addition, this model allows introducing the discharge of water from the snow reserves, its distribution in the different deposits and its routing through the hydrological system of the basin. Another additional advantage of the model is that it allows a water balance for an event and with it, estimates the volume of recharge coming from the snowmelt.

The SHEE computer application allows configuring models of hydrological processes such as, the spatial-temporal distribution of rainfall, the previous state of soil moisture and the mode of water routing through the basin, which has made it possible to carry out this investigation of a actual flood episode registered in the Esca river, where snow melting processes have had an outstanding influence.

Without considering the snowmelt, the January 2009 event of the Esca River presents an extraordinarily unbalanced water budget. That is why a basic model of thaw is introduced that is activated in periods of time where the temperature, taken in actual records, is higher, reaching a balanced water balance and a better adjusted simulated hydrograph. From the simulation of this episode the following observations are made:
(1) An estimate of the volume of melted snow (given as volume of water) is obtained, being 6.43 hm³ in the Isaba stream gauge and 22.79 hm³ in the Sigues stream gauge. The effective precipitation volumes are 11.47 and 19.27 hm³ in the respective catchments, so the snowmelt represents 36% and 54% of the total runoff (effective precipitation plus snowmelt).

(2) In terms relative to the catchment area, Isaba stream gauge produces greater total precipitation but lower runoff volume.

(3) The runoff due to thawing is notably higher in Sigues (45 mm compared to 34 mm in Isaba). This is explained because the melting of the snow has occurred in the lower part of the catchment. The importance that the snowmelt has in the genesis of floods is highlighted in this paper. To do this, another simulation is carried out without thawing, and a peak flood of only 80 m³/s is obtained, with a total runoff volume of 19.27 hm³, compared to 201 m³/s and 42.06 hm³ obtained by considering snowmelt.

Acknowledgments: This work has been partially subsidized by the Research Group "Analysis of Continental Sedimentary Basins" of the Government of Aragon and FEDER Funds to which gratitude is transmitted.

Author Contributions: All authors conceived and designed the experimental work, with special mention to J. Castillo-Mateo for having completed the mathematical development allowing its applicability to the actual cases of the Esca River.

References


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Assessment of snowmelt role for a flood event in a gauged catchment

Jesús Mateo-Lázaro, Jorge Castillo-Mateo, José Ángel Sánchez-Navarro, Víctor Fuertes-Rodríguez, Alejandro García-Gil, Vanesa Edo-Romero

1 Dept. of Earth Sciences, University of Zaragoza. Pedro Cerbuna, 12, 50009-Zaragoza, Spain; jesmateo@unizar.es; joseange@unizar.es; vanesa_edo@hotmail.com
2 Dept. of Mathematics, University of Zaragoza. Pedro Cerbuna, 12, 50009-Zaragoza, Spain; 720193@unizar.es
3 Dept. of Geography and Territorial Planning, University of Zaragoza. Pedro Cerbuna, 12, 50009-Zaragoza, Spain; 696825@unizar.es
4 Geological Survey of Spain (IGME), C/ Manuel Lasala nº 44, 9º B, 50006 Zaragoza, Spain; a.garcia@igme.es
* Correspondence: jesmateo@unizar.es; (00) +34 (9) 690 609948

Abstract: An actual event that happened in the Roncal Valley (Spain) is investigated and the results are compared between models with and without snowmelt. A distributed rainfall model is generated with the specific data recorded in the rain gauges of the catchment during the episode. To describe the process of water routing in the hydrological cycle of the basin, a model is used based on combinations of Parallel Linear Reservoirs (PLR model), distributed by the basin and tip-out into its drainage network configured using a digital terrain model (DTM). This PLR model allows simulating the different actual reservoirs of the basin, among them including the snow and its contribution due to its melting that, in the model, depends on the temperature. The PLR model also allows for a water budget of the episode where, in addition to the effective rainfall contribution, the part that comes from the thaw is taken into account. The PLR model also allows determining the amount of water that exists in the basin before and after the episode, a data of great interest. When comparing the simulations with and without taking into account the thawing process, it is evident that the intervention of the reservoir of snow has been decisive for a flood to have occurred.

Keywords: Availability of water resources; Snowmelt; Floods; Hydrological processes; PLR models; SHEE software

1. Introduction

There are numerous works that have been carried out in recent years in different lines of flood research, but there are few that include melting processes as a direct cause to the flood phenomenon. The process of snowmelt has been considered in this paper within a flood model with hydro-meteorological methods or models of rainfall-runoff. We have introduced the melting process as an additional contribution that flows through the hydrological system of the basin.

Hydrological processes related to snow (snowfall, snowpack, snowmelt) occur in large regions of the Earth. The snowmelt is one of the processes that intervene in the hydrological cycle and interacting with many other processes. This article focuses on the phenomenon of melt-induced flooding and the changes it causes in the runoff regime, but this issue and its consequences have already been widely studied using a multitude of approaches [1, 2].
The tendency and the variability of the discharge in the rivers and their relation with the runoff coming from the snowmelt is a recurrent topic even in recent studies [3-6]. Sensitivity studies of the variables that intervene in the melting processes are another key issue, for example, Reference [7] evaluates the sensitivity of a snowmelt runoff model with temperature input data, in a region with complex temperature elevation gradients.

Another phenomenon to be highlighted, which is also caused by the melting process, is the time lag in the water balance. This lag, which takes place between precipitation in the form of snow and the runoff, which is another of the topic variables we quantify in this article. Recently, other authors have contributed to shed some light on this topic [8, 9]. Other authors have developed rain-snow separation methods within time series and their lag with runoff [10-12]. Reference [13] uses data from the temporary Jena estimate of the snow cover thickness of the snow cover to study the time lag. Reference [14] models the relationships between the snow cover depletion, of the snow cover with the influence of the snow accumulation heterogeneity of the accumulation of snow and with the melting energy. Reference [15] proposes calibration methods for the time lag of the snow-runoff.

In addition to the methods proposed in [23], there are recent publications that use models developed to implement the snow-runoff process. The well-known SWAT model has also been widely used in recent publications [1, 16-31]. Reference [15] develops a progressive segmented optimization algorithm to calibrate the temporal variation parameters of the snowfall-runoff model. Reference [14] conducts simulations of snowfall-runoff in various environments of mountain basins. The most frequent parameters used in the models are analysed by reference [32], which concludes with the development of hydrological basin models with accounting for the runoff due to from the snow thawing and showing that substantial progress has been made with-by using models with different sophistication levels.

Other authors focus their research on the forecast of melting processes and their consequences. Reference [33] performs prediction studies with about thawing processes happening in the Spanish Pyrenean chain, which is the research location area of our article. In other cases, the studies focus on urbanized areas such as that of Reference [34], where the effect of snow melting on discharge forecasts is highlighted, carrying out a study in an urbanized basin with clearly influenced by the snow processes on the increasing the goal runoff.

Above we have earlier referred to the relationship of between the melting process with-and other processes. Erosion and sediment transport are processes that maintain a relationship. In many cases, water melted from snow causes greater erosion of the soil than rainwater [35] so it is appropriate to investigate the differences in soil infiltration capacity during periods of rain or snow melting. Soil erosion in agricultural areas during winter and spring is a problem in many countries of the world, such as Norway [36], USA [37], Belgium [38], United Kingdom [39], Germany [40] and Russia [41]. In these areas, soil erosion during winter and spring depletes the nutrient-rich top layer and contributes elements (phosphorus, nitrogen) to freshwater bodies [42].

The period of droughts is another process that may be related to the snow melting processes, in this case due to an absence or prolonged decrease in the contribution of snow [43].

Energy and thawing processes are also processes related to each other. Reference [44] shows how changes in the composition or structure of the soil in large areas influence the energy input of to the soil and-therefore, the rate of thawing. Reference [14] demonstrates the influence of the spatial distribution of the snow cover thickness and heterogeneity into the distribution of fusion energy in extreme runoff events.

It can be said that the snow and thawing processes play an important role in the hydrological cycle, both both by themselves and by their direct relationship with other processes, as well as by their regulatory role of water flow and volume of the water reserve.

To carry out this work, we start with a flow circulation model using a methodology based on a combination of Parallel Linear Reservoirs (PLR model) [45, 46]. In hydrological science, reservoir models have been widely used to represent different characteristics of river basins. References [47-49] synthesize several works in this area of research. Currently, reservoir models are very
widespread and are based on the concept that a watershed is like a set of interconnected deposits
(rain, snow, aquifers, soil, biomass, etc.), each with different characteristics in terms of recharge,
storage and discharge [50]. The input hydrograph corresponds to the effective precipitation, also
called effective rainfall, rainfall excess, or recharge. This is why this model has to be combined
with another one that performs the transformation of the gross precipitation into effective
precipitation. It is very frequent, and it is going to be our case, to use the Curve Number
method of the SCS (SCS-CN model) to carry out this transformation.

The models of reservoirs are traditionally used in hydrology to represent different
characteristics of the basins, thus reference [49] they make a synthesis of different works in
this line. Recently, a line of research has been established with models of reservoirs distributed
according to geomorphological trajectories of flow within the basin. For example, in reference
[51], a conceptual model is developed based on the geomorphological properties of watersheds.

Unitary hydrograph models applying linear reservoirs distributed in cascade according to the
geomorphology of the basin are developed in reference [52].

This article investigates the cause of an actual flood event that occurred in the Roncal valley in
January 2009, where everything seems to indicate that fusion processes in the basin's snow
reservoirs contributed decisively to the activation of the flood. The work is carried out following the
methodology developed in reference [45], and for this the computer program SHEE (Simulation of
Hydrological Extreme Events), please find http://www.unizar.es/hidrologia) is used to do so, and
that allows to represent the basin through a distribution of reservoirs in parallel (PLR model) and
that takes into account the contributions due to the snow melt.

With regard to the investigation of the actual episode, the following scheme is followed: (1)
To create a distributed model of total rainfall. (2) To create a water circulation model
for the basin. The parameters of a reservoir model (Qa and α) are determined from the recession
curves of the actual hydrograph. (3) To create a precipitation model and, to generation of the
hyetographs of total precipitation using, using the Curve Number model, another effective
precipitation model. (4) To establishment of the water balance. Based on the results of the
simulation, a water balance is determined that determines the origin of the water causing the flood.

2. Methods

The PLR models are part of the computer program referred to above, SHEE (Simulation of
Hydrological Extreme Events) computer program, carried out in the Department of Earth Sciences of
the University of Zaragoza for its application in hydrological events. In essence, the program is an
adaptation of traditional hydrological models to the new technologies and data sources and
reproduces, through the use of models, the different intervening processes. In general, these
processes are that, in the general case, are the geometric model of the basin; the rain model that
distributes it in space and time; the rain-runoff transformation model that aims to differentiate (or
separate) between losses and runoff (losses are also called abstractions, retentions and runoff
deficit); and the flow circulation models (also called transit, propagation, routing, runoff and
discharge). Then, to this general scheme a new model is added that estimates the contribution of water coming from snow reservoirs.

Figure 1 shows the interface of the computer program which, in recent years, has been used in
the recent years, in numerous professional works on risks, spatial planning, civil and architectural
works, as well as in scientific publications [45, 46, 53-61]. The SHEE software SHEE has
numerous applications for either DEM management or hydrological processes simulation [62].

Obtaining new cartographic coverage with the combination of DEM and simulated processes is
also possible. The DEM management is achieved using the GDAL (Geospatial Data Abstraction
Library), which permits allowing for importing and exporting different archive formats and to
make getting new coverage from multiple archives. The program can combine coverage getting
different coordinate systems thanks to the use of the PROJ library from the USGS. Thousands of
terrestrial geodetic systems can be represented, transformed and converted between them. To do
that, the program is able to obtain the necessary Spatial Reference Organization parameters from the internet server transfer. Downloading information from the WMS remote server is also possible. With regard to the DEM characteristics, the SHEE program can manage any format, size, accuracy and reference system. For example, Global DEM has been used like SRTM30 (with file size 3.6 GB and grid size 30″, ~900 m), MDT5 of Spanish territory (120 GB and 5 m) and Lidar. The use of PLR models (Parallel Linear Reservoir) as a hydrological model integrated within the sequential processing algorithm of the catchment is a special case of hydrological application where every cell of the DEM is considered as a reservoir combination in parallel [63].

The future developments of the SHEE program are very promising. Recently, we have incorporated a module for the development and visualization of geological structures in three dimensions. In the near future, it will allow the development of combined hydrogeological models with complex subsurface structures. This implementation has resulted in the paper publication of Reference [55]. Therein, we present an application that visualizes three-dimensional geological structures with digital terrain models. The three-dimensional structures are displayed as their intersection with two-dimensional surfaces that may be defined analytically (e.g., sections) or with using grid meshes in the case of irregular surfaces such as the digital terrain models. Additionally, the process of generating new textures can be performed by a Graphics Processing Unit (GPU), thereby making real-time processing very effective and providing the possibility of displaying the simulation of geological structures in motion. Regarding the Graphics Processing Units, and since the DEM is becoming denser, we are currently completing the development of hydrological models with this technique through the sequential processing algorithm, whose main advantage is the shortening of the computation time, which can be reduced up to 100 times. Due to parallel processing, it is necessary to reprogram the sequential algorithms for computing drainage networks.

2.1. PLR models: characterization of a single linear reservoir

The hydrological relationships of a linear reservoir are governed by two equations, the flow or storage equation (equation 1) and the continuity equation or water balance equation (equation 2).

\[ Q = \alpha \cdot S \]  

(1)
\[ R = Q + \frac{dS}{dt} \]  

(2)

Where \( Q \) is the discharge (m\(^3\)/sec), \( S \) is the storage (m\(^3\)), \( \alpha \) is the depletion coefficient (sec\(^{-1}\)), \( R \) is the recharge that enters the reservoir (for example, in the form of effective precipitation) and \( t \) is the time (sec). From a Topology perspective, the depletion coefficient (\( \alpha \)) is the slope of the line that relates the storage with the discharge (Figure 2) and, hence, the name of the linear reservoir. The combination by combination of equations 1 and 2 results in the differential equation of runoff or discharge (with the form of the equation 3):

\[ Q_2 = Q_1 \cdot e^{-\alpha \Delta t} + R \cdot (1 - e^{-\alpha \Delta t}) \]  

(3)

Where \( Q_1 \) and \( Q_2 \) are the values of \( Q \) spaced apart by an elementary fraction of time (\( \Delta t \)) during which the recharge can be considered constant.

\[ \alpha = \tan(\phi) \]

Figure 2. Water routing for a linear reservoir.

2.2. PLR models: combination of linear reservoirs in parallel sets

A basin (or a cell if it is considering the areal division of the basin as cells of a grid) can be represented with a single reservoir or with a combination of reservoirs. The simplest model to represent a basin is by considering a single reservoir whose behaviour is representative of the basin's response. Evidently, the model is not very descriptive and the results obtained show biger deviations. In addition, a basin can be represented by a set of deposits, each one representative of certain characteristics of the basin. And also Furthermore, a basin can be divided into sub-basins or cells, each of which can be represented by a set of deposits. The possible combinations of combinations of reservoirs to build a model are unlimited, although they are few combinations give and simple with which acceptable results are achieved. In this work, we have used a combination of two reservoirs in parallel for each cell of the digital terrain model, where water enters according to a distributed model of effective precipitation. The combination of both reservoirs pours water into the drainage network whose flow is modelled with a classical method. This scheme is used in the SHEE program to meet the following qualities assumptions:

1. The calibration of the model is based on actual recession curves, that is, based on actual responses from the basin.
2. Each reservoir represents a set of characteristics of a specific basin, whose response differs markedly from the response of the characteristics represented by the other reservoirs.
3. As a result of the latter, the total hydrograph can be decomposed into several partial hydrographs that can be mapped into parts of the hydrological system (direct runoff hydrograph, underground runoff hydrograph, etc.).
4. The PLR model allows to ascertain the water stored in the reservoirs (i.e., in the basin) and to calculate a water balance for each episode.
5. Finally, for the circulation in channels, standard models (kinematic wave or Muskingum-Cunge) are widely contrasted for the circulation in channels.

For a combination of \( n \) linear reservoirs in parallel, the resultant is the sum of the reservoirs as shown in equations 4 and 5, and for each reservoir, as using equations 1 and 2 are fulfilled, without considering recharge, equations 6 and 7 are obtained.
\[ Q = \sum_{i=1}^{n} Q_i \quad (4) \]
\[ S = \sum_{i=1}^{n} S_i \quad (5) \]
\[ Q_i = Q_{oi} \cdot e^{-\alpha \Delta t} \quad (6) \]
\[ S_i = \frac{Q_i}{\alpha_i} \quad (7) \]

Equation 8 is obtained by combining equations 4 and 6. Equation 8, we arrive at equation 8 shows that, for an instant \( t \), there is a mathematical relationship between the flows of each deposit.

\[ \left( \frac{Q_1}{Q_{o1}} \right)^{\frac{1}{n'}} = \ldots = \left( \frac{Q_i}{Q_{oi}} \right)^{\frac{1}{n'}} = \ldots = \left( \frac{Q_{nr}}{Q_{onr}} \right)^{\frac{1}{n'}} \quad (8) \]

The recession curve of a hydrograph is a set of data flow vs time \( Q-t \) for in the case of the system of equations 8, whose resolution allows to obtain a set of \( Q_o \) parameters, \( \alpha \). With these parameters, and with them to establish a PLR model can be established. Once the model is established, hydrographs can be generated with using equations 3, 4 and 6, hydrographs can be generated according to the inputs \( R \) to the system. Also, in addition, using with equations 5 and 7, we have the amount of water stored in each reservoir of the basin is obtained, which thus allows us to carry out the water balance.

2.3 PLR models: snowmelt

Snowfall supposing implies a new contribution that has needs to be added to the entrances input along with the effective precipitation, and whose origin has to be looked for in a previous episode of precipitation in the form of snow. For a given process of snowmelt due to short events of intense rain, the factors of precipitation and temperature are considered as factors, as and as the most influential parameters in the fusion process. A simple model is to consider that snow melting is as linearly proportional to precipitation when it occurs, at temperatures above 0ºC. Thus, for a certain part of the hydrograph that coincides with temperatures above 0ºC, effective precipitation as an input to the surface runoff system can be replaced by total precipitation by adding snow melting. In this way, the runoff equation (equation 3) is modified by adding a new recharge term coming from the snow melting \( R' \), and by substituting in \( R \) the effective precipitation by total precipitation at \( R' \), as expressed in equation 9.

\[ Q_2 = Q_1 \cdot e^{-\alpha \Delta t} + (R + R') \cdot (1 - e^{-\alpha \Delta t}) \quad (9) \]

The main advantage of the PLR model is that, by allowing the water budget of an event to be considered, the amount of snowmelt recharge, \( R' \), can be estimated to equilibrate the water balance.

3. Data Source

3.1 Characterization of the basin

The catchment studied is that of the Esca river (Roncal valley), located in the Pyrenees ridge, between Aragon and Navarra, two regions of northeast Spain. The basin is preserved in a natural state, without reservoirs or significant alterations. Figure 3 shows an altimetry representation of the basin, the location of the gauging stations (two) and the pluviometry stations considered (four). Table 1 gives some of the most significant hydrological characteristics for this watershed.
Figure 3. Altimetry representation of the Esca river basin with the rain gauges (A063, A268, A259 and P016) and the two stream gauges (A063, A268) that also have rain gauges.

Table 1. Hydrological characteristics of the Esca River basins in Sigues and Isaba.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>ud</th>
<th>Isaba (A268)</th>
<th>Sigues (A063)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catchment area</td>
<td>km²</td>
<td>189.06</td>
<td>506.26</td>
</tr>
<tr>
<td>Length of the main channel</td>
<td>km</td>
<td>24.01</td>
<td>51.70</td>
</tr>
<tr>
<td>Average slope of the main channel</td>
<td>%</td>
<td>6.44</td>
<td>3.45</td>
</tr>
<tr>
<td>Average slope of the digital surface of the catchment</td>
<td>%</td>
<td>36.85</td>
<td>34.88</td>
</tr>
<tr>
<td>Average Curve Number (AMC II)</td>
<td></td>
<td>63.08</td>
<td>61.22</td>
</tr>
</tbody>
</table>

3.2 Melting event setting

The event investigated corresponds to the flood occurred between January 18 and 28, 2009. Table 2 shows its main characteristics, such as duration, peak flow, and the number of intervals considered for the treatment of the actual rain.

Table 2. Characteristics of the actual event investigated.

<table>
<thead>
<tr>
<th>Date</th>
<th>Rain duration</th>
<th>Time interval</th>
<th>Peak flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 18, 2009, 2:30 p.m.</td>
<td>245.25</td>
<td>981</td>
<td>201</td>
</tr>
</tbody>
</table>

3.3 Rainfall model

The rainfall data has been obtained from the data of the Spanish SAIH network that records the value of the precipitation with 15-minute intervals of 15 minutes. Figure 4 shows two isohyet...
maps of the event corresponding to the coverages generated from the accumulated precipitation in two of these intervals (the event requires the use of 981 layers). Spatial interpolation is performed by applying a distributed precipitation model based on the use of Radial Basis Functions (RBF) [64-66]. From these precipitation coverages, the computer program can generate a different hyetograph for each point of the basin.

Figure 4. Isohyet maps of the event occurred in January 2009 (equidistance 0.25 mm). A sequence of 2 coverage intervals of 15 minutes is presented. The whole event has 981 layers.

3.4 Reservoir model

The reservoir model is established from the actual hydrographs of the episode. The reservoir model is established by adjusting the parameters \( q_0 \) and \( \alpha \). For this purpose, the least squares method is applied to the specific recession curve by using equation 10 \( (q = Q/catchment\; area) \) to the specific recession curve \( (q = Q/catchment\; area) \) the least squares method is applied with the system of equations 10.

\[
q_i = \sum_{j=1}^{m} q_0j \cdot e^{-\alpha_j t_i} \tag{10}
\]

where \( m \) is the number of reservoirs (two in our case), \( q_i \) are the known values of the flow of the recession curve at time \( t_i \), and \( q_0 \) and \( \alpha \) are the unknowns. We thus have an overdetermined system of \( n \) equations is obtained, with \( n >> 2m \) unknowns, where \( n >> 2m \). Once stated and solved for the recession curve of the actual hydrograph, we arrive at the results shown in Table 3 for a model of two linear reservoirs in parallel, which will be used within the SHEE program to perform simulations, either considering or not dismissing the snowmelt process of snowmelt.

Table 3. Parameters of the parallel linear reservoirs for the event occurred in the Esca River.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reservoir</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td></td>
<td>1.43 E-06</td>
<td>1.67 E-05</td>
</tr>
<tr>
<td>( q_0 )</td>
<td></td>
<td>2.96 E-07</td>
<td>1.00 E+00</td>
</tr>
</tbody>
</table>

4. Results and Discussion
4.1 Simulation without snowmelt

The simulation of the event with using the SHEE program and without not considering snowmelt shows a notable disarrangement mismatch with reality. To achieve an adequate water balance, it is required to modifying the standard conditions to other very wet conditions by means of the curve number model is required, as seen in the ratio of total and effective rainfall hyetographs (Figure 5). It is evident that the effective rain obtained is unusually high. On the other hand, there is very little agreement between both hydrographs (Figure 6). In the actual hydrograph, a peak occurs in at 125 hours that does not occur in the simulation, while at 220 hours, the simulated values exceed the actual ones.

![Figure 5. Average Hyetographs in the Esca River basin in January 2009. Total precipitation was obtained directly by the interpolation method (blue) and effective precipitation, without not considering snowmelt (red) and with high curve number.](image)

4.2 Simulation with snowmelt

In the model with considering snowmelt, the average altitude of each of the two basins was taken into account, as well as the discharge contributions into each stream gauge. It has been observed that there is no proportional relationship between the area of each basin and its discharge contribution. This fact was to be as expected, because in winter the melting is greater at lower
altitude in winter, a circumstance that tends to be reversed towards spring, as there is more snow in the high areas.

The ratio of the peak-flow with a rapid melting of snow would be supported by the evolution of temperatures, a fact that can be seen in Figure 7. The station of Arangoiti is located at 1,350 meters with a cold period between 45 and 90 hours, while between 90 and 140 hours the temperature exceeds 0°C, reaching up to 8°C.

Figure 7. Temperature graph at the Arangoiti station during the episode of January 2009. Hyetographs of total and effective precipitation with snowmelt in Esca River.

With the model it has been estimated which should be the recharge by melting snow in the interval between 80 and 120 hours to be able to fit the hydric balance of the episode in less humid previous hydrological conditions than in the case of no snowmelt model. By using the model, the necessary recharge derived from snowmelt, which is needed in the interval between 80 and 120 hours to fit the hydric balance of the episode in less humid previous hydrological conditions than in the case of the no snowmelt model has been estimated. The optimal results are obtained with a melting value equivalent to 90% of the gross precipitation that occurred in that interval, that is, R' = 0.9·R. In this way, we obtain the hyetographs shown in Figure 7 and the hydrograph of Figure 8 are obtained, where previous dry hydrological conditions have been considered. Thus, in the simulation a hydrograph very similar to the actual one is obtained.
Figure 8. Simulated hydrograph considering snowmelt. Fragmented lines show the partial hydrographs for each reservoir.

Figure 9 shows the observed hydrograph obtained from Isaba stream gauge (A268), which is located in the interior of the basin and which can be compared with that observed at the exit at the Sigues stream gauge (A063). Figure 10 shows the simulated hydrograph at the point corresponding to the Isaba station.

Figure 9. Actual hydrographs obtained from Isaba (A268) and Sigues (A063).
Figure 1. Hydrographs observed and simulated at Isaba stream gauge (A268).

4.3 Water budget

Table 4 contains the results of the water balance of the episode studied, considering the temporal section interval between 0 and 200 hours. The balance is carried out from the two gauging stations (Isaba and Sigues), and the results are given in total units (hm³) for the entire basin corresponding to each gauging station. The results are also presented in specific units (mm), total units divided by the area of the corresponding basin. The last column represents a comparison between the results of the two gauging stations.

To elaborate the water balance, we start from the data and results of hyetographs and hydrographs that have been used in the modelling, which can be summarized in three components:

1. Total precipitation (Tp): It has been obtained from the model of distributed precipitation based on functions (RBF) shown in Figure 4, adding all the time 15-minute intervals every 15 minutes from the range between 0 to and 200 hours. The results of this integration coincide with the term Total Rainfall of the average hyetograph of Figures 5 and 7.

2. Snowmelt (Sm): it is determined in the distributed model calculated with the SHEE program, whose average representation coincides with the snowmelt fraction of the average hyetograph shown in Figure 7.

3. Total runoff (Tr): it is also obtained from the distributed model, and the average value is represented in the hyetograph shown in Figure 7 as the sum of two terms: runoff from rainfall and runoff from snowmelt.

Table 4. Benchmarking of the water budget (in the range 0-200 hours) in the stream gauges of Isaba and Sigues.

<table>
<thead>
<tr>
<th>Isaba</th>
<th>Sigues</th>
<th>Isaba</th>
<th>Sigues</th>
<th>Isaba / Sigues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tp</td>
<td>Total precipitation</td>
<td>31.79</td>
<td>67.61</td>
<td>168</td>
</tr>
<tr>
<td>Tr</td>
<td>Total runoff</td>
<td>17.90</td>
<td>42.06</td>
<td>95</td>
</tr>
<tr>
<td>Ep</td>
<td>Effective precipitation</td>
<td>11.47</td>
<td>19.27</td>
<td>61</td>
</tr>
<tr>
<td>Sm</td>
<td>Snowmelt</td>
<td>6.43</td>
<td>22.79</td>
<td>34</td>
</tr>
<tr>
<td>L</td>
<td>Losses</td>
<td>20.32</td>
<td>48.33</td>
<td>107</td>
</tr>
<tr>
<td>Hv*</td>
<td>Hydrograph volume</td>
<td>9.80</td>
<td>25.86</td>
<td>52</td>
</tr>
</tbody>
</table>

(*Hv is the volume measured between 0 and 200 hours. On the other hand, it remains still has to leave the basin (in Sigues stream gauge) 42.06-25.86 = 16.2, by adding the volume prior to the start of the event.

In short, the terms Tp, Tr and Sm are obtained from data and direct results of the model. The terms Ep and L can be obtained from equations 11 and 12, which are specific water balance equations:

1. Effective precipitation (Ep): it comes is described as runoff from rain.
   \[ \text{Ep} = \text{Tr} - \text{Sm} \]  
   (11)

2. Losses (L): it is the difference between the total precipitation and the effective precipitation.
   \[ \text{L} = \text{Tp} - \text{Ep} \]  
   (12)

The volume of the hydrograph (Hv) is obtained by integration of the actual hydrograph, in the 0-200 h range. The volume of water that remains remaining within the basin just at the 200 h coordinate is the difference between the total runoff (Tr) and the volume of the hydrograph (Hv), adding the volume present prior to the start of the episode. From the comparison of Table 4 and, analysing the specific values (mm), the following statements are deduced is deduced.
5. Conclusions

The hydrological modelling of watersheds by combination of deposits is considered a classic method, but it is in recent years that it has reached a great diffusion with the development and improvement of computers. A new model is presented that combines linear deposits in parallel, that representing the circulation of water through the reservoirs of the basin, and giving has excellent results in simulations of actual events. A quality that stands out in about this model is its calibration, which is based on actual recession curves that are the response of to the discharge of all the reservoirs of the basin. In addition, furthermore, this model allows introducing the discharge of water from the snow reserves, its distribution in the different deposits and its routing through the hydrological system of the basin. Another additional advantage of the model is that it allows establishing a water balance for an event and, thus, it estimates the recharge volume of the snowmelt coming from the snowmelt.

The SHEE computer application allows configuring models of hydrological processes, such as, the spatial-temporal distribution of rainfall, the previous state of soil moisture and the mode of water routing through the basin, which has made it possible to carry out this investigation of an actual flood episode registered in the Esca river, where snow melting processes have had an outstanding influence.

Without considering the snowmelt, the January 2009 event of the Esca River presents an extraordinarily unbalanced water budget. That is why a basic snowmelt model is introduced that is activated in periods of time where the temperature, taken from actual records, is higher, reaching a balanced water balance and a better adjusted simulated hydrograph. From the simulation of this episode, the following observations are made:

1. An estimate of the volume of melted snow (given as volume of water) is obtained, being 6.43 hm$^3$ at the Isaba stream gauge and 22.79 hm$^3$ at the Sigues stream gauge. The effective precipitation volumes are 11.47 and 19.27 hm$^3$, respectively, in the respective catchments. That way, the snowmelt represents 36% and 54% of the total runoff (effective precipitation plus snowmelt), respectively.

2. In terms relative to the catchment area, Isaba stream gauge produces greater total precipitation but lower runoff volume.

3. The runoff due to thawing is notably higher at Sigues (45 mm compared to 34 mm at Isaba). This can be explained because due to the snow melting of the snow has occurred in the lower part of the catchment.

The importance of the snowmelt in the genesis of floods is highlighted in this paper. To do this, another simulation is carried out without taking into account the thawing process. In that case, a peak flood of only 80 m$^3$/s is obtained, with a total runoff volume of 19.27 hm$^3$, compared to the 201 m$^3$/s and the 42.06 hm$^3$ obtained by considering the snowmelt.

Acknowledgments: This work has been partially subsidized by the Research Group “Analysis of Continental Sedimentary Basins” of the Government of Aragon and FEDER Funds to which gratitude is transmitted. We deeply appreciate the time spent by the Reviewers and Editors, who will undoubtedly contribute to the improvement of our manuscript.

Author Contributions: All authors conceived and designed the experimental work, with special mention to J. Castillo-Mateo for having completed the mathematical development allowing its applicability to the actual cases of the Esca River.

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Assessment of snowmelt role for a flood event in a gauged catchment

Jesús Mateo-Lázaro¹, Jorge Castillo-Mateo², José Ángel Sánchez-Navarro¹, Víctor Fuertes-Rodríguez³, Alejandro García-Gil⁴, Vanesa Edo-Romero¹

¹ Dept. of Earth Sciences, University of Zaragoza. Pedro Cerbuna, 12, 50009-Zaragoza, Spain; jesmateo@unizar.es; joseange@unizar.es; vanesa_edo@hotmail.com
² Dept. of Mathematics, University of Zaragoza. Pedro Cerbuna, 12, 50009-Zaragoza, Spain; 720193@unizar.es
³ Dept. of Geography and Territorial Planning, University of Zaragoza. Pedro Cerbuna, 12, 50009-Zaragoza, Spain; josemateo@unizar.es; joseange@unizar.es; vanesa_edo@hotmail.com
⁴ Geological Survey of Spain (IGME), C/ Manuel Lasala n° 44, 9° B, 50006 Zaragoza, Spain; a.garcia@igme.es

* Correspondence: jesmateo@unizar.es; (00) +34 (9) 690 609948

Received: date; Accepted: date; Published: date

Abstract: An actual event that happened in the Roncal Valley (Spain) is investigated and the results are compared between models with and without snowmelt. A distributed rainfall model is generated with the specific data recorded in the rain gauges of the catchment during the episode. To describe the process of water routing in the hydrological cycle of the basin, a model is used based on combinations of Parallel Linear Reservoirs (PLR model), distributed by the basin and tip-out into its drainage network configured using a digital terrain model (DTM). This PLR model allows simulating the different actual reservoirs of the basin, including the snow and the contribution due to its melting which, in the model, depends on the temperature. The PLR model also allows for a water budget of the episode where, in addition to the effective rainfall contribution, the part that comes from the thaw is taken into account. The PLR model also allows determining the amount of water that exists in the basin before and after the episode, a data that results of great interest. When comparing the simulations with and without taking into account the thawing process, it is evident that the intervention of the reservoir of snow has been decisive for a flood to have occurred.

Keywords: Availability of water resources; Snowmelt; Floods; Hydrological processes; PLR models; SHEE software

1. Introduction

There are numerous works carried out in the recent years in different lines of flood research, but there are few that include melting processes as a direct or added cause to the flood phenomenon. The process of snowmelt is considered in this paper within a flood model with hydro-meteorological methods or models of rainfall-runoff. We have introduced the melting process as an additional contribution that flows through the hydrological system of the basin.

Hydrological processes related to snow (snowfall, snowpack, snowmelt) occur in large regions of the Earth. Snowmelt is one of the processes intervening in the hydrological cycle and interacting with many other processes. This article focuses on the phenomenon of melt-induced flooding and the changes it causes in the runoff regime, but this issue and its consequences have already been widely studied using a multitude of approaches [1, 2].
The tendency and the variability of the discharge in the rivers and their relation with the runoff coming from the snowmelt is a recurrent topic even in recent studies [3-6]. Sensitivity studies of the variables that intervene in the melting processes are another key issue, for example, Reference [7] evaluates the sensitivity of a snowmelt runoff model with temperature input data, in a region with complex temperature elevation gradients.

Another phenomenon to be highlighted, which is also caused by the melting process, is the time lag in the water balance. This lag takes place between precipitation in the form of snow and the runoff, which is another of the variables we quantify in this article. Recently, some authors have shed some light on this topic [8, 9]. Other authors have developed rain-snow separation methods within time series and their lag with runoff [10-12]. Reference [13] uses data from the temporal estimate of the snow cover thickness to study the time lag. Reference [14] models the relationships between the snow cover depletion and the influence of the snow accumulation heterogeneity and the melting energy. Reference [15] proposes calibration methods for the time lag of the snow-runoff.

In addition to the methods proposed in [23], there are recent publications that use models developed to implement the snow-runoff process. The well-known SWAT model has also been widely used in recent publications [1, 16-31]. Reference [15] develops a progressive segmented optimization algorithm to calibrate the temporal variation parameters of the snowfall-runoff model. Reference [14] conducts simulations of snowfall-runoff in various environments of mountain basins. The most frequent parameters used in the models are analysed by reference [32], concluding with the development of hydrological basin models accounting for the runoff due to the snow thawing and showing that substantial progress has been made by using models with different sophistication levels.

Other authors focus their research on the forecast of melting processes and their consequences. Reference [33] performs prediction studies about thawing processes happening in the Spanish Pyrenean chain, which is the research location area of our article. In other cases, the studies focus on urbanized areas such as that of Reference [34], where the effect of snow melting on discharge forecasts is highlighted, carrying out a study in an urbanized basin clearly influenced by the snow processes increasing the runoff.

We have earlier referred to the relationship between the melting process and other processes. Erosion and sediment transport are processes that maintain a relationship. In many cases, water melted from snow causes a greater erosion of the soil than rainwater [35] so it is appropriate to investigate the differences in soil infiltration capacity during periods of rain or snow melting. Soil erosion in agricultural areas during winter and spring is a problem in many countries of the world, such as Norway [36], USA [37], Belgium [38], United Kingdom [39], Germany [40] and Russia [41]. In these areas, soil erosion during winter and spring depletes the nutrient-rich top layer and contributes elements (phosphorus, nitrogen) to freshwater bodies [42].

The period of droughts is another process that may be related to the snow melting processes, in this case due to an absence or prolonged decrease in the contribution of snow [43].

Energy and thawing processes are also related to each other. Reference [44] shows how changes in the composition or structure of the soil in large areas influence the energy input to the soil and, therefore, the rate of thawing. Reference [14] demonstrates the influence of the spatial distribution of the snow cover thickness and heterogeneity to the distribution of fusion energy in extreme runoff events.

It can be said that the snow and thawing processes play an important role in the hydrological cycle, both by themselves and by their direct relationship with other processes, as well as by their regulatory role on water flow and volume of the water reserve.

To carry out this work, we start with a flow circulation model using a methodology based on a combination of Parallel Linear Reservoirs (PLR model) [45, 46]. In hydrological science, reservoir models have been widely used to represent different characteristics of river basins. References [47-49] synthesize several works in this area of research. Currently, reservoir models are very widespread and are based on the concept that a watershed is like a set of interconnected deposits (rain, snow, aquifers, soil, biomass, etc.), each with different characteristics in terms of recharge,
storage and discharge [50]. The input hydrograph corresponds to the effective precipitation, also
called effective rainfall, rainfall excess, or recharge. This is why this model has to be combined with
another one performing the transformation of the gross precipitation into effective precipitation. It is
very usual, and it is going to be our case, to use the Curve Number method of the SCS (SCS-CN
model) to carry out this transformation.

The models of reservoirs are traditionally used in hydrology to represent different
characteristics of the basins, thus reference [49] presents a synthesis of different works in this line.
Recently, a line of research has been established with models of reservoirs distributed according to
geomorphological trajectories of flow within the basin. For example, in reference [51], a conceptual
model is developed based on the geomorphological properties of watersheds. Unitary hydrograph
models applying linear reservoirs distributed in cascade according to the geomorphology of the
basin are developed in reference [52].

This article investigates the cause of an actual flood event that occurred in the Roncal valley in
January 2009, where everything seems to indicate that fusion processes in the basin's snow
reservoirs contributed decisively to the activation of the flood. The work is carried out following the
methodology developed in reference [45]. The computer program SHEE (Simulation of Hydrological
Extreme Events, please find http://www.unizar.es/hidrologia) is used to do so, allowing to represent
the basin through a distribution of reservoirs in parallel (PLR model) and taking into account the
contributions due to the snow melt.

With regard to the investigation of the actual episode, the following scheme is followed: (1) To
creation a distributed model of total rainfall. (2) To create a water circulation model for the basin.
The parameters of a reservoir model (Qe and α) are determined from the recession curves of the
actual hydrograph. (3) To create a precipitation model and to generate the hyetographs of total
precipitation by using the Curve Number model, another effective precipitation model. (4) To
establish the water balance. Based on the results of the simulation, a water balance is calculated that
determines the origin of the water causing the flood.

2. Methods

The PLR models are part of the SHEE (Simulation of Hydrological Extreme Events) computer
program, carried out in the Department of Earth Sciences of the University of Zaragoza for its
application in hydrological events. In essence, the program is an adaptation of traditional
hydrological models to the new technologies and data sources and reproduces, through the use of
models, the different intervening processes. In general, these processes are the geometric model of
the basin; the rain model that distributes it in space and time; the rain-runoff transformation model
that aims to differentiate (or separate) between losses and runoff (losses are also called abstractions,
retentions and runoff deficit); and the flow circulation models (also called transit, propagation,
routing, runoff and discharge). Then, to this general scheme, a new model is added that estimates
the contribution of water coming from snow reservoirs.

Figure 1 shows the interface of the computer program which has been used in the recent years
in numerous professional works on risks, spatial planning, civil and architectural works, as well as
in scientific publications [45, 46, 53-61]. The SHEE software has numerous applications for either
DEM management or hydrological processes simulation [62]. Obtaining new cartographic coverage
from the combination of DEM and simulated processes is also possible. The DEM management is
achieved using the GDAL (Geospatial Data Abstraction Library), which allows importing and
exporting different archive formats and getting new coverage from multiple archives. The program
can combine coverage from different coordinate systems thanks to the use of the PROJ4 library from
the USGS. Thousands of terrestrial geodetic systems can be represented, transformed and converted.
To do that, the program obtains the necessary Spatial Reference Organization parameters from the
internet server transfer. Downloading information from the WMS remote server is also possible.
With regard to the DEM characteristics, the SHEE program can manage any format, size, accuracy
and reference system. For example, Global DEM has been used as SRTM30 (with file size 3.6 GB and
grid size 30", ≈900 m), MDT5 of Spanish territory (120 GB and 5 m) and Lidar. The use of PLR
models (Parallel Linear Reservoir) as a hydrological model integrated within the sequential processing algorithm of the catchment is a special case of hydrological application where every cell of the DEM is considered as a reservoir combination in parallel [63].

Figure 1. SHEE program interface. This program uses digital terrain models and hydrological models, actual or simulated rain, soil moisture and circulation through the drainage network.

The future developments of the SHEE program are very promising. Recently, we have incorporated a module for the development and visualization of geological structures in three dimensions. In the near future, it will allow developing combined hydrogeological models with complex subsurface structures. This implementation has resulted in the paper publication of Reference [55]. Therein, we present an application that visualizes three-dimensional geological structures with digital terrain models. The three-dimensional structures are displayed as their intersection with two-dimensional surfaces that may be defined analytically (e.g., sections) or using grid meshes in the case of irregular surfaces such as the digital terrain models. Additionally, the process of generating new textures can be performed by a Graphics Processing Unit (GPU), thereby making real-time processing very effective and providing the possibility of displaying the simulation of geological structures in motion. Regarding the Graphics Processing Units, and since the DEM is becoming denser, we are currently completing the development of hydrological models with this technique through the sequential processing algorithm, whose main advantage is the shortening of the computation time, which can be reduced up to 100 times. Due to parallel processing, it is necessary to reprogram the sequential algorithms for computing drainage networks.

2.1. PLR models: characterization of a single linear reservoir

The hydrological relationships of a linear reservoir are governed by two equations, the flow or storage equation (equation 1) and the continuity equation or water balance equation (equation 2).

\[ Q = \alpha \cdot S \quad (1) \]

\[ R = Q + \frac{dS}{dt} \quad (2) \]

Where \( Q \) is the discharge (m\(^3\)/sec), \( S \) is the storage (m\(^3\)), \( \alpha \) is the depletion coefficient (sec\(^{-1}\)), \( R \) is the recharge that enters the reservoir (for example, in the form of effective precipitation) and \( t \) is the time (sec). From a Topology perspective, the depletion coefficient (\( \alpha \)) is the slope value relating the storage with the discharge (Figure 2) and, hence, the name of the linear reservoir. The combination of equations 1 and 2, results in the differential equation of runoff or discharge (equation 3).
\[ Q_2 = Q_1 \cdot e^{-\alpha \Delta t} + R \cdot (1 - e^{-\alpha \Delta t}) \]  

(3)

Where \( Q_1 \) and \( Q_2 \) are the values of \( Q \) separated by an elementary fraction of time (\( \Delta t \)) during which the recharge can be considered constant.

\[ Q = \sum_{i=1}^{n} Q_i \]  

(4)

\[ S = \sum_{i=1}^{n} S_i \]  

(5)

\[ Q_i = Q_{oi} \cdot e^{-\alpha_i \Delta t} \]  

(6)

\[ S_i = \frac{Q_i}{\alpha_i} \]  

(7)

2.2. PLR models: combination of linear reservoirs in parallel sets

A basin (or a cell considering the areal division of the basin as cells of a grid) can be represented with a single reservoir or with a combination of reservoirs. The simplest model to represent a basin is by considering a single reservoir whose behaviour is representative of the basin's response. Evidently, the model is not very descriptive and the results obtained show big deviations. In addition, a basin can be represented by a set of deposits, each one representative of certain characteristics of the basin. Furthermore, a basin can be divided into sub-basins or cells, each of which can be represented by a set of deposits. The possible combinations of reservoirs to build a model are unlimited, although few combinations give acceptable results. In this work, we have used a combination of two reservoirs in parallel for each cell of the digital terrain model, where water enters according to a distributed model of effective precipitation. The combination of both reservoirs pours water into the drainage network whose flow is modelled with a classical method. This scheme is used in the SHEE program to meet the following assumptions:

1. The calibration of the model is based on actual recession curves, i.e., based on actual responses from the basin.
2. Each reservoir represents a set of characteristics for an specific basin, whose response differs markedly from the response of the other reservoirs.
3. As a result of the latter, the total hydrograph can be decomposed into several partial hydrographs that can be mapped into parts of the hydrological system (direct runoff hydrograph, underground runoff hydrograph, etc.).
4. The PLR model allows to ascertain the water stored in the reservoirs (i.e., in the basin) and to calculate a water balance for each episode.
5. Finally, standard models (kinematic wave or Muskingum-Cunge) are widely contrasted for the circulation in channels.

For a combination of \( n \) linear reservoirs in parallel, the resultant is the sum of the reservoirs as shown in equations 4 and 5; and for each reservoir, using equations 1 and 2 without considering recharge, equations 6 and 7 are obtained.

Equation 8 is obtained by combining equations 4 and 6. Equation 8 shows that, for an instant \( t \), there is a mathematical relationship between the flows of each deposit.

\[ \left( \frac{Q_1}{Q_{oi}} \right)^{\frac{1}{\alpha_1}} = \ldots = \left( \frac{Q_{nr}}{Q_{onr}} \right)^{\frac{1}{\alpha_{nr}}} \]  

(8)

The recession curve of a hydrograph is a set of data flow vs time; \( Q \sim t \) in the case of the system of equation 8, whose resolution allows to obtain a set of \( Q_{oi} \) parameters, \( \alpha_i \). With these parameters, a PLR model can be established. Once the model is established, hydrographs can be generated using
equations 3, 4 and 6, according to the inputs \( (R_i) \) to the system. In addition, using equations 5 and 7, the amount of water stored in each reservoir of the basin is obtained, thus allowing carrying out the water balance.

2.3 PLR models: snowmelt

Snow thawing implies a new contribution that needs to be added to the input along with the effective precipitation, and whose origin has to be looked for in a previous episode of precipitation in the form of snow. For a given process of snowmelt due to short events of intense rain, precipitation and temperature are considered as factors, and as the most influential parameters in the fusion process. A simple model will consider snow melting as linearly proportional to precipitation when occurring at temperatures above 0ºC. Thus, for a certain part of the hydrograph that coincides with temperatures above 0ºC, effective precipitation as an input to the surface runoff system can be replaced by total precipitation by adding snow melting. In this way, the runoff equation (equation 3) is modified by adding a new recharge term coming from the snow melting \( (R') \), and by substituting the effective precipitation by total precipitation at \( R \), as expressed in equation 9.

\[
Q_2 = Q_1 \cdot e^{-\alpha \Delta t} + (R + R') \cdot (1 - e^{-\alpha \Delta t})
\]  

The main advantage of the PLR model is that, by allowing the water budget of an event to be considered, the amount of snowmelt recharge, \( R' \), can be estimated to equilibrate the water balance.

3. Data Source

3.1 Characterization of the basin

The catchment studied is that of the Esca river (Roncal valley), located in the Pyrenees ridge, between Aragon and Navarra, two regions of northeast Spain. The basin is preserved in a natural state, without reservoirs or significant alterations. Figure 3 shows an altimetry representation of the basin, the location of the gauging stations (two) and the pluviometry stations considered (four). Table 1 gives some of the most significant hydrological characteristics for this watershed.

![Figure 3. Altimetry representation of the Esca river basin with the rain gauges (A063, A268, A259 and P016) and the two stream gauges (A063, A268) that also have rain gauges.](image)
Table 1. Hydrological characteristics of the Esca River basins in Sigues and Isaba.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>ud</th>
<th>Isaba (A268)</th>
<th>Sigues (A063)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catchment area</td>
<td>km²</td>
<td>189.06</td>
<td>506.26</td>
</tr>
<tr>
<td>Length of the main channel</td>
<td>km</td>
<td>24.01</td>
<td>51.70</td>
</tr>
<tr>
<td>Average slope of the main channel</td>
<td>%</td>
<td>6.44</td>
<td>3.45</td>
</tr>
<tr>
<td>Average slope of the digital surface of the catchment</td>
<td>%</td>
<td>36.85</td>
<td>34.88</td>
</tr>
<tr>
<td>Average Curve Number (AMC II)</td>
<td></td>
<td>63.08</td>
<td>61.22</td>
</tr>
</tbody>
</table>

3.2 Melting event setting

The event investigated corresponds to the flood occurred between January 18 and 28, 2009. Table 2 shows its main characteristics, such as duration, peak flow, and the number of intervals considered for the treatment of the actual rain.

Table 2. Characteristics of the actual event investigated.

<table>
<thead>
<tr>
<th>Date</th>
<th>Start time</th>
<th>End time</th>
<th>Rain duration</th>
<th>Time interval</th>
<th>Peak flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 18, 2009, 2:30 p.m.</td>
<td>January 28, 2009, 7:30 p.m.</td>
<td>245.25</td>
<td>981</td>
<td>201</td>
<td></td>
</tr>
</tbody>
</table>

3.3 Rainfall model

The rainfall data has been obtained from the Spanish SAIH network that records the value of the precipitation in 15-minute intervals. Figure 4 shows two isohyet maps of the event corresponding to the coverages generated from the accumulated precipitation in two of these intervals (the event requires the use of 981 layers). Spatial interpolation is performed by applying a distributed precipitation model based on the use of Radial Basis Functions (RBF) [64-66]. From these precipitation coverages, the computer program can generate a different hyetograph for each point of the basin.

![Figure 4. Isohyet maps of the event occurred in January 2009 (equidistance 0.25 mm). A sequence of 2 coverage intervals of 15 minutes is presented. The whole event has 981 layers.](image-url)
3.4 Reservoir model

The reservoir model is established from the actual hydrographs of the episode by adjusting the parameters \(q_0i\) and \(\alpha_i\). For this purpose, the least squares method is applied to the specific recession curve by using equation 10 (\(q = Q/\text{catchment area}\)).

\[
q_t = \sum_{j=1}^{m} q_{0j} \cdot e^{-\alpha_j t_i} \quad (10)
\]

where \(m\) is the number of reservoirs (two in our case), \(q_i\) are the \(n\) known values of the flow of the recession curve at time \(t_i\), and \(q_{0j}\) and \(q_{0j}\) are the unknowns. Therefore, an overdetermined system of \(n\) equations is obtained, with \(2m\) unknowns, where \(n \gg 2m\). Once stated and solved for the recession curve of the actual hydrograph, the results shown in Table 3 are obtained for a model of two linear reservoirs in parallel, which will be used within the SHEE program to perform simulations, either considering or dismissing the snowmelt process.

Table 3. Parameters of the parallel linear reservoirs for the event occurred in the Esca River.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reservoir</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>1.43 E-06</td>
</tr>
<tr>
<td>(q_0)</td>
<td>2.96 E-07</td>
</tr>
</tbody>
</table>

4. Results and Discussion

4.1 Simulation without snowmelt

The simulation of the event using the SHEE program and not considering snowmelt shows a notable mismatch with reality. To achieve an adequate water balance, modifying the standard conditions to very wet conditions by means of the curve number model is required, as seen in the ratio of total and effective rainfall hyetographs (Figure 5). It is evident that the effective rain obtained is unusually high. On the other hand, there is very little agreement between both hydrographs (Figure 6). In the actual hydrograph, a peak occurs at 125 hours that does not occur in the simulation, while at 220 hours, the simulated values exceed the actual ones.

Figure 5. Average Hyetographs in the Esca River basin in January 2009. Total precipitation was obtained directly by the interpolation method (blue) and effective precipitation, not considering snowmelt (red) and with high curve number.
4.2 Simulation with snowmelt

In the model considering snowmelt, the average altitude of each of the two basins was taken into account, as well as the discharge contributions into each stream gauge. It has been observed that there is no proportional relationship between the area of each basin and its discharge contribution. This fact was to be expected, because the melting is greater at lower altitude in winter, a circumstance that tends to be reversed towards spring, as there is more snow in the high areas.

The ratio of the peak-flow with a rapid melting of snow would be supported by the evolution of temperatures, a fact that can be seen in Figure 7. The station of Arangoiti is located at 1,350 meters with a cold period between 45 and 90 hours, while between 90 and 140 hours the temperature exceeds 0°C, reaching up to 8°C.

Figure 6. Hydrographs of the January 2009 event of the Esca River in Sigues (A063 stream gauge), actual and simulated, not considering snowmelt.

Figure 7. Temperature graph at the Arangoiti station during the episode of January 2009 and hyetographs of total and effective precipitation with snowmelt in Esca River.
By using the model, the necessary recharge derived from snowmelt, which is needed in the interval between 80 and 120 hours to fit the hydric balance of the episode in less humid previous hydrological conditions than in the case of the no snowmelt model has been estimated. The optimal results are obtained with a melting value equivalent to 90% of the gross precipitation occurred in that interval, that is, $R' = 0.9 \cdot R$. In this way, the hyetographs shown in Figure 7 and Figure 8 are obtained, where previous dry hydrological conditions have been considered. Thus, in the simulation, a hydrograph very similar to the actual one is obtained.

Figure 8. Simulated hydrograph considering snowmelt. Fragmented lines show the partial hydrographs for each reservoir.

Figure 9 shows the observed hydrograph obtained from Isaba stream gauge (A268), which is located in the interior of the basin and can be compared with that observed at the exit, at the Sigues stream gauge (A063). Figure 10 shows the simulated hydrograph at the point corresponding to the Isaba station.

Figure 9. Actual hydrographs obtained from Isaba (A268) and Sigues (A063).
4.3 Water budget

Table 4 contains the results of the water balance of the episode studied, considering the temporal interval between 0 and 200 hours. The balance is carried out from the two gauging stations (Isaba and Sigues) and the results are given in total units (hm$^3$) for the entire basin corresponding to each gauging station. The results are also presented in specific units (mm), i.e., total units divided by the area of the corresponding basin. The last column represents a comparison between the results of the two gauging stations.

To elaborate the water balance, we start from the data and results of hyetographs and hydrographs used in the modelling, which can be summarized in three components:

(1) Total precipitation (Tp): it has been obtained from the model of distributed precipitation based on functions (RBF) shown in Figure 4, adding all the time 15-minute intervals in the range between 0 and 200 hours. The results of this integration match the term Total Rainfall of the average hyetograph of Figures 5 and 7.

(2) Snowmelt (Sm): it is determined in the distributed model calculated with the SHEE program, whose average representation matches the snowmelt fraction of the average hyetograph shown in Figure 7.

(3) Total runoff (Tr): it is also obtained from the distributed model, and the average value is represented in the hyetograph shown in Figure 7 as the sum of two terms: runoff from rainfall and runoff from snowmelt.

<table>
<thead>
<tr>
<th></th>
<th>Isaba</th>
<th>Sigues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tp (Total precipitation)</td>
<td>31.79</td>
<td>67.61</td>
</tr>
<tr>
<td>Tr (Total runoff)</td>
<td>17.90</td>
<td>42.06</td>
</tr>
<tr>
<td>Ep (Effective precipitation)</td>
<td>11.47</td>
<td>19.27</td>
</tr>
<tr>
<td>Sm (Snowmelt)</td>
<td>6.43</td>
<td>22.79</td>
</tr>
<tr>
<td>L (Losses)</td>
<td>20.32</td>
<td>48.33</td>
</tr>
<tr>
<td>Hv* (Hydrograph volume)</td>
<td>9.80</td>
<td>25.86</td>
</tr>
</tbody>
</table>

(*) Volume measured between 0 and 200 hours. On the other hand, it still has to leave the basin (in Sigues stream gauge) 42.06 - 25.86 = 16.2, by adding the volume prior to the start of the event.
In short, the terms $T_p$, $T_r$, and $S_m$ are obtained from data and direct results from the model. The terms $E_p$ and $L$ can be obtained from equations 11 and 12, which are partial water balance equations:

1. Effective precipitation ($E_p$): in Figure 7 it is described as runoff from rain.
   
   $$E_p = T_r - S_m$$

2. Losses ($L$): it is the difference between total precipitation and effective precipitation.
   
   $$L = T_p - E_p$$

The volume of the hydrograph ($H_v$) is obtained by integration of the actual hydrograph within the 0-200 h range. The volume of water remaining within the basin at the 200 h coordinate is the difference between the total runoff ($T_r$) and the volume of the hydrograph ($H_v$), adding the volume present prior to the start of the episode. By comparing Table 4 and analysing the specific values (mm), the following statements are deduced:

1. Based on the observed data: Isaba basin shows a greater proportion of gross precipitation, although the output is similar (considering the output volume is equal to the volume observed in the hydrographs).

2. Based on data from the simulation: at the Isaba basin, the higher the average altitude of the basin, the lesser the thawing and the greater the losses. Part of those observations can be attributed to snow retention.

5. Conclusions

The hydrological modelling of watersheds by combining deposits is considered a classic method, but it is in recent years that it has reached a great diffusion with the development and improvement of computers. A new model is presented that combines linear deposits in parallel, representing the circulation of water through the reservoirs of the basin and giving excellent results in simulations of actual events. A quality that stands out about this model is its calibration, which is based on actual recession curves that are the response to the discharge of all the reservoirs of the basin. Furthermore, this model allows introducing the discharge of water from the snow reserves, its distribution in the different deposits and its routing through the hydrological system of the basin. Another additional advantage of the model is that it allows establishing a water balance for an event and, thus, it estimates the recharge volume coming from the snowmelt.

The SHEE computer application allows configuring models of hydrological processes, such as the spatial-temporal distribution of rainfall, the previous state of soil moisture and the mode of water routing through the basin. All the aforementioned has made it possible to carry out this investigation of an actual flood episode registered in the Esca river, where snow melting processes have had an outstanding influence.

If not considering the snowmelt, the January 2009 event of the Esca River presents an extraordinarily unbalanced water budget. That is why a basic thawing model is introduced that is activated in periods of time where the temperature, taken from actual records, is higher, reaching a balanced water balance and a better adjusted simulated hydrograph. Based on the simulation of this episode, the following observations are derived:

1. An estimate of the melted snow volume (given as volume of water) is obtained, being 6.43 hm$^3$ at the Isaba stream gauge and 22.79 hm$^3$ at the Sigues stream gauge. The effective precipitation volumes are 11.47 and 19.27 hm$^3$, respectively. That way, the snowmelt represents 36% and 54% of the total runoff (effective precipitation plus snowmelt) respectively.

2. With regard to the catchment area, Isaba stream gauge produces greater total precipitation but lower runoff volume.

3. The runoff due to thawing is notably higher at Sigues (45 mm compared to 34 mm at Isaba). This can be explained due to the snow melting occurring in the lower part of the catchment.

The importance the snowmelt possesses in the genesis of floods is highlighted in this paper. To do this, another simulation is carried out without taking into account the thawing process. In that case, a peak flood of only 80 m$^3$/s is obtained, with a total runoff volume of 19.27 hm$^3$, compared to the 201 m$^3$/s and the 42.06 hm$^3$ obtained when considering the snowmelt.
Acknowledgments: This work has been partially subsidized by the Research Group "Analysis of Continental Sedimentary Basins" of the Government of Aragon and FEDER Funds to which gratitude is transmitted. We deeply appreciate the time spent by the Reviewers and Editors, who will undoubtedly contribute to the improvement of our manuscript.

Author Contributions: All authors conceived and designed the experimental work, with special mention to J. Castillo-Mateo for having completed the mathematical development allowing its applicability to the actual cases of the Esca River.

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