Innovative risk assessment framework for hydraulic control of irrigation reservoirs' breaching

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Abstract

This research introduces an innovative framework aimed to develop a risk assessment to analyse the breaching hydraulic control of non-impounding reservoirs for irrigation purposes, called here Irrigation Reservoirs (IRs). This approach comprises an analytical method based on several empirical formulas where the one that best fits the different geometric characteristics of IRs' water systems is chosen. Furthermore, a stochastic framework allows for the incorporation of the occurrence probability as a tool to characterize the IRs' risk analysis. This occurrence probability has two components: probability based on the bottom elevation of a final breach and probability based on the failure mode (piping in this case). In risk assessment terms, the ultimate product comprises the maximum hazard probability maps that allow a significant improvement in the representation of the artificial flooding effect. This research has been successfully applied in two dimensions, synthetically and realistically, in the Las Porteras and Macías Picavea IRs' water systems (Spain). This approach maybe improves the management of this type of hydraulic infrastructure and their surrounding area by reducing the risk of experiencing negative consequences derived from an uncontrolled hydraulic breaching.

1. Introduction

Safety and risk are topics of growing popularity because of the sociopolitical conjuncture of recent decades. In the broadest sense, safety refers to the absence of risks or threats, both in the individual and collective perspective. Society demands tools to guarantee safety in terms of tolerable risk. The robustness of these tools is based on the recognition of the factors that bring uncertainty to the behavior of the system. Under this systemic approach, the correct definition of "inputs" becomes vitally important to ensure that the results are acceptable. The risk reduction strategy involves decision-making by safety analysts. To achieve the expected objectives by optimizing resources, these decisions are based on a deep knowledge of the environment (Aronica et al. 2012). Recent decades have confirmed that risk analysis is a very valuable tool for decision-making in multiple scientific disciplines. Administrations, as guarantors of this security, have been aware of these currents, promulgating regulations, guidelines, and instructions.

In recent years, flood risk management has been the subject of numerous regulatory developments on the supranational, European Union, and regional scales. These developments have obliged the owners to ensure the safety of their hydraulic infrastructures. Within the scope of Spain's legislation, Royal Decree 9/2008 amends the Public Hydraulic Domain Regulation, approved by Royal Decree 849/1986, and introduces a new section concerning dam, reservoir, and IRs (IRs) safety. For the first time, IRs were mentioned in legislation as opposed to dams, their counterparts. This fact, together with the publication of the Royal Decree 903/2010 on the evaluation and management of flood risk, Directive 2007/60/EC defines a new management framework in which the new infrastructure must be readapted in light of its potential danger. However, the current trend continues to unify the safety requirements of dams, reservoirs, and IRs under the same regulation, regardless of where they are located and who owns them. Despite similarities, the nature of IRs and dams is completely dissimilar, and the differences are

remarkable. Therefore, treating risk analysis with the same approach for IRs and dams is doubtlessly incorrect.

IRs are associated with the emergence of irrigation technology, so it is a very significant object of study for society. IRs need to be differentiated from dams largely because of the following reasons. An IRs 's location is one of the most important differences from dams because it limits the stage of solicitation, the failure mode and the potentiality of the damage caused. This fact offers notable uncertainty because a priori, the failure zone is unknown. On the other hand, the advantage of an off-river IRs location means that the failure hydrograph may be enclosed in the first moments of the collapse. Moreover, in the case of IRs, the event associated with the predominant failure mode is clearly localized. The consequences caused by the outflow hydrograph are limited to a smaller spatial context than a natural hydrological process.

The reality of the current situation of IRs in Spain is far from being known, given the large unknown number of them. The latest attempts to make an inventory supposed an IRs umber close to 65,000. The largest number of IRs is concentrated in the Mediterranean area, which is an area of great agricultural activity. On the other hand, the current number of large dams in Spain is close to 1,400. Therefore, an enormous "perception gap" between the two sets of water regulatory infrastructures can be observed. Owners of IRs, mainly Irrigation Communities, complain about their security obligations, which are the same as those of a large dam. These obligations rely on certain requirements, which are based mainly on the movable water height (above 5.00 m) and its corresponding volume (above 100,000 m³). Irrigation communities make claims related to the normative demands inherited from the dam world, based on the obvious differences between IRs and dams listed in Table 1. This fact indicates the need for specific regulations and studies on irrigation IRs.

Table 1. Main differences between dams and IRs

Dams	IRs
Built across a stream or river	Off-river location
Are built over the river Materials are selected	Part of the reservoir is dug out. The other part is raised with the excavated materials.
Are supplied with runoff water (no controlled)	The embankment is waterproofed
Subject to flooding	Rarely subject to flooding
Wide outflow systems without integration problems	Narrow outflow systems with integration problems
Spillway is a fundamental safety element	Spillway is a secondary safety element
1300 large dams in Spain	The number of IRs is unknown in Spain, approximately 65,000
Have multiple functions	Fundamental pillar of irrigation in Spain

Moreover, specific studies on irrigation IRs risk assessment are scarce in the scientific literature. There is practically no specific bibliography of IRs. In the case of tailing IRs, the safety analysis has improved, but the effects are not comparable to those of water IRs. Fortunately, it is possible to extrapolate some behaviors from embankment dams to IRs. Embankment dams hold an important position in the scientific literature, especially in safety. A considerable amount of literature has been published on the characterization of embankment dam breaches (e.g., Froehlich 1987,2008; MacDonald and Langridge-Monopolis 1984; Von Thun and Gillette 1990). Furthermore, the failure mode of earth dams has been widely studied, especially overtopping (e.g., Coleman et al. 2002) and internal erosion (e.g., Fell et al. 2003). Additionally, in recent years, different organizations are working on a specific analysis for IRs to improve their safety, such as ICOLD (2016) and MAPAMA (2012). Moreover, the incipient popularization of IRs in Spain is causing the necessary development of scientific studies about their peculiarities. These studies cover several fields, such as the calculation schema used (e.g., Soler et al. 2012), or questioning the safety system of IRs (e.g., Sánchez, 2014; Espejo 2017). However, further investigation and experimentation on IRs water systems is strongly recommended.

IRs water system characterization is firmly associated with the geomorphological variability of the environment. The roughness and terrain slope around the IRs are the most important parameters. The estimation of geomorphological parameters is conditioned by the resolution and accuracy of the Digital Elevation Model (DEM). The Digital Terrain Model (DTM), generated from the DEM, conditions the routing of the outflow hydrograph produced by a IRs failure. The terrain conditions all hydrological processes, both natural and accidental, and consequently, its correct representation is essential. Fortunately, the terrain can be represented with advisable accuracy using geometric methods. For this case study, Laser Imaging Detection and Ranging (LIDAR) or aerial photogrammetry are perfect tools to cover the

representation of the terrain (Molina et al. 2014). Therefore, the IRs water system restricts the mitigation measures and the behavior of the failure hydrograph.

Actions to palliate flooding due to IRs breaching can be classified into structural and non-structural (Gendreau and Gilard 1997). Schanze et al. (2008) proposes ordering the mitigation measures according to three fields: construction (structural vs. non-structural), effect (reduction hazard vs. vulnerability reduction) and functionality (instruments vs. measures). The purpose of this study is to act within the second aspect (effect) on the reduction of dangerousness. Identification of the element of the system that acts under the prism of risk reduction is an essential factor in the modification of the hydrological-hydraulic behavior of the affected basin drainage (Salazar 2013).

This paper mainly aimed to establish an innovative risk assessment framework for the hydraulic control of IRs breaching. This will be largely useful to predict the hydraulic operation of IRs breaching through numerical simulation (Bladé et al. 2014) in terms of the probability of the occurrence of a certain maximum flow.

2. Methodology

This methodology comprises 3 consecutive phases: pre-process, process, and post-process. The pre-process phase has 3 sub-stages: study of the breach geometric parameter estimation, sectorization and stochastic analysis. The process phase contains the hydraulic simulation sub-stage. Finally, the post-process phase has 2 sub-stages: maximum hazard probability mapping and mitigation measures assessment for the failure hydrograph (Fig. 1).

2.1 Pre-process

Breach geometric parameters estimation

Most IRs placed in irrigated areas must be classified and registered by their owners and comply with the safety obligations that such classification entails. Therefore, it is necessary to know the typology of IRs in a territory, in this case Spain, with the aim of clearly identifying the problem.

Therefore, it is necessary to reverse the current situation and analyze the existing records that allow the characterization of geometric IRs. To delimit the areas of greatest concentration in the legislation, a representative sample of 231 IRs, was used for this purpose. This analysis considers the movable water height and its corresponding volume. In this way, the geometric characteristics of IRs are established through the study of the hydraulic response caused by the breach.

Currently, there are three methods of IRs breach analysis, which differ in the physical basis on which they are based: Empirical Models (EM), Parametric and Analytical Models (PAM) and Physical Base Models (PBM).

First, it is unfeasible to conduct the analysis using PBM due to the economic cost involved, the required facilities and the team of professionals needed to build the model. On the other hand, performing the analysis with PAM would allow for the reproduction of the behavior of the IRs embankment. Therefore, the conditional probability of breaking could be estimated given a load scenario.

With a complete geotechnical analysis, it would be possible to define a model that represents the response of the IRs breaking system. From this model, it would be feasible to extract the probability density function (PDF) of IRs breaking through the geotechnical parameter of IRs embankment. This process is not addressed by the owners of IRs due to the high cost and complexity of geotechnical tests. This fact has led us to discard the analysis using PAM.

Consequently, the EM, based on numerical simulation, was chosen as the best method of analysis to be adopted for this research. This type of analysis provides the best solution in terms of time and cost, as opposed to the other types of analysis. Furthermore, the results obtained may be extrapolated to a multitude of IRs with the same characteristics.

Therefore, based on the generated record and the EM analytical method, selecting the empirical formula that best fits the characteristics and behavior of the IRs is possible. This selection is based on an adapted methodological proposal on dam breaches by the state of Colorado (2010) and applied to this research IRs sample. In accordance with normative requirements, three application fields are distinguished according to analyzed dam magnitude: minor dams, small dams and large dams (State of Colorado 2010). The aim of these application fields is to recommend the empirical formula that adequately responds to the predictable behavior of this type of dam. In this way, this recommendation serves as a reference for managers and users of these water infrastructures.

The definitive selection of the formula was associated with a characterization factor, called Storage Intensity (SI , in cubic meters per meter, m^3/m), which relates the reservoir volume stored (V_w , expressed in cubic meters, m^3) with water depth above the breach (H_w , expressed in meters), ($SI = V_w/H_w$). This factor, introduced by the state of Colorado (2010), delimits the application fields of some empirical formulas. This formula delimitation is based on the sensitivity to SI variation.

For this purpose, the variables evaluated were breach characterization (final breach width and breach formation time) and failure hydrograph. These variables most influence a hypothetical IRs' structural failure (Ahmadisharaf et al. 2016) in terms of flooding. The previous inputs, together with the evolution of these flows through the natural drainage network, define the main study items.

This research proposes a IRs breaching characterization based on the hydraulic response in the form of a hydrograph generated by a structural failure. Among the multitude of existing empirical formulas, those that are best adapted to the existing IRs rupture records in a territory were chosen for this analysis. The selected empirical formulas comprise MacDonald Landgridge-Monopolis's expression (MLM84; MacDonald and Langridge-Monopolis 1984), Von Thun-Gillette's expression (VTG; Von Thun and Gillette 1990), Froehlich's expression (F95; Froehlich 1995), the expression of a Spanish technical guide for

classification of dams according to risk potential expression (GUIDE; MAPAMA 1996), which is a variant of the proposed expression by Froehlich (1987) and Froehlich's expression (F08; (Froehlich 2008).

The study of the causes of earth dam failure carried out by several authors (e.g., Aboelata and Bowles 2008; Sills et al. 2008) concluded that the main mode of failure is quality problems in 42% of cases, in which 60% are related to siphoning. Therefore, the most widespread failure mode in this type of solution, "piping" or internal erosion, was chosen (Foster et al. 2000). This study considered siphoning as the only mode of failure. Therefore, to characterize the IRs according to their rupture behavior, different synthetic types of IRs were constructed, with different movable water heights and various dimensions, covering the geometric variability susceptible to normative obligations.

Given the aforementioned information, it is possible to construct a numerical model to analyze the hydraulic response of IRs in a wide range of cases. For this purpose, the studied empirical formulas will facilitate the geometric characteristics of the breaches for each case. Thus, the equation that best fits the IRs characteristics, based on the movable water height and its corresponding volume, was selected. Then, it was possible to select the correct empirical formula for each case of study, from which the breach parameters that feed a model of hydraulic simulation of IRs' failure were obtained. Therefore, it was possible to develop a breach model to make a comparative analysis of the results for each synthetic IRs. This premise was achieved by studying the sensitivity of these results to the variation of movable water height, water volume and associated water load. Obtaining and analyzing the failure hydrograph plays a key role in this methodological approach, since according to the selected empirical formula for each geometric type of IRs, the resulting failure hydrograph will be different.

Sectorization

One of the greatest uncertainties in the application of IRs risk analysis is the location of the breach geometric axis in the numerical simulation. There is no preferential section for the location of the breach geometric axis (Chauhan and Bowles 2004). Therefore, palliating this uncertainty plays a key role in the methodological approach of this paper.

The main aim of this methodological phase is to perform the sectorization of the area surrounding the IRs. To achieve this objective, it is necessary to analyze the IRs water system. Transfer to reality demands the characterization of the geomorphological environment of the affected basin. This approach aims to ensure a complete analysis of the entire closure dam by sectoring it in its entirety and to propose a single representative type of breach for each sector. This avoids the arbitrariness in its location and ensures that the behavior of the entire closure dam is analyzed. This sectoring requires a thorough knowledge of the surface on which the discharge flows must evolve. Among the possibilities for analysis, geomorphometry has been used, particularly focused on the first vulnerable zone. Technically, this is carried out by delineating the drainage basins.

Certainly, geomorphological characterization is considered a valid and objective tool for identifying the areas susceptible to channeling the failure hydrograph. The morphometric analysis of the digital model

studies the relief and orography of surface; on the other hand, it characterizes it through additional parameters which are described in Olaya and Conrad (2009). This type of study is based on a focal analysis, which studies the cell values and its environment to obtain a definitive value. To characterize the area surrounding the IRs, it is necessary to define the main geomorphological parameters.

The geometric axis breach is based on the Horton-Strahler stream order (Horton 1945; Strahler 1957), mainly due to its ease of implementation. Therefore, the threshold that defines the sector's channel was established according to the number of cells that feed it. A useful indicator for choosing the representative Horton-Strahler order number is the Topographic Wetness Index (TWI). The TWI, defined by Sørensen et al. (2006), indicates the susceptible zones of accumulating wetness, which helps to explain the involved hydrological processes. This fact helps to determine a sufficiently representative stream order number to avoid the excessive fragmentation of the border zone sectors of the IRs, which would impair the feasible implementation of the methodology.

Later, once the geomorphological analysis was performed and the natural drainage network of the receiving basin was known, it was necessary to locate the geometric axis of IRs' rupture. This was done by delineating an axis on the intersection of the outer slope of the IRs with natural terrain. Once this axis was traced, it was possible to obtain the minimum absolute elevation for each sector. Thus, the bottom elevation of the final breach was defined for use in stochastic analysis.

Stochastic analysis

Once the empirical formula that better responds to IRs' characteristics and the breach location was known, the breaching analysis could be addressed. An innovative approach for a better and more accurate cartographic representation of the area most likely to be dangerous is proposed. The definition of current regulation associated to different return periods for flooding studies maybe improved considering this approach. These regulations concerned natural floods, and artificial floods caused by water infrastructure failure were not considered.

Given the scarcity of real data that allow for experimental validation, it is necessary to choose techniques that replicate the event and analyze its results in detail. This stochastic framework requires the implementation of the Monte Carlo method (Díaz-Emparanza 2002), which requires previous knowledge of the PDF of the object variable (Tung 2011). Due to the lack of data, characterizing this experiment was necessary to use a triangular PDF proposed in the scientific literature (Johnson 1997). The determination of triangular PDF parameters, including minimum, maximum and mode, were obtained according to the indications by Ahmadisharaf et al. (2016). This employed triangular PDF and was based on the bottom elevation of the final breach (Ahmadisharaf et al. 2016).

The Hydrologic Engineering Center and Hydrologic Modeling System (HEC-HMS) software, version 4.2.1, was used to apply the Monte Carlo method. The HEC-HMS model was developed by the US Army Corps of Engineers (USACE 2000). In this method, 5,000 simulations were carried out (Díaz-Emparanza 2002) per every type defined by its height and for each of the 4 empirical formulas mentioned above. On one

hand, this allowed for the validation of the triangular PDF; on the other hand, it proposed another adjustment to the distribution for the generated flows.

Therefore, there were four sequential objectives in this phase: (1) Determining the occurrence probability of breach considering its final bottom elevation through a triangular PDF; (2) Using the parameters obtained in the selected empirical formula of the first phase to simulate IRs breaches with the Monte Carlo Method; (3) Applying the results of the Monte Carlo method in each sector to determine its geomorphometric probability; and (4) Analyzing the results in terms of maximum generated flows and adjusting a PDF to those flows in the synthetic IRs .

2.2 Process: Hydraulic Simulation

To develop probability maps and to propose structural measures that laminate the generated hydrograph, it was necessary to develop a 2D hydraulic model associated with each breach and considered scenario. This hydraulic model was substantiated on the resolution of the 2D shallow water equations (also known as the two-dimensional Saint-Venant equations; Tayfur et al. 1993). In this phase, both synthetic IRs and real cases were analyzed, which allowed for the validation of the laws of hydraulic behavior. The implementation of the model was carried out in free software called IBER (Bladé et al. 2014). This software has been successfully used in cases similar to this study. The model solved the two-dimensional shallow water equations with an unstructured finite volume solver. The IBER model implements a breach geometric parameter estimation model based on GUIDE expression. This option was not considered, since the trapezoidal breach parameters obtained in the first stage were used.

One of the most important issues in the design of hydraulic simulation models is the selection of the DTM. The DTM characteristics, which need to be defined, are associated with the cartographic source used for the elaboration of the DEM (Vaze et al. 2010). In this sense, the selection of the DTM should pay attention to parameters such as resolution, accuracy, and discretization of the ground system in the hydraulic simulation software. In this case, the LIDAR data of the 2010 Spanish National Plan of Aerial Orthophotography (PNOA) flight were used for the elaboration of the DTM. These data had an initial density of 0.5 points m^2 and an altimetric accuracy < 0.40 m (ETN 2001). Consequently, a DTM obtained from the PNOA LIDAR data source was considered a reliable basis for the scope of this study. The simulation duration was 7,200 s.

Furthermore, many authors have studied the relevance of these factors in the interpretation of the hydraulic functioning of the drainage network. Those authors make several recommendations about the model characteristics. In this sense, it was necessary to work with high-resolution models (small pixel size) to improve the reliability of the model's hydraulic results. This is because the model solves the shallow water equations with an explicit scheme (Bladé et al. 2014). For the case studies of this paper, the geometry model created in IBER had a higher resolution than similar studies of dam breaks. The triangles of the numerical mesh used for hydraulic calculation had the following characteristics: 1.0 m

minimum side, 50.0 m maximum side and a tolerance (maximum vertical distance between the DTM and the generated geometry) of 0.2 m.

In sum, in this phase, the aim was to implement the two-dimensional simulation of the breach parameters, obtained in the previous stage, in the overland flow. IBER allows for the export of the hydraulic results in the Arc Info ASCII grid format. Therefore, for the post-process stage, it was useful to obtain maximum maps of both hydraulic variables and hazards. This was of great importance to achieve the maximum hazardous area maps.

2.3 Post-Process

To validate the approaches performed until now, it was necessary to apply the stage methodology exposed to real cases. The main aim of this stage was obtaining the maximum hazard probability maps as reliable tool for the establishment of forthcoming hazard attenuation measures. Under this approach, the results offered by the synthetic IRs were validated regarding the results provided by real IRs. There are several methodological approaches available to validate the results, which can verify and calibrate parameters of a mathematical model based on real data. Other proposals allow for the evaluation of similar behavior between different models. In this respect, it was appropriate to validate the data by comparing the results of the synthetic IRs with those from real IRs.

Maximum hazard probability mapping

The results obtained from previous stages made it possible to create a new cartography. This product would improve the management of flood risks caused by IRs' existence.

The regulations regarding flood risk management have proposed the sectoring of the territory based on natural floods in return periods of 4, 100 and 500 years. This conception was not adapted for flooding caused by the failure of hydraulic infrastructures. However, it has been considered by the scientific community (e.g., Di Baldassarre 2010). Proposing a new method for generating risk maps due to the failure of hydraulic infrastructures is considered necessary. Consequently, a probabilistic characterization of results for each sector allowed for the production of maximum hazard probability maps. Probabilistic characterization responded to occurrence probability based on the bottom elevation of the final breach and failure mode.

To achieve the proposed objectives, the following workflow was proposed:

1. Characterization of each sector by the probabilities of geomorphological analysis.
2. Characterization of each sector by the probabilities of failure mode (piping), according to the scientific literature, (Foster, et al. 2000b).
3. Obtaining the overall probability of each sector as a result of the previous partial probabilities.
4. Transformation of this probability for its total computation with respect to 1, for each sector.

5. Reclassification of maximum hazard rasters obtained from hydraulic simulation.
6. Overlap of reclassified rasters of all sectors.
7. Obtaining the sum of all previous rasters by map algebra.
8. Reclassification of the previous results according to the following criteria: low probability ($< 33\%$), medium probability ($33\% < P < 67\%$) and high probability ($> 67\%$).
9. Creation of a maximum hazard probability map of the desired threshold.

3. Case Study

3.1 Synthetic Implementation

Regarding the breaking behavior, the IRs' characterization comprises the development of several synthetic IRs. For this purpose, 10 different synthetic IRs with 3 different movable water heights (5.00, 7.50 and 10.00) were designed. The slope of the walls inside and outside the IRs was the same, 2.50H/1V. The smallest IRs had a quadrangular base of 25.0×25.0 m, which gradually increased until 300.0×300.0 m in the largest IRs. The synthetic IRs types covered all safety regulations for the scope and multitude of SIs (Fig. 2). Therefore, the sample IRs geometry was characterized by a wide range of synthetic IRs, which allowed for the study of its breaking behavior.

3.2 Real Implementation

The main aim of this analysis was obtaining the cartography of maximum hazard probabilities. For the development of case studies, sectorization, breach parameters drawn from the empirical formula from the first stage and, the stochastic analysis, were implemented.

To implement this methodology, two types of water systems were chosen that differ in geomorphological characteristics. In this sense, the case studies included the Macías Picavea IRs (Valladolid), with a high altimetric gradient, and the Las Porteras IRs (Ávila), with a low altimetric gradient (Fig. 3).

Macías Picavea IRs had an earthfill wall with a height of 6.75 m, reservoir capacity of 201,623.00 m³ (Normal Pool Level) and a IRs crest of 5.0 m. The second studied case, Las Porteras IRs, had a wall height of 7.50 m, reservoir capacity of 397,261.00 m³ (Normal Pool Level) and crest of 4.5 m. Both case studies were located in the Castilla and Leon region, Spain, in the Duero River basin. In this sense, hypothetical piping failure was used for both case studies.

4. Results

4.1 Estimation of breach geometric parameters

The sample of 231 IRs was considered representative of the average geometric reality of existing IRs. This record revealed that in the study territory, there was a greater density of IRs with approximately 5 m water height and 20,000 m³ reservoir volume (minor dams in the classification of the state of Colorado (2010)); however, there was also great variability. Given this context, the empirical formula best suited to changes in movable water height and reservoir volume should be chosen.

As a criterion for validating the obtained results by the applied expressions, given the lack of real data, breach progression method estimators and breach development estimators have been used. Erosion rate (ER , in meters per second, m/s) can be used as a check of the set methods and parameters (State of Colorado 2010). A linear progression was considered valid when $1.6 < ER / Hw < 21.0$, where $ER = B_{avg} / tf$. A whole breach development was considered valid when $B_{avg} / Hb > 0.60$, where Hb is the height, in meters, of the breach and B_{avg} is the average width of the final breach expressed in meters (m).

The analysis of the results revealed that the maximum and minimum flow rates for the same IRs greatly differed depending on the empirical formula used. In medium size IRs (250,000 m³), the flow rate value doubled. This is undoubtedly an indicator of the level of uncertainty associated with this analysis and the need for its continued revision.

The VTG formula showed logarithmic behavior for a movable water height below 5 m. Above this height, the growth was parabolic, softening in the central zone. The comparison between empirical formulas proposed by several authors revealed that the expression presented in MAPAMA (1996) overestimated flow rates. GUIDE overestimated the flow rate by 35-50% with respect to MLM84 and 20% with respect to F08. The results confirmed that MLM84 is more versatile for small IRs (minor dams). F08 showed the best fit and sensitivity to SI variation.

After applying new validation schemes in terms of formation time, Bowles et al. (2014) considered reasonable formation times associated with the expression $tf = 2 Vw / Qp$, where Qp is the peak breach flow rate, in cubic meters per second (m³/s) and tf is the breach formation time in seconds (s). That made it possible to certify that the expressions chosen for each application field are appropriate, such as those with the lowest outflow peak, longer formation time and greater lamination of the hydrograph. Fig. 4 revealed the empirical formula that best meets those conditions for each IRs' normative requirements in the application field. A second empirical formula (2nd choice) to corroborate the initial premise was proposed.

4.2 Sectorization

Generated watershed algorithms are based on drainage network definition and on the number of input cells chosen. In this analysis, the following software was used: SAGA GIS v.5.0 for its level of geomorphometric analysis and Global Mapper v.18.2 for its versatility.

The breach geometric axis location was based on stream order 4. Therefore, the threshold was determined according to the number of cells that feed the drainage channel. Uncertainty arises when deciding on a sufficiently representative stream order to avoid an excessive number of basins

surrounding the IRs. As mentioned above, the TWI has been a great help in recognizing the drainage network in the DTM and avoiding the mentioned uncertainty.

For the Las Porteras IRs case study, different cell thresholds have been studied for the same stream order: 123,456, 12,345 and 1,234. Fig. 5 shows that the cell threshold 12,345 responds to stream order 4 and reflects the reality revealed by the geomorphometric study in the Las Porteras IRs case. If a very small cell number is proposed for basin definition, it would be unfeasible to apply the methodology, as the number of watersheds calculated would be very large. Therefore, in this case study, the selection of 12,345 cells and stream order 4 allows for sectorizing the IRs embankment according to the specified conditions.

Finally, once the IRs sectors are known, it is necessary to identify the minimum height of each sector (on the intersection of the outer IRs slope with natural terrain). In the case of the Las Porteras IRs, there were 4 sectors as a result. In the case of the Macias Picavea IRs, the result was 9 sectors. The breaches' geometric axes should be located on the position of minimum elevations for each sector, and after that, the stochastic analysis should be applied.

4.3 Stochastic analysis

For each IRs, each height and empirical formula, the Monte Carlo framework obtained a distribution of the hydrograph's attributes. Additionally, with the implementation of the Monte Carlo method, the occurrence probability was achieved for each breach of case studies. These parameters correspond to the bottom elevation of the final breach predicted by stochastic analysis, following the triangular PDF.

Once the method was applied, the average, maximum and minimum hydrographs together with the standard deviation were obtained for each case. This allowed for a prediction of the range of results in each case. Then, with the hydrographs obtained and to characterize the breach, the breach bottom elevation results were adjusted to new PDFs. The adjustment was performed again to a triangular PDF validated by 3 methods: Kolmogorov-Smirnov (Massey 1951), Anderson-Darling (Anderson and Darling 1954) and Chi-square (Lancaster 1969). This adjustment has been found to be correct for the reality of the IRs. The base elevation of the breach showed a failure rate with exponential growth when approaching the IRs wall crest, which denoted randomness in the failure process.

To finally analyze the results obtained in terms of peak outflow generated, for each synthetic IRs and height, box plots were constructed. Jointly, mean confidence intervals were also determined. Then, selecting from among more than 50 probability distributions, the one that offers the best fit in the *Q-Q* plot was developed. Therefore, the resulting peak outflows of 60% of analyzed IRs could be adjusted to a Wakeby distribution, which was proposed by Houghton (1978). The Wakeby distribution is a suitable probabilistic model to represent maximum daily or instantaneous flood flows in a region. A smaller percentage of obtained flow rates has been fitted to other probability distributions such as Johnson SB (Campos-Aranda 2015) or Beta-Dagum (Domma and Condino 2017).

In keeping with the analysis of generated flow rates, three different behaviors were detected in IRs of similar size. The three smallest IRs had a slight asymmetry of simulated peak flows, more pronounced

than intermediate and large IRs. This asymmetry was due to higher extreme values than in other cases. Data dispersion dissipated as IRs height increased, as shown in Fig. 6. The three largest IRs had the same tendency of data and thus the same frequency distribution. To conclude, as the size of the synthetic IRs increased, the bias in the peak outflow data gradually reduced (Fig. 6).

4.4 Maximum hazard probability maps

Since delimiting the inherent uncertainties in the IRs failure process is crucial, these maps demonstrate the interest in adopting the proposal methodology. This development in the information provided will improve decisions on spatial planning.

Once the hydraulic simulations are calculated, mapping the area of maximum hazards is possible. To produce the final mapping of the maximum hazard probabilities, the probability data from the stochastic analysis phase was necessary. The occurrence probabilities based on the bottom elevation of the final breach (geomorphometric) were multiplied by the probabilities of the failure mode (causal), and the resulting probability was computed with respect to 1. The corresponding probability was assigned to each sector obtained from the sectorization phase. Finally, three hazard groups were distributed to reclassify the probability raster.

Since the characteristics of IRs water systems of case studies were dissimilar, the maximum hazard behavior was different in the two case studies, as spatially represented in Fig. 7. In the Las Porteras Irrigations reservoir case, most of the maximum hazards were in the IRs close to the infrastructure. In contrast, in the Macias Picavea Irrigation reservoir case, the maximum hazard zone was located in the area where the flow had stabilized. This was due to the steep terrain. This fact demonstrates the importance of the geomorphology of the environment in this type of study. Moreover, the flat areas around Las Porteras Irrigations reservoir partially retained the flood generated by IRs failure. It would therefore be interesting to apply mitigation measures at Las Porteras Irrigations reservoir.

5. Discussion And Conclusions

An innovative risk assessment framework for the hydraulic control of IRs breaching was implemented in this study. Four empirical breach prediction methods, including F08, VTG, MLM84 and GUIDE, were compared to obtain the empirical formula that best adapts to each geometry IRs in a territory, in this case Spain. A stochastic analysis was used to obtain the occurrence probabilities related to the bottom elevation of the final breach. Sectorization and hydraulic simulation were very useful tools to produce the maximum hazard probability maps.

The study of the breach geometric parameter estimation was effective. This study characterized the hydraulic operation of IRs and defined the empirical formula that best responds to the geometric reality of each case. However, the restrictions of the method used should always be considered: it only evaluated a failure mode (internal erosion), and the embankment cohesion was considered null.

One of the issues in this study was the lack of IRs' records. This problem was solved with a representative sample of 231 IRs and the development of synthetic IRs covering the geometric characteristics of the IRs water system. This approach was validated by verifying that the hydraulic operation of real case studies (Las Porteras and Macias Picavea IRs) closely approximated the studied synthetic IRs.

Moreover, the infeasibility of tackling an exhaustive geotechnical analysis and building a PAM led to the implementation of an EM. This decision was based on the ease of EM implementation, access to required data and viable extrapolation of results. This EM relies exclusively on geometric parameters.

The comparison between empirical formulas proposed by several authors revealed that the formula, presented in some relevant reports, overestimate the flow rates. The SI parameter and movable water height were proven to be robust parameters for characterizing the potential risk of the hydraulic infrastructure and delimiting the scope of each formula.

The location of the breach geometric axis of the hypothetical failure was objectively justified after applying the proposed methodology. The IRs' embankment was divided according to exclusively geomorphological factors. Furthermore, although IRs' failure is an artificial event, the importance of receiving basin characteristics was revealed. Therefore, the receiving basin conditioned the failure hydrograph, so it was necessary to include its study in IRs' risk analysis.

The models developed to analyze mitigation measures allowed us to deduce that a potential measure is a buffer taken as a feasible low-cost measure. It is important to note that mitigation measures will be feasible if geomorphological conditions in the IRs' environment allow it. The proposed solution should not be implemented in IRs with high-gradient bordering areas.

The stochastic analysis, not addressed so far in IRs, showed its strengths and weaknesses in the analysis. Implementing the Monte Carlo model allowed for the determination of the breach occurrence probability independent of the probability associated with the failure mode. The probability achieved after applying the Monte Carlo method was based on exclusively geometric factors, since it was associated with the bottom elevation of the final breach. The main weakness in applying this framework of analysis was focused on the utilized triangular PDF. Thus, the option of proposing new PDFs supported by a broad range of case studies remains open for upcoming studies. Furthermore, the Wakeby distribution proved to be the best fit for peak outflow data obtained from stochastic analysis.

Hydraulic simulation was the tool used to produce maximum hazard probability maps using parameters obtained from previous phases. One of the main conclusions of this stage was the sensitivity of the hydraulic results when working with different discretization of DTM. This is one of the research lines that remains open and worthy of study.

Maximum hazard probability maps are a new contribution to flood risk managers and land-use planners. Causal occurrence probability and probability associated with the bottom elevation of breaches have

been used. The proposal presented in this paper improves the knowledge of the territory's response before the existence of these infrastructures with failure risk.

The problem due to the lack of a record of IRs and failed IRs has been expounded during the study. Therefore, it would be of interest to systematically address the IRs registration throughout the territory. This knowledge would make it possible to characterize the IRs reliably, validating the results with geometric methods. This effort would result in better risk management. Thus, the development of a centralized and open access database would allow us to advance in the knowledge of failure modes, being able to limit the uncertainties associated with failure mode.

It was stated that the analysis mode used in this study was through the Empirical Model. The convergence of the three existing analysis modes (EM, PAM and PBM) would be a very interesting development. This development would be useful to determine the laws of behavior in IRs' failure.

Acting on the nature of the cartographic source is considered necessary. In this sense, LIDAR cartography was used in this work. The next step will be to use other cartographic sources, resolution and accuracy to reliably establish the minimum cartographic characteristics required.

Geometric parameters have been considered for the study of the potentiality risk of IRs' collapse. There are other uncertain parameters that can be included in the analysis. Therefore, the probabilistic model has considerable room for improvement.

The ultimate goal of this whole methodology is the development of a Decision Support System (DSS) which considers hydraulic and geometric parameters and determine the risk infrastructure for possible hazards. Therefore, the next step of this research is automating the proposal methodology through software development considering free distribution tools.

Declarations

-Ethical Approval: Not applicable

-Consent to Participate: All authors whose names appear on the submission

1) made substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data; or the creation of new software used in the work;

2) drafted the work or revised it critically for important intellectual content;

3) approved the version to be published; and

4) agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

-Consent to Publish:

All authors whose names appear on the submission give their consent to publish this paper in case it is accepted

-Authors Contributions:

F.E., and J.L.M. conceived, designed and lead the research and paper editing; S.Z. was supporting the paper editing and the research conceptualization; R.M. was in charge of the analytical development. The Discussion and Conclusions sections were addressed by all authors, and all authors wrote the paper.

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Figures

Figure 1

General Methodology

Figure 2

Relationship between geometry of each synthetic IRs Type (PT) and SI

Figure 3

Location of case studies

Figure 4

Application field representation of suitable empirical method for each IRs normative requirements

Figure 5

Sectorization of Las Porteras IRs' water system for stream order 4 and different cell thresholds. (a) 123,456 cells; (b) 12,345 cells; (c) 1,234 cells

Figure 6

Box-plot of obtained simulated peak flow rate for (a) PT-01; (b) PT-04; (c) PT-07; (d) PT-10

Figure 7

Maximum hazard probabilities map. (a) Las Porteras IRs . (b) Macías Picavea IRs