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"Error Propagation of Digital Elevation Model Obtained by Low Cost UAVs for Flood Models"

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Resumen
Las inundaciones fluviales representan uno de los riesgos naturales más importantes en las ciudades andinas por su recurrencia e impactos económicos. Una gestión adecuada del riesgo de inundación requiere información de la probabilidad de ocurrencia y profundidad de inundación para eventos en diferentes periodos de recurrencia. El objetivo del artículo es evaluar la potencialidad del uso de los Modelos Digitales de Elevaciones (DEM) producidos con aerofotogrametría de bajo costo con vehículos aéreos no tripulados (UAV), utilizando un tramo del río Santa Bárbara. Para el análisis se usará un escenario de inundación con un período de retorno de 50 años y dos modelos de inundación Hec-ras y un modelo basado en agentes (ABM). Las principales fases son: (i) Análisis geoestadístico de la estructura espacial de los errores. (ii) Generación de dos conjuntos de DEMs sintéticos utilizando simulación geoestadística. (iii) Simulación con los dos modelos de inundaciones utilizando los conjuntos de DEMs sintéticos, y (iv) análisis de propagación de errores. Los resultados indican que un DEM generado con UAV es útil y una alternativa factible para realizar la simulación de inundaciones por desborde de ríos por su detalle al paso de tiempo en cambios en la zona. Los ABM son de gran utilidad para la generación de escenarios de inundación gracias a sus posibilidades de automatización y de ejecución en corto tiempo. Además, los valores de sensibilidad y especificidad con ABM del DEM con UAV indican una alta capacidad para detectar las áreas inundadas y capacidad media – alta para áreas seguras.

Palabras claves: modelo de inundación; aerofotogrametría; probabilidad de inundación; modelo basado en agentes.

Abstract
River floods represent one of the most important natural hazards in the Andean cities due to their recurrence and economic impacts. Adequate flood risk management requires information on the probability of occurrence and depth of flood for events in different periods of recurrence. The objective of the article is to evaluate the potential use of Digital Elevation Models (DEM) produced with low cost aerial photogrammetry with unmanned aerial vehicles (UAV), using a section of the Santa Bárbara River. For the analysis, a flood scenario with a 50-year return period and two Hec-ras flood models and an agent-based model (ABM) will be used. The main phases are: (i) Geostatistical analysis of the spatial structure of errors. (ii) Generation of two sets of synthetic DEMs using geostatistical simulation. (iii) Simulation with the two flood models using the sets of synthetic DEMs, and (iv) analysis of the propagation of errors. The results indicate that a DEM generated with UAV is useful and a feasible alternative to carry out the simulation of floods due to overflow of rivers due to their detail over time in changes in the area. The ABMs are very useful for the generation of flood scenarios thanks to their possibilities of automation and execution in a short time. In addition, the values of sensitivity and specificity with ABM of the DEM with UAV indicate a high capacity to detect flooded areas and medium - high capacity for safe areas.

Keywords flood models; aerial photogrammetry; Flood probability; agent-based model

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1. INTRODUCTION

A great number of floods occasioned by the overflow of rivers have attired interest during the last years due to their destructive potential and the great socioeconomic and environmental repercussions they cause (Baldassarre et al., 2017; Fleming, 2002; IPCC 2007). In 2015 at least 20 floods occurred in the Highlands of Ecuador, Azuay being the most affected province with a total of 15 reported floods; spates collapsed sewers and overflew various channels (D´Ercole et al. 2015; Basold et al. 2015).

Flood risk has increased because of human settlements in alluvial plains and anthropic activities. This problem requires measures to protect and mitigate its impact in such alluvial plains (Baldassarre et al. 2017). Despite the efforts of the authorities, flood risk management is still non-existent. Prevention plans to reduce flood losses require proper information about susceptible areas to these event. Possible flood maps are a key element for obtaining this kind of information (Merwade et al. 2008).

Two-dimensional (2D) hydraulic models are useful to delimit flood hazard maps since they estimate the level of the surface of the water in the plains with geometric precision. Using a geometric 2D model obtained from poor or low quality terrain data can produce even more conservative result than a one-dimensional model (1D), which only simulates the level of the complex section (channel and plains) (Merwade et al. 2008; Gharbi et al. 2016).

To apply 2D hydraulic models, channel information and terrain elevation data in DEM are needed. Each data contains errors that can be spread according to the results of the hydraulic simulation (e.g., water level). Data gathering methods, generalization processes or data storage methods and their effects produce linear flaws in vertical direction. Therefore, it is common that any flood map generated by simulation have errors related to the flooded surface and the depth of the water (Hesselink, Annika W. and Kwadijk 2003; James and Robson 2014). Merwade et al. (2008) and Jung and Merwade (2015) estimated the uncertainty rates and evaluated the relative sensitivities of the Manning (N), channel (Q) and topography (T) variables in the flood model with the Hornberger-Spear-Young method (Monte Carlo simulations), and found that topography and flow were the main variables that contributed to the change of the flood area (Abily et al. 2016; Pappenberger et al. 2008).

Additionally, Leon, Heuvelink, and Phinn (2014) informed that the spatial distribution of elevation errors demonstrates a certain tendency to group related to land occupation. The analysis revealed that the smallest errors are found in "constructions" and homogeneous environments like houses, roads and bare ground. The largest errors were found in vegetation areas, including scattered trees and mangroves, and on sandy beaches (Van den Hoek et al. 2014; Kalyuzhnaya and Boukhanovsky 2015; Tobergte and Curtis 2016).

Unlike analytical methods that focus on modeling and characterizing the result of a system in its entirety (top-down approach), ABM seeks to represent the behavior and interactions of the individual agents and local objects that compose the system, obtaining as a result a behavioral pattern at the level of the system (bottom-up approach). Agents (autonomous decision-making entities) interact with each other and their environment, making analytical-based decisions on the functions and rules prescribed by the modeler (Quezada and Canessa 2010). In this way, ABMs are useful tools to study the behavior that comes from a complex system as a result of particularities in the components of the system and its operation.

One method to generate a DEM is aerial photogrammetry with UAVs. This allows the generation of high-quality data (e. g. 0.5m) and at relatively low costs in areas where this information does not exist. However, DEMs derived from aerial photogrammetry with UAVs are not exempt from errors. Therefore, it is necessary to evaluate the spatial structure and its effects on flood models (James and Robson 2014; Leon, Heuvelink, and Phinn 2014). In Ecuador there are DEMs derived from topographic maps, satellite images, and photogrammetric flights with medium and low resolutions. Nevertheless, in recent years it has been more common to find DEM products made from aerial photogrammetry with UAVs.

The objective of this study is to evaluate the feasibility of the DEMs produced with UAVs for flood studies. Specifically, the objective is to analyze the propagation of vertical errors of the DEMs in flood simulation. For this, it is necessary to compare the results of flood mapping from a DEM generated with low cost UAV with a DEM obtained from official sources. Two types of simulation were used to analyze this, one based on the HEC-RAS hydraulic model (2D) and another based on an ABM on a stretch of the Santa Bárbara River in the Ecuadorian Andes. In this manner, the study allows understanding the effects of the intrinsic incertitude of the flood maps used in the field of risk management. This investigation has two main impacts listed below:

1) It contributes to the understanding about the propagation of vertical errors of the DEMs generated with low cost UAVs to create flood maps in physical 2D flood models and in ABM, providing information about its feasibility for the study of floods.
2) It is the first study of this nature in Ecuador. Therefore, the results of this research will contribute to field of flood risk management, providing information on the feasibility of low cost techniques for the generation of DEMs as well as their possible advantages and limitations.

2. METHODOLOGY

For the study of error propagation of DEMs in flood models, we suggest to perform Monte Carlo (MC) simulations of a flood event in the section of study using synthetic DEMs with a similar spatial structure of altitudinal errors to the original DEMs generated using geostatistical techniques.

The main phases of this investigation are the following:

(I) Geostatistical analysis of the spatial structure of errors of a DEM produced using a low-cost UAV and a DEM from official sources (SIGTierras project).

(II) Generation of two sets of synthetic DEMs with an equivalent spatial structure of errors such as the DEMs, as its origin source using geostatistical simulation.

(III) Flood simulation in a 2D hydraulic model and an agent-based conceptual model using the sets of synthetic DEMs.

(IV) Analysis of error propagation of DEM in the results of hydraulic model. The following subsections provide information about the area of study, basic data and details of each phase.

2.1 Area of Study

The area of study includes the zone of influence of the Santa Bárbara River, in a stretch of approximately 4 km through the urban area of Gualaceo, east-central area of the province of Azuay, covering an approximate area of 104 ha (Fig 1). This is part of the sub-basin of the Santa Bárbara River, which belongs to the Paute River basin.

In the highlands, the temperature is low, a natural distinction of high areas of the mountain ranges where the ecosystems of the Cloud Forest and the Andean Moorlands settle. The annual rainfall in this region ranges from 800 to 1,100 mm year-1. The rainy season includes the months of April, May, June and July, while the dry season corresponds to the months of August, September, October and November (Datos Geográficos | I. Municipalidad de Gualaceo 2017). It has an average temperature of 17ºC, a mild and cold weather (Campozano et al. 2016).

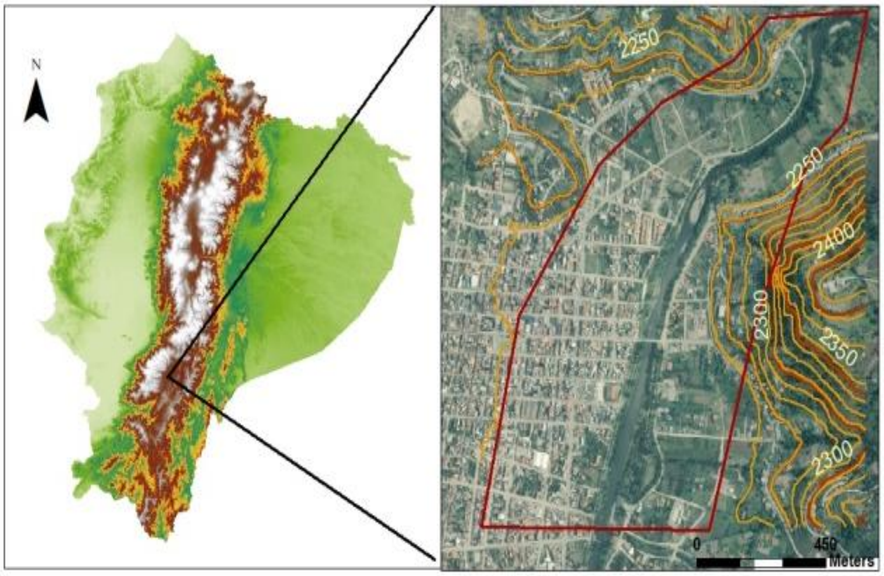

Fig 1The study area consists of the region of influence in the Santa Bárbara River as it passes through the city of Gualaceo, province of Azuay (Ecuador).

2.2 Data

To conduct this research, data sets provided by the Department of Water Resources and Environmental Sciences of the University of Cuenca were used:

UAV photography. A set of digital aerial photographs captured with a low-cost tetrarotor UAV, DJI brand, Phantom 3 model, with a Garmin VirbX digital camera installed, and built-in GPS. PhotoScan Pro software was required to carry out photogrammetric processing. The final product obtained was an orthophotography of 0.5 cm of spatial resolution and a digital model of elevations of horizontal spatial resolution of 3 m (DEM_UAV). This resolution was used to maintain parity with the DEM from reference,

Reference DEM (DEM_ST). A raster file with a digital model of elevations of 3 m of spatial resolution and orthophotography provided by the SIGTierras project of the Ministerio de Agricultura, Ganadería, Acuacultura y Pesca (MAGAP, 2012). This DEM was used as reference since it constitutes official information and is widely used in several applications in Ecuador.

Flow data obtained by SENAGUA (2014). Flow values of a return period of 50 years corresponding to a maximum flow (Q max) of 879.8 $m^3 s^{-1}$, and minimum flow of 18.9 $m^3 s^{-1}$. These data were used for simulations in the two Hec-ras models and ABM.

Checkpoints. A three-dimensional coordinates file surveyed in the field using a weather station in the area of study. This data set was used for the calculation of errors.

2.3 Geostatistical Analysis of the Spatial Structure of Errors

The altitudinal errors of the DEMs may demonstrate spatial dependence (Leon, Heuvelink, and Phinn 2014), this dependence is studied by geostatistics. The Kriging method of geostatistical interpolation is extensively detailed in literature. (For a deeper explanation, see Hengl, 2009). To apply this technique it is important to know the spatial structure of the variable in question, which can be represented by a semivariogram that describes the variance of the data at different distance intervals. The semivariogram can be adjusted to a theoretical model with spherical, exponential or Gaussian form, allowing it to extract a series of parameters that will be used for interpolation and definition of degree and scale of spatial variation. These parameters are the following:

- The range that indicates the distance where the spatial dependence of the variable disappears or becomes negligible.
- The nugget that indicates the variance left unexplained by the model, and is calculated as the intercept on the y-axis and the semivariogram.
- The threshold (sill) is the maximum semi-variance found between pairs of points. It must coincide with the variance of the population.
- The proportion of the variance detailed by the distance given by the degree of spatial variation, and consequently, the degree of uncertainty when interpolating points (Gallardo 2006).

Therefore, the elevation values of the DEM_UAV and the DEM_ST were compared with a random sample of 250 field checkpoints. By doing this the spatial structure of the altitudinal errors was determined. This data was adjusted to a semivariogram for each DEM. The exponential Gaussian and spherical semivariogram models were evaluated, as they are the most used in hydrological studies e.g. (Adhikary, Yilmaz, and Muttil 2014; Leon, Heuvelink, and Phinn 2014; Villatoro, Henríquez, and Sancho 2008). The process was performed with the "Gstat" library in the R-studio 2.10 software (see, Raftery 2018).

2.4 Generation of Sets of Synthetic DEMs Using Geostatistical Simulation

To incorporate the values of the random errors in synthetic DEMs, the MC simulations are applied with Kriging, which estimates a weighted measure of the observations with data derived from the degree of spatial correlation (Wechsler 2007; Morán and Luna 2014). The estimation is a linear weighted average of the *n* available observations. Probable map distributions are called stochastic modeling or MC simulation due to the random generation of uncertain variables used to simulate. The Kriging method is considered to be the best-unbiased linear predictor of the values in locations left unobserved (Kleijnen 2009; Moncada Gómez and Sousa Júnior 2011).. The basic idea behind stochastic simulations is to obtain new "artificial" realizations so that they possess the same statistical properties of the sample (Bruce, Barry, and Stuam 2008; Kleijnen 2009).

A convergence analysis conducted by Orellana (2017) on the same data set revealed that 300 estimations could be sufficient for the accumulated standard deviation values of water depth to be stabilized. Unfortunately, due to limited time and computational resources for this research, it was required to use 100 estimations for each DEM. The Kriging simulations were performed in R version 2.10 software (R Core Team 2016). The synthetic DEMs will be used as input to the two-dimensional hydraulic model and the ABM for flood simulation.

2.5 Flood Simulation in a Two-dimensional Hydraulic Model and an Agent-based Model

The error propagation analysis was made in two flood models. The first is the 2D hydraulic model implemented in HEC-RAS 5.0.3 software (ACE, 2008). This model is based on differential equations of water flow (physically based) to simulate flood events with topography information, input flow (Hydrogram) and boundary conditions (Timbe and Timbe 2012). The results of the model include flooded surface and depth maps. This model is frequently mentioned in literature and widely used for flood simulation. However, the 2D version of HEC-RAS has limited possibilities for automation. Each simulation must be manually executed by changing the input alone DEM.

The second method is a simplified conceptual model, the ABM (Orellana, Timbe, and Pinos 2017). In this procedure, water behavior is simplified by modeling only its interaction with topography and with water in adjacent locations, without directly considering physical laws such as terrain friction and therefore turbulent flow velocity (Izquierdo et al. 2008; Quezada and Canessa 2010). The code has been written in NetLogo language by researchers from the Department of Water Resources and Environmental Sciences, based on previous models from Wageningen University. Preliminary experiments suggest that this properly calibrated model would be partially comparable with a hydraulic model, at least in the intermediate zones of the area of study (Orellana 2017). The advantage of this method is its great capacity of automation allowing hundreds or thousands of simulations to be executed in series and parallels. Beyond the potential and limitations of the ABM to produce a reliable map of flood danger, its main advantage is its automation, which allows studying the propagation of errors in a relatively faster way.

For this study, flood simulation was performed taking into account a non-stationary flow with maximum value (Q max) for a return period of 50 years equal to 879.8 m^3s^{-1}. To avoid stability problems with the dry channel a minimum flow of 18.9 m^3s^{-1} was used at the beginning of the simulation.
100 simulations were performed for each model with each set of synthetic DEMs: HEC-RAS / DEM_ST, HEC-RAS / DEM_UAV, ABM / DEM_ST, and ABM / DEM_UAV.

2.6 Error Propagation Analysis

Once generated the different sets of simulations, descriptive statistics were calculated in each cell of the map. The following summary maps were devised:

a) Mean water depth value
b) Variance and
c) Flood probability

In addition to this, a zoning map was generated. For this purpose, it was necessary to classify each cell of flood probability map as safe (flood probability <0.05) or unsafe (flood probability> = 0.05).

The zoning map developed with HEC-RAS / DEM_ST was used as reference. The other three probability maps were compared with it to obtain four groups of cells; True Positive (TP), when flood was detected in an unsafe cell; False Positive cell (FP), when a flood was detected by mistake in a safe cell; True Negative (TN), when no flood was detected in a safe cell; and False Negative (FN), when the flood was not detected in an unsafe cell (Morán and Luna 2014). Finally, the sensitivity and specificity values of each of the three maps evaluated were obtained. Sensitivity is the probability of the model to correctly detect unsafe areas, it was calculated as the ratio between the number of cells classified as VP and the total number of flooded cells (Donis 2012), that is:

$$\mathbf{Sensibility} = \frac{\mathbf{VP}}{\mathbf{VP} + \mathbf{FN}}$$

The specificity is the probability of model to properly detect all safe areas calculated as the ratio between the cells classified as TN and the total safe cells (Donis 2012), that is:

$$\mathbf{Specificity} = \frac{\mathbf{VN}}{\mathbf{VN} + \mathbf{FP}}$$

3. RESULTS

3.1 Spatial Distribution of Altitudinal Errors

Figures 2 and 3 show the semivariograms of the elevation error values of the DEM_ST and DEM_UAV respectively. The comparative analysis of several semivariogram models indicated that the exponential model presents a better fit than the spherical or gaussian model for the two DEMs. In this way, the best fit for the DEM_ST presented a threshold of 0.5 with a range of 50m and a nugget of 0.24. While the DEM_UAV showed a threshold of 0.63 with a range of 20m and a nugget of 0.49.

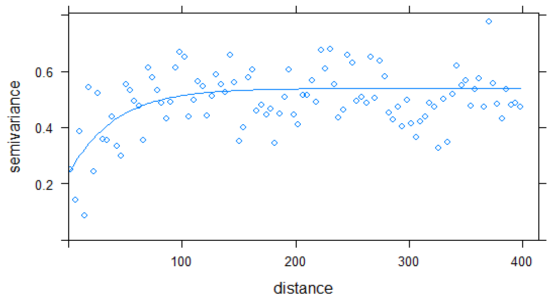

Fig 2 Semivariogram with exponecial model of altitudinal errors of the DEM_ST

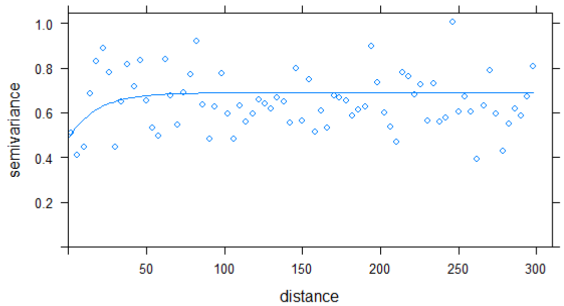

Fig 3 Semivariogram with exponecial model of altitudinal errors of the DEM_UAV.

3.2 Flood simulation

The average flood depth was estimated in 100 simulations for each DEM in the two models, creating maps for their visualization (Fig. 4). We can see which areas with the greater detail of depths we have with the DEM_UAV because it takes into account avenues and earthworks. In Fig. 4b and 4d, the greatest depth excluding the channel is 4.5m, but in the upper right, there is an accumulation of water with a depth of 7.5m since there was a movement of land that was captured by the DEM_UAV. In contrast, the greater depth in Fig. 4a and 4c is 3m. The difference in depth values obtained may be due to the detail of terrain obtained with each DEM, since a process is carried out to exclude vegetation and buildings when generating the DEM_UAV.

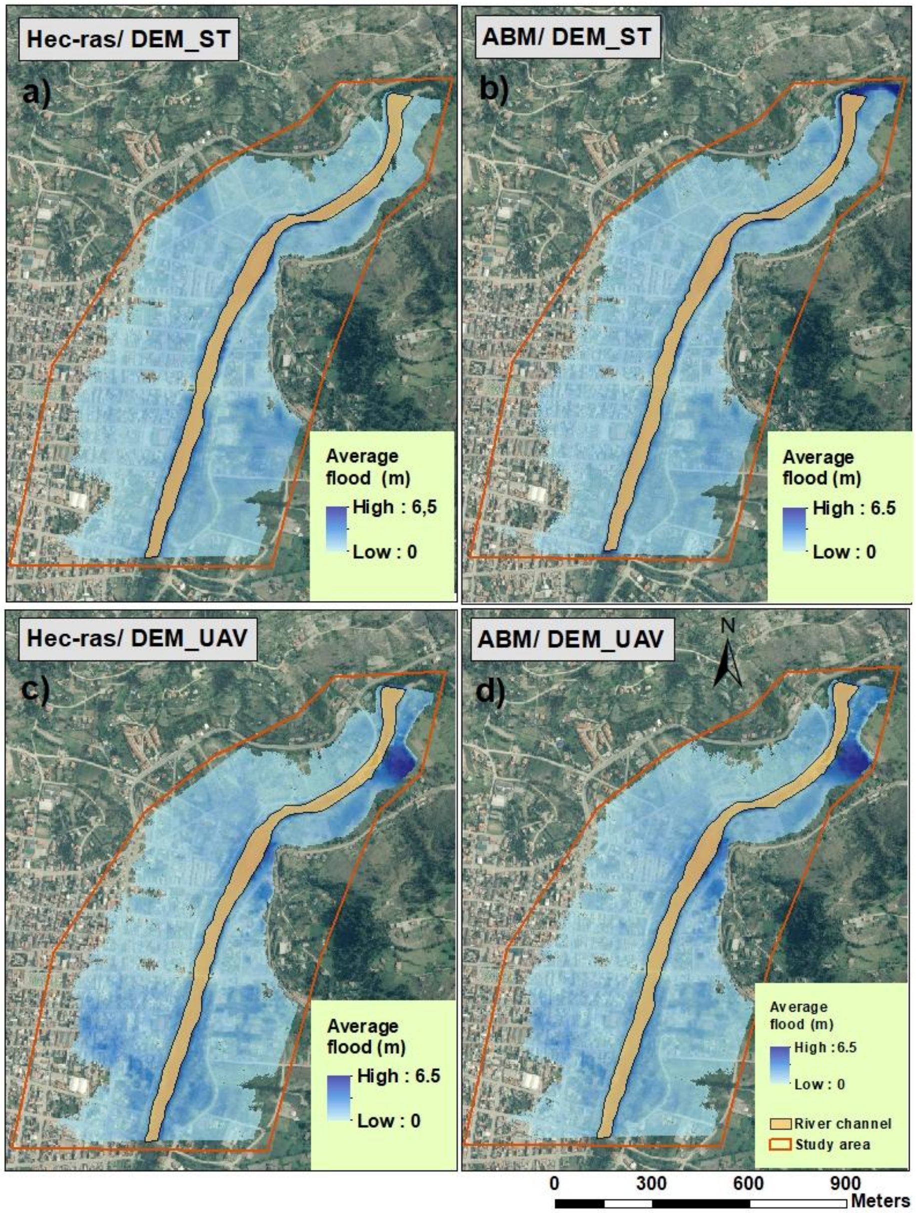

Fig 4 Average flood depth map a) Generated with Hec-ras and DEM_ST model. b) Hec-ras model and DEM_UAV. c) Model ABM and DEM_ST. d) model ABM and DEM_UAV.

The uncertainty propagated by errors of DEM_UAV and DEM_ST in Hec-ras and ABM was analyzed with the variance maps of the depth (Fig. 5). Disregarding the channel in the analysis, the variance values for the Hec-ras model with the DEM_ST goes from 0 to 1.5. For the ABM model with the DEM_ST, its variance goes from 0 to 2.4, being the highest value for the DEM_ST. For the Hec-ras map with the DEM_UAV the variance goes from 0 to 2.5 as in the ABM model with the DEM_UAV. The variances in the histograms of Fig. 6 are observed with better clarity.

The values of the variances appear to be greater in the simulations with the DEM_UAV. This might be due to the process of eliminating all types of vegetation and constructions. Therefore, when creating the DEM there may be greater altitudinal errors in places where there are buildings and high vegetation, this explains the high variance values in different locations. In addition, it is possible to observe that, considering the variance maps and the depth maps, where there is greater variance, there also is a greater flooding.

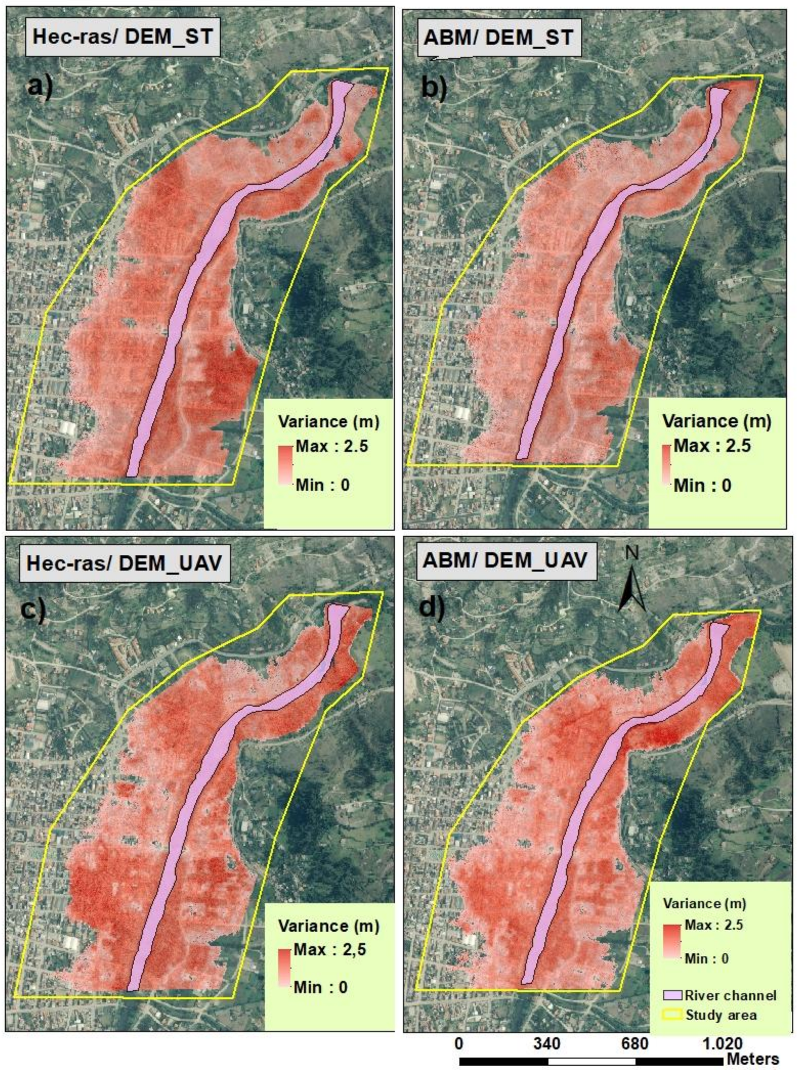

Fig 5 Flood variance map a) Generated with Hec-ras and DEM_ST model. b) Hec-ras model and DEM_UAV. c) Model ABM and DEM_ST. d) model ABM and DEM_UAV.

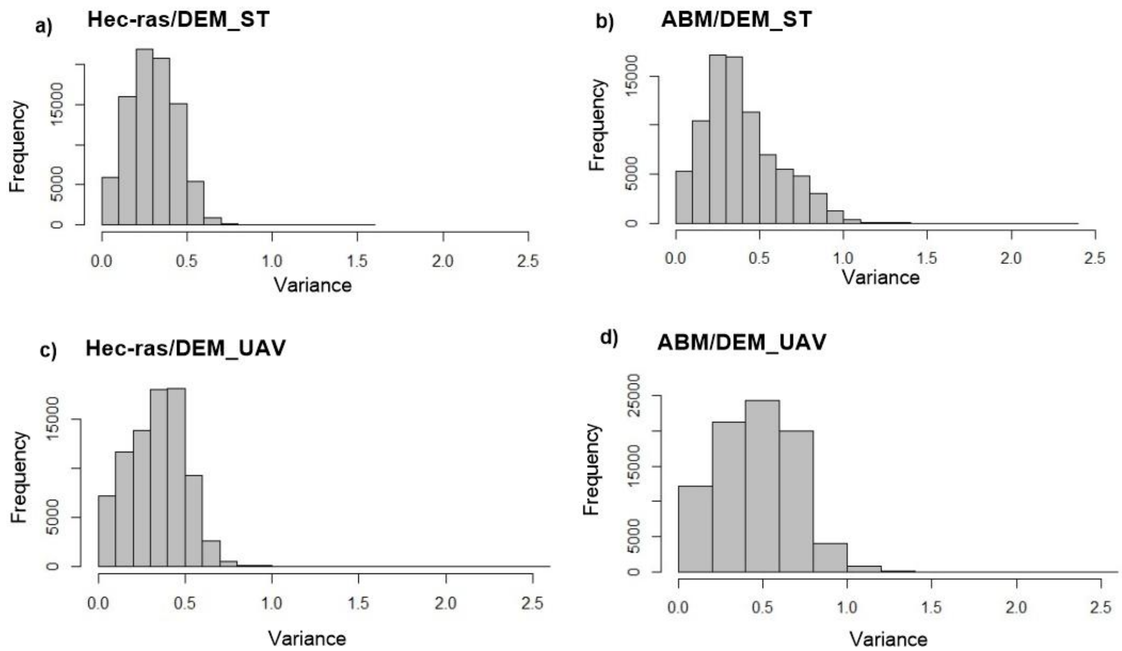

Fig 6 Flood variance histogram. a) Generated with Hec-ras and DEM_ST model. b) Model ABM and DEM_ST. c) Hec-ras model and DEM_UAV. d) Model ABM and DEM_UAV.

Flood probability maps classified into two probability ranges were used to illustrate the uncertainty of the simulation models: 0> p≥ 0.05 (safe area) and 0.05> p≥1 (unsafe area) (Fig. 7). The unsafe area on the map with the DEM_ST in Hec-ras (Fig. 7a) is 77 ha, for the ABM model with the DEM_ST is an area of 76.7 ha, for the DEM_UAV in the Hec-ras model is 76 ha, and finally with the ABM and DEM_UAV is 79 ha. The different models produced similar flood surfaces, with a variation of 1 to 2 ha. However, it is important to notice that the simulations with the DEM_UAV show more detail in flood regarding road network and terrain elevations. It is possible to observe that the surface corresponding to the probability 0> p≥ 0.05 is greater for the maps created with the ABM model which implies that the influence of the altitudinal errors in this type of simulations is greater for hydraulic models.

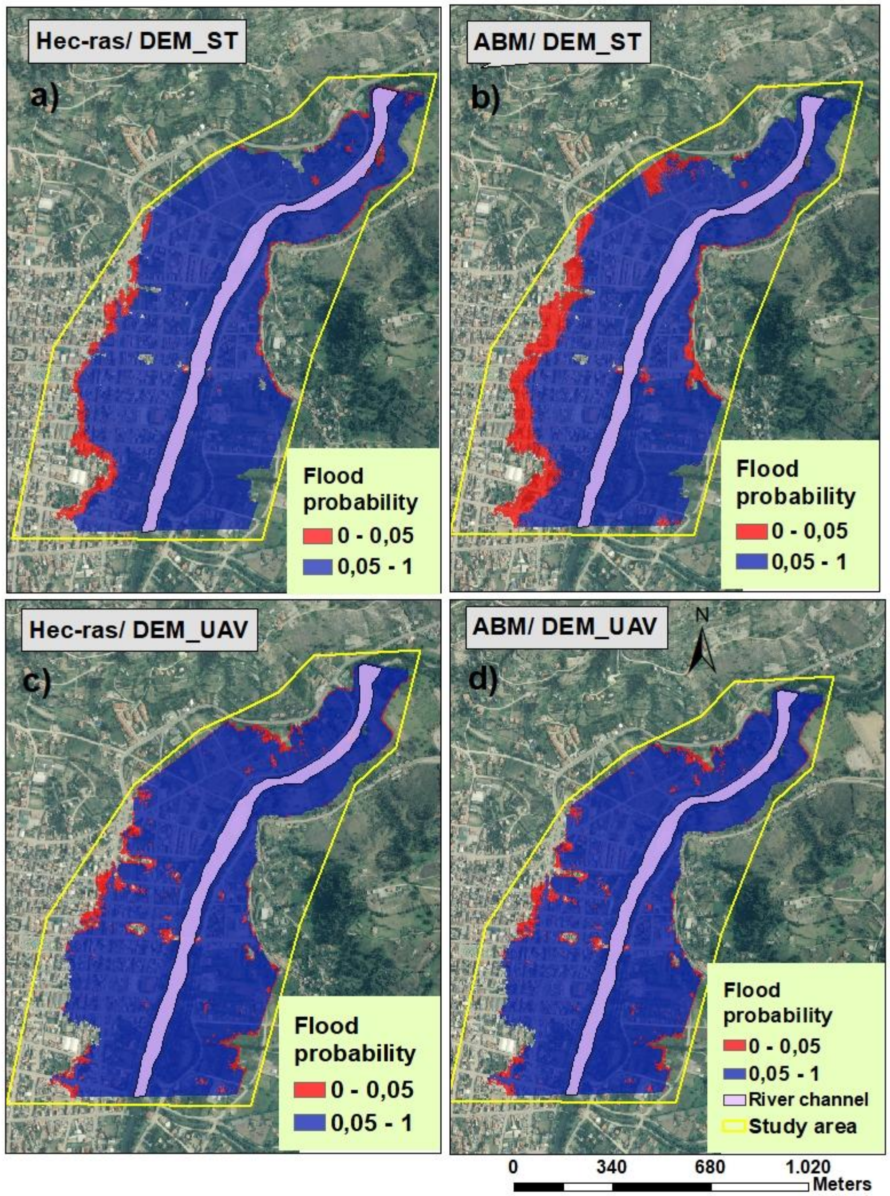

Fig 7 Flood probability map. a) Generated with the Hec-ras and DEM_ST model. b) Hec-ras model and DEM_UAV. c) Model ABM and DEM_ST. d) Model ABM and DEM_UAV.

Table 1 shows the values of TP, FP, TN and FN. Using such tools; sensitivity and specificity data were obtained by taking the map with DEM_ST in Hec-ras as reference. It shows as well the validation maps of each of the values in Figure 8. The simulation that obtained the highest sensitivity value was the ABM model with DEM_ST, being 0.915. Nevertheless, it is observed that the other two simulations have also a high sensitivity. This indicates their ability to correctly represent the unsafe areas in comparison with the base simulation Hec- Ras - DEM_ST. Similarly; the simulation that obtained a higher specificity value was the ABM model with the DEM_ST, a value of 0.935 that revealed a relatively high capacity to identify the safe or non-flooded areas. In contrast, the other two combinations presented even lower values than 0.83 and 0.81, meaning less capacity to identify safe areas.

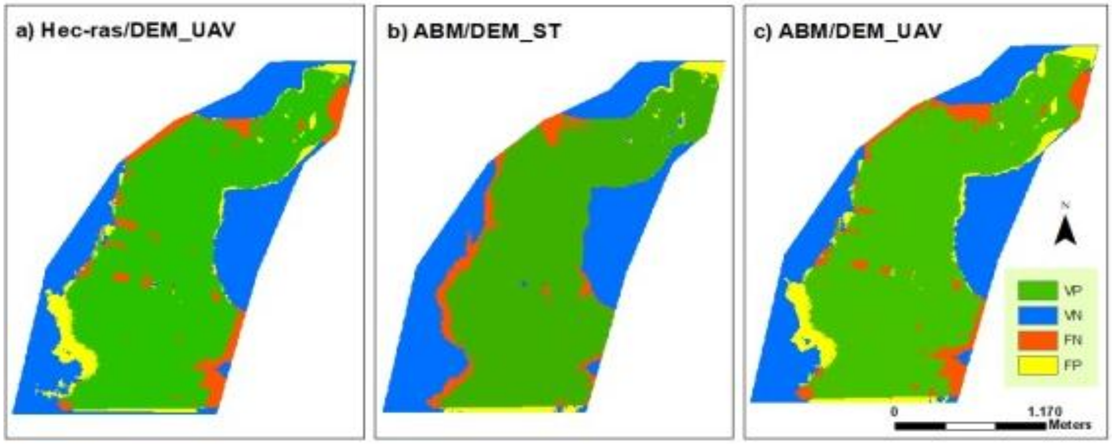

Fig 8 Validation maps. a) Generated with the Hec-ras and DEM_UAV model. b) Model ABM and DEM_ST. c) Model ABM and DEM_UAV.

Table 1. Values of true positives and false negatives used to calculate sensitivity and specificity.

	Hec-ras/DEM_UAV	ABM/DEM_ST	ABM/DEM_UAV
TP	71791	72866	71866
FP	6552	2512	7315
FN	7808	6733	7733
TN	31886	35926	31123
Sensibility	0.902	0.915	0.903
Specificity	0.83	0.935	0.81

4. DISCUSSION

In the simulations based on DEM produced with a low cost UAV (DEM_UAV) it is evident that this method can produce results in greater detail in the flooded area since it includes urban morphological elements in great detail. In addition, the ease and time of acquisition allows including changes in the morphology of the land, such as earthworks. The analysis of sensitivity and specificity showed that, although a simulation based on a DEM_UAV allows adequately identifying most of the flooded areas compared to a simulation based on a DEM from official sources, the identification of safe areas is less reliable. In other words, the simulation would be less useful to define places free of flood risk. This is especially certain in areas with a flood probability of 0> p≥0.05, so it should be stricter at the safe zone classification threshold.

In the analysis of error propagation of the DEM_UAV regarding the DEM_ST it was found that there might be greater influence of the altitudinal errors in the DEM_UAV, it is likely due to the process of obtaining the DEM. In zones of buildings and higher vegetation, greater variance of depth was obtained where there is possibly greater altitudinal error. Therefore, the depth and the flooding area vary to the results obtained with the DEM_ST. As found in the study by Saksena and Merwade (2015), the elevations of the water surface (WSE) along the stream and the flood area have a linear relation with the spatial resolution and vertical precision of the DEMs. Also, this is corroborated by the studies of Merwade et al., (2008) and Saksena and Merwade (2015) who found that the elevation of the water surface from a hydraulic model is affected by the flow input, resolution and precision of the DEM as well as the relation of the flood area with the vertical error.

Considering the use of simulations based on ABM, the results indicate that these models are able to reproduce with a certain precision those coming from a hydraulic model like the Hec-Ras model. The most obvious differences occur at the extremes, where the ABM tends to underestimate and overestimate the depth of water at the origin and at the exit, respectively. This effect could be due to the fact that the ABM, since it is a conceptual model, does not incorporate the friction of the different types of coverage as in the hydraulic model. In this way, it makes the water flow with greater speed, causing water accumulation at the ends. The values of sensitivity and specificity of the simulations with ABM indicate a very high capacity to detect flooded areas and medium-high capacity for safe areas. Hence, its application should consider the accuracy in the classification threshold of safe areas for making decisions about risk management.

5. CONCLUSIONS

The objective of this study was to evaluate the potential use of a digital elevation model (DEM) produced with low-cost digital aerophotogrametry for the study of floods, using a case study in Santa Bárbara River in the Ecuadorian Andes for a scenario of flood in a return period of 50 years. Additionally, the use of results of simulations performed with agent-based models was explored as an alternative to two-dimensional hydraulic models**.**

The results obtained reveal that the DEM produced with low cost UAV photogrammetric techniques could be a useful alternative for simulating floods occasioned by the overflow of rivers, since they would allow changes in the area of interest. This conclusion is in line with what was found in the study by Escalante, Cáceres, and Porras (2016), which indicates that UAV systems are an alternative for the acquisition of high spatial and temporal resolution images and that have shown great potential for a fast response in different scenarios. Moreover, Corredor D. (2016) indicates that topographic surveys made with drones save much time in gathering information and their results present very good precisions that can be used in many projects.

The main utility of flood simulations carried out in ABM would be directed to the interactive generation of flood scenarios to promote a discussion and debate of risk management strategies thanks to its possibilities of automation and execution in short time. Likewise, they can help to communicate the concepts of uncertainty, sensitivity and specificity for an informed discussion with decision makers and the general public. In addition, they could be used for a rapid qualitative and visual representation of the flooded surface as long as their limitations are properly managed and communicated.

One of the limitations in this study was the reduced number of estimations by simulation as a result of the restrictions of 2D Hec-ras automation. However, the use of ABM languages does allow automation, which offers a viable alternative since its results are acceptable for flood risk study and the study of how altitudinal errors of digital elevation models are propagated to maps of danger of flood. Hopefully in the near future hydraulic models incorporate more advanced automation functionalities.

This work opens new possibilities for future research, such as the analysis of larger areas with different characteristics to determine its generality. Nevertheless, the possibilities of pre-processing of DEMs for correction and reduction of errors using field control points in the aerophotogrammetric process must be explored. It is possible to expand the ABM models to incorporate the effects of the different soil cover. All these studies will improve the understanding about the risk of flooding in Andean areas, which will result in better risk management in the region.

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