Enhancing Flood Hazard Estimation Methods on Alluvial Fans Using an Integrated Hydraulic, Geological and Geomorphological Approach

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Abstract. Due to the uncertainty concerning the location of flow paths on active alluvial fans, alluvial fan floods could be more dangerous than riverine floods. The United States Federal Emergency Management Agency (FEMA) used a simple stochastic model named FAN for this purpose, which has been practiced for many years. In the last decade, this model has been criticized as a consequence of development of more complex computer models. This study was conducted on three alluvial fans located in northeast and southeast of Iran using a combination of FAN model, the hydraulic portion of FLO-2D model and geomorphological information. Initial stages included three steps: a) identifying the alluvial fans' landforms, b) determining the active and inactive areas of alluvial fans, and c) delineating 100-year flood within these selected areas. This information was used as an input in the mentioned three approaches of: I) FLO-2D model, II) geomorphological method, and III) FAN model. Thereafter, the results of each model were obtained and Geographical Information System (GIS) layers were created and overlaid. Afterwards, using a scoring system, the results were evaluated and compared. The goal of this research was to introduce a simple, but effective solution to estimate the flood hazards. It was concluded that the integrated method proposed in this study has the superiority in projecting alluvial fan flood hazards with minimum required input data, simplicity and affordability, which are considered the primary goals of such comprehensive studies. These advantages are more highlighted in the underdeveloped and third world countries which may well lack the detailed data and financially cannot support such costly projects. Furthermore, such a highly cost effective method could be greatly advantageous and pragmatic for the developed countries.

1 Introduction

Alluvial fan floods are considered to be serious hazards, since the flooding that emerges from the apex of an alluvial fan, moves fiercely toward the downstream while carrying a large portion of substrate load and debris (King and Mifflin, 1991; Coe et al., 2003; Garfi et al., 2007; Merheb et al., 2016). Moreover, alluvial fans are made of larger size sediments which may have some degree of cohesive material that lies on a steep slope. These two characteristics

could lead to "avulsion", formation of new channels during flooding events, which causes major flow path displacement (Blair and McPherson, 2009). Estimation of flood hazards on alluvial fans has been a major dispute among hydrologists for many years (Gaume et al., 2009; Bedrossian et al., 2014; Nguyen et al., 2014; Vennari et al., 2016). In fact, due to "avulsion" the characteristics of alluvial fan flooding are more important than other flooding features, which could consequently increase the risk of damage (Calcaterra et al., 2000, 2003; Lancaster et al., 2012; Santangelo et al., 2012). As stated by National Research Council: "the area of deposition on an alluvial fan shifts with time, but the next episode of flooding is more likely to occur where the most recent deposits have been laid down, than where deposits of greatest antiquity occur" (National Research Council, 1996).

Utilizing the alluvial fan characteristics, the United States Federal Emergency Management Agency (FEMA) developed a method to assess the flood risk of alluvial fans. The FEMA guidelines allow a number of delineation methodologies that include geomorphic method, one and two-dimensional fixed bed hydraulic modelling, and composite methods that combine engineering and geologic approaches (Federal Emergency Management Agency, 2003). The first attempt to address the alluvial fan flood complexities was performed by Dawdy (1979), who developed a probability-based model. The model was based on a mathematical formulation that was developed after a series of catastrophic alluvial fan floods and debris flows in the 1970s. FEMA correctly recognized that riverine floodplain delineation techniques did not adequately depict the flood hazards on active alluvial fans, and adopted Dawdy's equations to better describe the flood risks associated with non-riverine processes such as avulsions, high rates of sediment transport, and net aggregation (Dawdy, 1979). FEMA applied this approach directly in a number of alluvial fan floodplain delineation studies in the 1980s, and thereafter, the FAN model was developed (Federal Emergency Management Agency and Federal Insurance Administration, 1990). FAN model is a DOS based software package that uses Dawdy's basic equations, as well as a modification proposed by DMA Consulting Engineers (1985), to predict flow depths and velocities on alluvial fans on a regular basis (French et al., 1993).

During the last decade, FAN model has been profoundly criticized by some researchers (House et al., 1991; Field and Pearthree, 1992; French, 1992; Pearthree et al., 1992; French et al., 1993; Fuller, 1990, 2013) since it does not consider the physical characteristics of alluvial fans. Despite of all the critics raised about this model, it still can be a useful tool to delineate alluvial fan flooding. In addition, it is a simple model to predict flood risk. According to this model, the areas subjected to alluvial fan flooding are assumed to have an equal width (Federal Emergency Management Agency and Federal Insurance Administration, 1990). This width is referred to as the contour width, since it is measured along a contour. However, the hydraulic models fill the sinks based on topographic maps, and depth and velocity are just computed as a point. Nevertheless, in order to interpret the risk of flood areas, hazard zones are required rather than simply hazard points (Gallien, 2016).

Alluvial fan flows are two-dimensional, therefore, the application of one dimensional flow hydraulic models on alluvial fans has the following limitations: I) difficulties and inaccuracies in determining flow direction on floodplains; II) lack of flood volumes in determining the flooding boundaries, and III) problem with the uncertain nature of flood discharge calculation (Volker et al., 2007; Yunsheng, 2009). Marchi et al. (2010) used an integrated approach to analyse the hydro-geomorphic processes and their interactions with torrent control works and applied it to a large alluvial fan in the southern Carnic Alps (north-eastern Italy). Their study encompassed field observations,

interpretation of aerial photographs, analysis of historical documents, and numerical modelling of debris flows (Marchi et al., 2010).

In addition, it has been found that geological and geomorphological data have great impacts on estimation of avulsion intensities (Fuller, 2012). Studies conducted on 100-year floods in alluvial fans using the mentioned methods, emphasize the fact that formulating a framework for the geological-geomorphological features of the area can profoundly improve our understanding about their role in flood risk assessment (House, 2005). In another study integrated geologic maps, geomorphic analysis and a two-dimensional hydrodynamic model (LISFLOOD) was used to assess flood hazards (Pelletier et al., 2005). In another study, a multi-criteria index to assess flood hazard areas in a regional scale was introduced (Kazakis et al., 2015). Accordingly, a flood hazard index (FHI) was proposed and a spatial analysis in geographic information system (GIS) environment was applied for the estimation of its value. Recently, a framework was presented for mapping potential flooding areas integrating GIS, fuzzy logic and clustering techniques, and multi-criteria evaluation methods (Papaioannou et al., 2015). To sum up, the geological maps could be a powerful tool in better analysing avulsion due to incorporating the effects of erosion and sedimentation. In fact, using geomorphological analysis can provide: I) a context for understanding the basic system processes, II) understanding the type of processes that has been occurred from the past up to present, and III) calibration or verification of hydraulic modelling results (Calcaterra et al., 2003; Garfi et al., 2007; Santo et al., 2015).

The goal of this study was to examine the applicability of overlaying three layers of land/ground susceptible to erosion, water erosion potential, and hydraulic flooding zones in alluvial fans with the least needed data. The Ferizy and Ardak alluvial fans in Khorassan Province and the Sarbaz fan in Sistan & Baloochestan Province, which are all located in arid regions in the eastern part of Iran, were considered for this study. In this paper, a new method is introduced and applied for each data layer and the results are discussed.

2 Methods and Materials

In this study, a simple flowchart was followed to achieve the final flood hazard map, which is illustrated in Fig. 1. The proposed model needs four input data in order to obtain a flood hazard map, which are Q_{100} hydrograph, topographic map, normalized difference vegetation index (NDVI) and field investigations.

Five steps have been followed to achieve this goal:

1. FAN model was established using the 100 year return period hydrograph and the average slope which was extracted from topographical maps.
2. FLO-2D model was executed by using the 100 year return period hydrograph and topographical maps.
3. Active and inactive areas were distinguished by considering topographical maps, NDVI and field investigations.
4. Thereafter, all the models, results and field investigations were georeferenced and overlapped in GIS as separated layers and each layer was appointed a score using a scoring system from zero to 1.5.
5. Finally, the score of layers was multiplied and afterwards the pixels with the highest value and pixels with zero score were considered to be the highest and the lowest hazard zones, respectively.

2.1 Input Data

2.1.1 Hydrograph (Q_{100})

Thirty-five years of hydrometric data was obtained from Water Authority Company for each area. Afterwards, the 100-year return period hydrographs (Q_{100}) was developed, based on collected data for all three fans in a spreadsheet. These hydrographs were used in FAN model and FLO-2D as input data. Figure 2 (a, b, and c) illustrates the Q_{100} hydrographs for the Ardak, Ferizy and Sarbaz fans, respectively.

2.1.2 Topographic Map

Georeferenced elevation maps were downloaded in Tiff files format from USGS (United States Geological Survey) website for all three fans by resolution of 50m×50m. Afterwards, using GIS tool, the average slope map was derived from elevation map and used as an input in FAN model.

Georeferenced elevation maps were used as FLO-2D model input; however, contour maps were the primary input of this model. The process of converting elevation maps to contour maps was performed in FLO-2D model, therefore, no extra calculations were needed. Figure 3 (a, b, and c) shows the elevation map for the Ardak, Ferizy and Sarbaz fans, respectively.

2.1.3 Normalized Difference Vegetation Index (NDVI)

To cover all three study areas, two Landsat 8 OLI Images (path/row: 159/35 and 156/42) on May 13 for the Ardak and Ferizy fans and May 24 for the Sarbaz fan were downloaded from the USGS website by spatial resolution of 30m×30m. These two images were clipped to alluvial fan borders.

To calculate NDVI, first the reflectance of bands 4 and 5 (red and infrared) were calculated based on Landsat 8 user handbook (Zanter, 2016) and then the following equation was applied on bands 4 and 5 reflectance (Li et al., 2013).

$$NDVI= ((\rho_{NIR}-\rho_{Red}))/((\rho_{NIR}+\rho_{Red})) \tag{1}$$

Where, ρ_{NIR} and ρ_{Red} are reflectance of near infrared band and reflectance of red band, respectively.

2.1.4 Field Investigations

Field trips to the Ardak and Ferizy fan (May 20th) and to the Sarbaz fan (May 25th, 2015), were carried out to assess some geomorphological features for delineation of the active and inactive areas. These information included slope, drainage patterns, topographic contour, superficial characteristics, desert pavement, desert varnish, colour and distinctive vegetation (Coe et al., 2003; Garfi et al., 2007; Elkhrachy, 2015; Vennari et al., 2016). This investigation was performed in order to find out active and inactive areas and validate the satellite images. The observations are presented in Table 1.

Landsat 8 aerial photographs was used to determine active or inactive areas, which were downloaded from the USGS website. The evaluation was done by using the surface colour and vegetation detection in photos. A dark surface colour indicated an inactive zone, while lighter surfaces represented more active areas (Lohani et al., 2006).

2.2 Models

2.2.1 FEMA's FAN Model

As stated before, the FEMA method uses Dawdy's theory to delineate alluvial fan flooding to develop the FAN model (Federal Emergency Management Agency and Federal Insurance Administration, 1990). Based on Dawdy's theory the flood channel occurs randomly in active alluvial fans. Therefore, each point in an active area of a fan has similar chance to become a new channel as other points; so each point has the tendency to undergo flood. Hence, the probability of flood incidence in this model can be determined as follows (for more information see FAN model manual):

$$P(H = 1) = \int_{q_0}^{\infty} P_{H|Q}(1, q) f_Q(q) dq \tag{2}$$

$$H = \begin{cases} 1 & \text{if the location is inundated} \\ 0 & \text{if the location is not inundated} \end{cases}$$

Where Q is a random variable denoting the magnitude of the flood, $P_{H|Q}(1,q)$ is the probability that a location will be inundated, given that a flood of magnitude q is occurring and f_Q is Probability Density Function (PDF) defining the likelihood that a flood of a magnitude between q and q+dq will occur in any given year.

Based on the assumptions of this model all areas of the alluvial fan could be subjected to flooding and there is a fixed relation between flooding depth and discharge (Federal Emergency Management Agency and Federal Insurance Administration, 1990; Federal Emergency Management Agency, 2003). The flood hazard areas on an alluvial fan are identified as Zone AO. An AO zone is defined as the flood insurance rate zone that corresponds to the areas of l00-yr shallow flooding (usually sheet flow on sloping terrains), where average depths are between 0.3048 m and 0.9144 m. The flood hazard area on an alluvial fan is subdivided into separate AO zones with similar flooding depths (water depth plus velocity head) and velocities (Zhao and Mays, 1996). Figure 5 is an example of AO zones according to depth and velocity (Federal Emergency Management Agency and Federal Insurance Administration, 1990).

2.2.2 FLO-2D Model

FLO-2D is a two dimensional flood routing hydraulic model which is commonly used by civil environmental engineers to delineate flood hazard maps, implement floodplain zoning, and design flood mitigation schemes (Yunsheng, 2009; Mollaei et al., 2016a). In this model the full dynamic wave equation and central finite-difference routing scheme with eight potential flow directions are used to predict the progression of a flood hydrograph over a system of square grid elements (O'Brien and Gonzalez-Ramirez, 2011). This model is characterized by some substantial advantages (Fuller, 2010):

I) Runoff can flow anywhere along the dominant boundary, not only at the concentration point;

II) Peak discharge can be generated anywhere within the model domain, not just at the concentration route;

III) In adjacent alluvial fans, the flow can be easily modelled along unconfined boundaries;

IV) Watershed parameters were distributed over each small grid cell rather than being lumped over large sub-basins, and,

V) There is no need to estimate hydrologic routing parameters or average the hydraulic routing cross sections, since routed hydrographs are inherited in the model.

The FLO-2D-based model revealed that floods are not transferred via a single channel at fan evaluation sites and flow path locations could be predicted if floods have minimal sediment transport and relatively a constant topography (Fuller, 2010).

This model is sensitive to grid size and topographical data. To increase the accuracy of the model, small size grids and topographical data with minimum distance between contour lines should be used (Fuller, 2012). In this study, FLO-2D model was used only as a hydraulic model; therefore, a precision of 30m by 30m grid size and 50m by 50m topographical data were chosen, while the values of Manning coefficients were determined according to the land use information.

2.2.3 Geomorphological Analysis

Geomorphological features for delineation of active and inactive areas include: slope, drainage patterns, topographic maps, superficial characteristics, desert pavement and varnish, colour and distinctive vegetation (Field and Pearthree, 1992; Coe et al., 2003; House, 2005; Garfi et al., 2007; Lancaster et al., 2012; Santangelo et al., 2012; Fuller, 2013). For this purpose, in addition to utilizing Arial photographs, a field trip was performed to inspect and distinguish the active and inactive areas of the three alluvial fans as suggested by FEMA (Federal Emergency Management Agency, 2003). This was performed by using the surface colour and vegetation detected in photos. A dark surface colour is an indication of an inactive zone, while lighter surfaces represent areas that are more active. Figures 6a, 6b and 6c illustrate the aerial images of the Ardak, Ferizy and Sarbaz alluvial fans, respectively. The density of natural vegetation provides useful insights about inactiveness of an area. For instance, areas with annual plants could be considered as an active area, while, areas with perennial plants were considered as inactive. In addition, observation of human activities or weathering footprints (desert pavement, desert varnish and limestone cracks or grooves) can provide useful information about the extension of inactiveness of an area (Garfi et al., 2007). Finally, distributary, braided and branching drainage patterns are characteristics of active areas, whereas tributary patterns are an indicator of inactive areas. For this purpose, the 2015 Arial images of the three alluvial fans were downloaded from the USGS website.

2.3 Overlaying the GIS Layers

Hazardous zones in FLO-2D and FAN models and geomorphological characteristics studies were defined based on their depths, velocities and areas of activeness. These criteria are presented in Table 2. Note that FLO-2D model classified inundated areas as hazardous zones based on criteria presented in Table 2. This model assumes the rest of the areas as being out of the flooding hazard.

2.4 The study Area

This study was performed on three separated alluvial fans (Ferizy, Ardak and Sarbaz) in Iran. The Ferizy fan is located on the northern piedmont slopes of the Binalood Mountains in Khorasan province. Currently, it is under development

by agricultural, residential and also industrial projects. Chenaran industrial area is situated right below the hydrographic apex (Mollaei et al., 2016b).

The Ardak fan is located on the southern piedmont slopes of the Hezarmasjed Mountains, in the Khorasan province. This alluvial fan is a result of the Ardak river aggradations, and has been subjected to extensive agricultural

5   development due to its fertile soil, which was also followed by residential developments (Mollaei et al., 2016a).

The Sarbaz fan is located on the southern piedmont of the Sistan Mountains in Sistan & Baloochestan province (south-eastern Iran). Due to its arid climate, this fan suffers from low average precipitations, high temperatures, low humidity, poor vegetation index, high aggradations and high volume of runoff and wind erosion. Sarbaz fan has been formed as a consequence of Sarbaz river aggradations, and unlike Ardak and Ferizy fans, it has not gone under much

10   development. Historic data indicate occurrence of heavy floods and serious destructions in this area, which has been a consequence of flash floods. In the last last 60 years over 300 floods occurred in Khorasan, while only 60 floods were recorded in Sistan & Baloochestan province. According to historic data Khorasan province has had the highest rank in number of flood occurrence whereas Sistan and Baloochestan had the fifth ranking, resulting in 19.3 and 33.8 million dollars damage to each province, respectively (Khorsandi et al., 2016).

15   **3 Results and Conclusions**

3.1 FAN Model Results

FAN model output was a text file, which was interpreted in ArcGIS as a shape file for each fan. FAN model results are illustrated in Fig. 7 (a, b, and c) for the Ferizy, Ardak and Sarbaz fans, respectively. The results are shown in different colours, which correspond to different depths (m) and velocities (m.s^{-1}), as explained in Table 3.

20   **3.2 FLO-2D Model Results**

FLO-2D model outputs were a shape file with spatial resolution of 30m. This model produced three different results of depth (m), velocity (m.s^{-1}) and hazard map (low, medium and high). Its criteria are also explained in Table 3. Figure 8 (a, b, and c) illustrates the depth results of FLO-2D model for the Ferizy, Ardak and Sarbaz fans, respectively. Also Fig. 9 (a, b, and c) illustrates the velocity results of FLO-2D model for the mentioned fans.

25   **3.3 Geomorphological Analysis Results**

A comparison of the geomorphological characteristics of the three fans showed that while Ardak fan had the greatest area, slope and discharge, the Ferizy fan had the lowest discharge (Table 3). In Table 4, a comparison of the three fans with regard to their effective characteristics on flood hazards is presented.

As it can be seen from Table 4, the Sarbaz fan is characterized by high velocity, low channel stability and low

30   developments. The Ardak fan has steep slopes, high peak discharge and large drainage area. The Ferizy fan does not have any specific characteristics as compared to the Sarbaz and Ardak fans, except for the low channel stability and lower flood hazards. The geomorphic map of the Ardak fan shows that with the exception of its main channel, other parts of this alluvial fan are developed by agricultural and residential activities. Urbanization of any part of the alluvial fan would create a resistance to abrupt changes of flow direction from its main channel, while the agricultural lands,

especially those under annual crops, would intensify this phenomenon even on the inactive areas of the fan. Obviously, orchards or woodlands are less susceptible to this event as compared to farmlands.

3.4 Integrated Results

By integrating the results of these three approaches and using the scoring system, each fan was classified under four categories of flood hazard: very high, high, medium, low and very low. Figure 9 (a, b and c) shows the final flood hazard map for Ferizy, Ardak and Sarbaz fans, respectively.

As shown in Fig. 10 (a, b and c) the flood hazard area, apart from their distance from apex of the fan, is also defined based on their distance from riverbanks. In other words, the areas in which the river channels are located or previously used to be flood channels, are categorized as high hazardous zones.

3.5 Conclusions

In this paper, a simple but effective solution to estimate flood hazard is proposed. The presented approach suggests a combination of FAN model, geomorphological approach and a simple portion of the hydraulic model of FLO-2D.

The FAN model estimates depth and velocity of a flood and requires low input data. However, its results are not accurate to locate the occurrence of depth and velocity of flood in alluvial fans. On the other hand, FLO-2D model produces accurate depth and velocity results, but, at the same time, it requires too many detailed input data (spatially and temporally) which are costly, time consuming and cumbersome. It should be emphasized that in many third world and underdeveloped countries, it is impossible to obtain such detailed information due to lack of advanced technology. Besides, FLO-2D is considered as a complex model which requires a trained operator to work with. In geomorphological approach the flood depth and velocity are not determined, and only active and inactive areas could be recognized. The new approach presented in this paper, not only indicates the active and inactive areas, but also estimates accurately the flood depth and velocity, while using the minimum input data; further, it is simple to be applied. Table 5 summarizes all the pros and cons about of FLO-2D, FAN model, the geomorphological approach, and the suggested integrated model.

As illustrated in table 5, it can be concluded that the integrated method proposed in this study has the superiority in projecting alluvial fan flood hazards with minimum required input data, simplicity and affordability, which are considered the primary goals of such comprehensive studies. These advantages are more highlighted in the underdeveloped and third world countries which may well lack the detailed data and financially cannot support such costly projects. Furthermore, such a highly cost effective method could be greatly advantageous and pragmatic for the developed countries.

For further studies, it is suggested that HEC-RAS model be used along with FAN model and geomorphological approach and the pertaining results be validated by executing the FLO-2D model utilizing full input data as a reference model.

4 References

Bedrossian, T. L., Hayhurst, C. A., Short, W. R. and Lancaster, J. T.: Surficial Geologic Mapping and Associated GIS

Databases for Identification of Alluvial Fans, Environ. Eng. Geosci., 20(4), doi:10.2113/gseegeosci.20.4.335, 2014.

Blair, T. C. and McPherson, J. G.: Processes and Forms of Alluvial Fans, in Geomorphology of Desert Environmen, edited by A. . Parsons and A. . Abrahams, pp. 413–467, Springer., 2009.

Calcaterra, D., Parise, M., Palma, B. and Pelella, L.: Multiple debris flows in volcaniclastic materials mantling carbonate slopes, Debris-flow hazards Mitig. Mech. Predict. assessment. Balkema, Rotterdam, 99–107, 2000.

Calcaterra, D., Parise, M. and Palma, B.: Combining historical and geological data for the assessment of the landslide hazard: a case study from Campania, Italy, Nat. Hazards Earth Syst. Sci., 3(1/2), 3–16, 2003.

Coe, J. A., Godt, J. W., Parise, M. and Moscariello, A.: Estimating debris-flow probability using fan stratigraphy, historic records, and drainage-basin morphology, Interstate 70 highway corridor, central Colorado, USA, in Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment, edited by: Rickenmann, D. and Cheng, Ch., Proceedings 3rd International DFHM Conference, Davos, Switzerland, pp. 207–217., 2003.

Dawdy, D.: Flood Frequency Estimates on Alluvial Fans, J. Hydraul. Div., 105(11), 1407–1413, 1979.

Elkhrachy, I.: Flash Flood Hazard Mapping Using Satellite Images and GIS Tools: A case study of Najran City, Kingdom of Saudi Arabia (KSA), Egypt. J. Remote Sens. Sp. Sci., 18(2), 261–278, doi:10.1016/j.ejrs.2015.06.007, 2015.

Federal Emergency Management Agency: Guidelines and Specifications for Flood Hazard Mapping Partners, Vol. 1 Flood Stud. Mapp., (April), 1–26 [online] Available from: www.fema.gov/fhm/dl_cgs.shtm, 2003.

Federal Emergency Management Agency and Federal Insurance Administration: An Alluvial FAN Flooding Computer Program- User Manual., 1990.

Field, J. J. and Pearthree, P. A.: Geologic Mapping of Flood Hazards' in Arizona : An Example From the White Tank Mountains Area , Maricopa County, Arizona Geological Survey., 1992.

French, R. H.: Preferred Directions of Flow on Alluvial Fans, J. Hydraul. Eng., 118(7), 1002–1013, doi:10.1061/(ASCE)0733-9429(1992)118:7(1002), 1992.

French, R. H., Fuller, J. E. and Waters, S.: Alluvial fan: Proposed New Process-Oriented Definitions for Arid Southwest, J. Water Resour. Plan. Manag., 119(5), 588–598, 1993.

Fuller, J.: Gaps in Fema Guidance for Delineating Flood Hazards on Active Alluvial Fans, J. Flood Eng., 4(1), 29–38, 2013.

Fuller, J. E.: Misapplication of the FEMA Alluvial Fan Model: A Case History, Hydraul. Arid Lands, 367–377, 1990.

Fuller, J. E.: Floodplain Delineation Study for Richland Ranchettes., 2010.

Fuller, J. E.: Theoretical And Practical Deficiencies In The Fema Fan Methodology., 2012.

Gallien, T. W.: Validated coastal flood modeling at Imperial Beach, California: Comparing total water level, empirical and numerical overtopping methodologies, Coast. Eng., 111, 95–104, doi:10.1016/j.coastaleng.2016.01.014, 2016.

Garfi, G., Bruno, D. E., Calcaterra, D. and Parise, M.: Fan morphodynamics and slope instability in the Mucone River basin (Sila Massif, southern Italy): significance of weathering and role of land use changes, Catena, 69(2), 181–196, 2007.

Gaume, E., Bain, V., Bernardara, P., Newinger, O., Barbuc, M., Bateman, A., Blaškovičová, L., Blöschl, G., Borga, M. and Dumitrescu, A.: A compilation of data on European flash floods, J. Hydrol., 367(1), 70–78, 2009.

House, P. K.: Using geology to improve flood hazard management on alluvial fans - An example from Laughlin, Nevada, J. Am. Water Resour. Assoc., 41(6), 1431–1447, doi:10.1111/j.1752-1688.2005.tb03810.x, 2005.

House, P. K., Pearthree, P. A. and Vincent, K. R.: Flow patterns, flow hydraulics, and flood-hazard implications of a recent extreme alluvial-fan flood in southern Arizona, Geol. Soc. Am. Abstr. with Programs, 23(5), A121, 1991.

5   Kazakis, N., Kougias, I. and Patsialis, T.: Assessment of flood hazard areas at a regional scale using an index-based approach and Analytical Hierarchy Process: Application in Rhodope-Evros region, Greece, Sci. Total Environ., 538, 555–563, doi:10.1016/j.scitotenv.2015.08.055, 2015.

Khorsandi, H., Faghiri, G. and Kalantar, A.: Investigation of Flood Damage, Tehran., 2016.

King, S. G. and Mifflin, E. R.: Alluvial Fan Flooding, in Inspiration–come to the headwaters: Proceedings of the
10   Fifteenth Annual Conference of the Association of State Floodplain Managers, p. 243, Natural Hazards Research and Applications Information Center, University of Colorado, Denver, Colorado., 1991.

Lancaster, J. T., Spittler, T. E. and Short, W. R.: Using Digital Geologic Maps to Assess Alluvial-Fan Flood Hazards, Sacramento, California., 2012.

Li, P., Jiang, L. and Feng, Z.: Cross-comparison of vegetation indices derived from landsat-7 enhanced thematic
15   mapper plus (ETM+) and landsat-8 operational land imager (OLI) sensors, Remote Sens., 6(1), 310–329, doi:10.3390/rs6010310, 2013.

Lohani, B., Mason, D. C., Scott, T. R. and Sreenivas, B.: Extraction of tidal channel networks from aerial photographs alone and combined with laser altimetry, Int. J. Remote Sens., 27(1), 5–25, doi:10.1080/01431160500206692, 2006.

Marchi, L., Cavalli, M. and Agostino, V. D.: Hydrogeomorphic processes and torrent control works on a large alluvial
20   fan in the eastern Italian Alps, Nat. Hazards Earth Syst. Sci., 10, 547–558, 2010.

Merheb, M., Moussa, R., Abdallah, C., Colin, F., Perrin, C. and Baghdadi, N.: Hydrological response characteristics of Mediterranean catchments at different time scales: a meta-analysis, Hydrol. Sci. J., 61(14), 2520–2539, 2016.

Mollaei, Z., Madani, H., Moghimzadeh, H., Davary, K. and Faridani, F.: Predicting Avulsion Potential On Alluvial Fans Using FLO-2D Model- A Case Study, in 9th WORLD CONGRESS OF EWRA "Water Resources Management
25   in a Changing World: Challenges and Opportunities," p. 12, EWRA, Istanbul, Turkey., 2016a.

Mollaei, Z., Madani, H., Faridhosseini, A. and Davary, K.: Prediction Of Avulsion Phenomenon On Alluvial Fans Using Flo-2d Hydraulic Model, Iran Water Resour. Res., 11(34), 172–181, 2016b.

National Research Council: Alluvial Fan Flooding, National Academies Press, Washington, D.C., 1996.

Nguyen, C. C., Gaume, E. and Payrastre, O.: Regional flood frequency analyses involving extraordinary flood events
30   at ungauged sites: further developments and validations, J. Hydrol., 508, 385–396, 2014.

O'Brien, K. and Gonzalez-Ramirez, N.: Pocket Guide Basic FLO-2D Model., 2011.

Papaioannou, G., Vasiliades, L. and Loukas, A.: Multi-Criteria Analysis Framework for Potential Flood Prone Areas Mapping, Water Resour. Manag., 29(2), 399–418, doi:10.1007/s11269-014-0817-6, 2015.

Pearthree, P. A., Demsey, K. A., Onken, J., Vincent, K. R. and House, P. K.: Geomorpidc Assessment of Flood-Prone
35   Areas on the Southern Piedmont of the Tortolita Mountains, Pilvia County, Arizona, Tucson, Arizona., 1992.

Pelletier, J., Mayer, L., Pearthree, P., House, P., Demsey, K., Klawon, J. and Vincent, K.: An integrated approach to flood hazard assessment on alluvial fans using numerical modeling, field mapping, and remote sensing, Geol. Soc.

Am. Bull., 117(9–10), 1167–1180, doi:10.1130/B255440.1, 2005.

Santangelo, N., Daunis- i- Estadella, J., Di Crescenzo, G., Di Donato, V., Faillace, P. I., Martín- Fernández, J. A., Romano, P., Santo, A. and Scorpio, V.: Topographic predictors of susceptibility to alluvial fan flooding, Southern Apennines, Earth Surf. Process. Landforms, 37(8), 803–817, 2012.

Santo, A., Santangelo, N., Di Crescenzo, G., Scorpio, V., De Falco, M. and Chirico, G. B.: Flash flood occurrence and magnitude assessment in an alluvial fan context: the October 2011 event in the Southern Apennines, Nat. Hazards, 78(1), 417–442, 2015.

Vennari, C., Parise, M., Santangelo, N. and Santo, A.: A database on flash flood events in Campania, southern Italy, with an evaluation of their spatial and temporal distribution, Nat. Hazards Earth Syst. Sci., 16(12), 2485, 2016.

Volker, H. X., Wasklewicz, T. A. and Ellis, M. A.: A topographic fingerprint to distinguish alluvial fan formative processes, Geomorphology, 88(1–2), 34–45, doi:10.1016/j.geomorph.2006.10.008, 2007.

Yunsheng, S.: Alluvial Fan Floodplain Mapping East Ojai FLO-2D Floodplain Study., 2009.

Zanter, K.: LANDSAT 8 (L8) DATA USERS HANDBOOK., 2016.

Zhao, B. and Mays, L. W.: ALLUVIAL-FAN METHOD, J. Hydraul. Eng., 122(June), 325–332, 1996.

Table 1. Observation conclusions from field investigations.

	Fan	*Location*	*Latitude*	*Longitude*
1	Ferizy	Apex	36.54889	59.09964
2	Ferizy	Jam Ab	36.57275	59.10208
3	Ferizy	Industrial Area of Chenaran	36.57275	59.10208
4	Ferizy	Farms	36.60528	59.10227
5	Ferizy	Ring road	36.61469	59.11415
6	Ardak	Apex	36.74175	59.39865
7	Ardak	Farms	36.73803	59.39892
8	Ardak	Rural area	36.73184	59.39389
9	Sarbaz	Apex	26.20120	61.73763
10	Sarbaz	Inactive area	26.18299	61.74807
11	Sarbaz	Suldan village	26.15361	61.78557

Table 2. Flood criteria to delineate hazard map.

Hazardous	Velocity (m.s^{-1})		Depth (m)		Geomorphological Characteristics
	FAN Model	FLO-2D Model	FAN Model	FLO-2D Model	
Very High	V>2.0	V>1.5	D>1.0	D>1.0	Active
High	1.5-2	1.2-1.5	0.5-1.0	1.2-1.5	Active
Medium	1.3-1.5	1.0-1.2	0.3-0.5	1.0-1.2	Active/Inactive
Low	1.0-1.3	0.5-1.0	0.15-0.3	0.5-1.0	Inactive
Very Low	V<1.0	0.0-0.5	D<0.15	0.0-0.5	Inactive

Table 3. The characteristics of three alluvial fans.

Characteristic	Ferizy	Ardak	Sarbaz
Watershed area (apex)(km^2)	283	497	72
Alluvial fan area (km^2)	155	436	70
Average Alluvial fan slope (%)	1.04	1.83	1.03
Average Elevation (m)	1192.7	1284.8	267.5
Average Temperature (°C)	17	17	32
Average Precipitation (mm)	167	166	96
Q_{100} at apex (m^3/s)	80.8	221.4	108
Fan profile shape	Concave	Concave	Concave
Drainage Pattern	Channelized Tributary	Channelized Tributary	Channelized Distributary

Table 4. Characteristics of three fans as regard to their flood hazards (velocity, V, and depth, D, are in m.s^{-1} and m, respectively).

	Ardak	Ferizy	Sarbaz
NDVI	0.115 to 0.71	-0.157 to 0.768	-0.161 to 0.427
FLO-2D $\{$	$0 < V < 1.5$ $0 < D < 1.5$	$0 < V < 1.5$ $0 < D < 1.5$	$0 < V < 1.5$ $0 < D < 1.5$
FAN $\{$	$0 < V < 2$ $0.15 < D < 1$	$0 < V < 2$ $0.15 < D < 1$	$0 < V < 2$ $0.15 < D < 1$
Active / Inactive	0 to 1	0 to 1	0 to 1
Final Score	0 to 3.195	0 to 3.456	0 to 1.921

Table 5. Pros and Cons of three models and the suggested integrated model

Characteristics Models	FAN	FLO-2D	Geomorphological Approach	Suggested Integrated Model
Depth	✓	✓	-	✓
Velocity	✓	✓	-	✓
Active/Inactive	-	-	✓	✓
Fine Resolution Results	-	✓	-	✓
Required Input Data	Low	High	Low	Low
Degree of Simplicity	Simple	Complex	Relatively complex	Simple
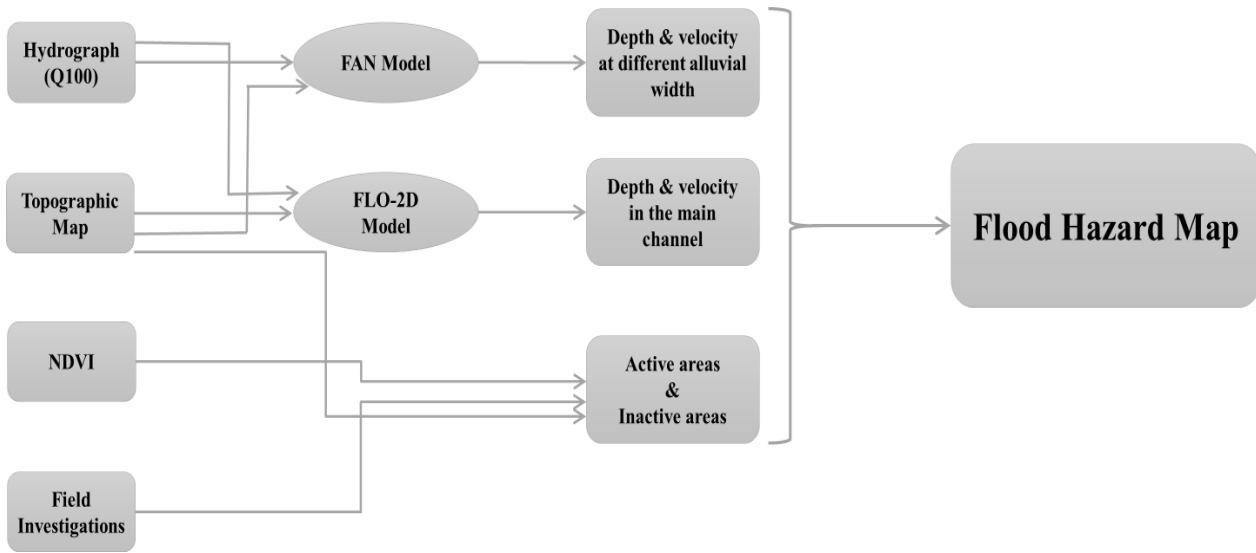
Figure 1. The proposed flow chart to achieve flood hazard map.
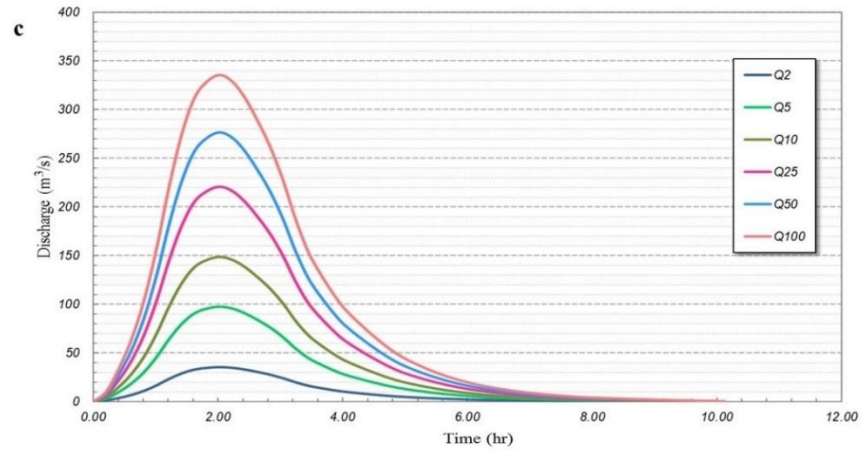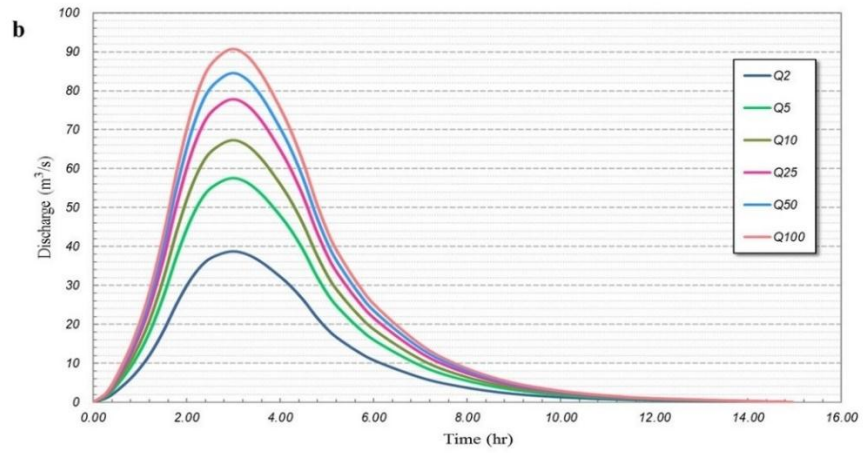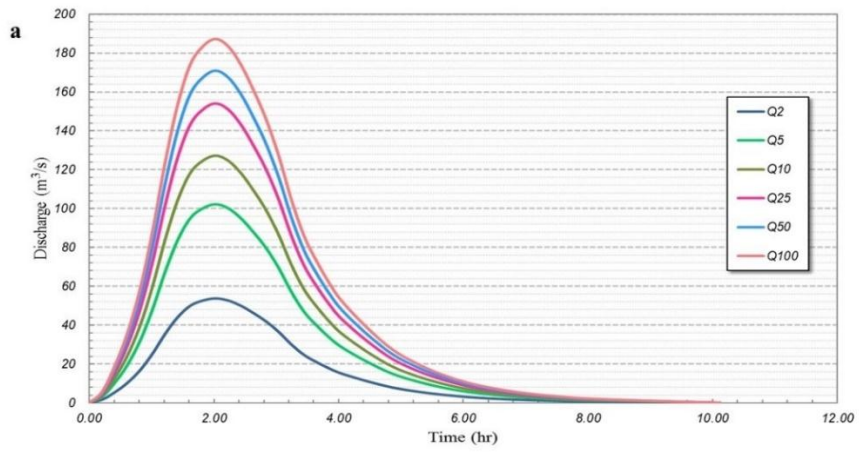
Figure 2. Q₁₀₀ for the: a) Ardak, b) Ferizy, and c) Sarbaz fans.
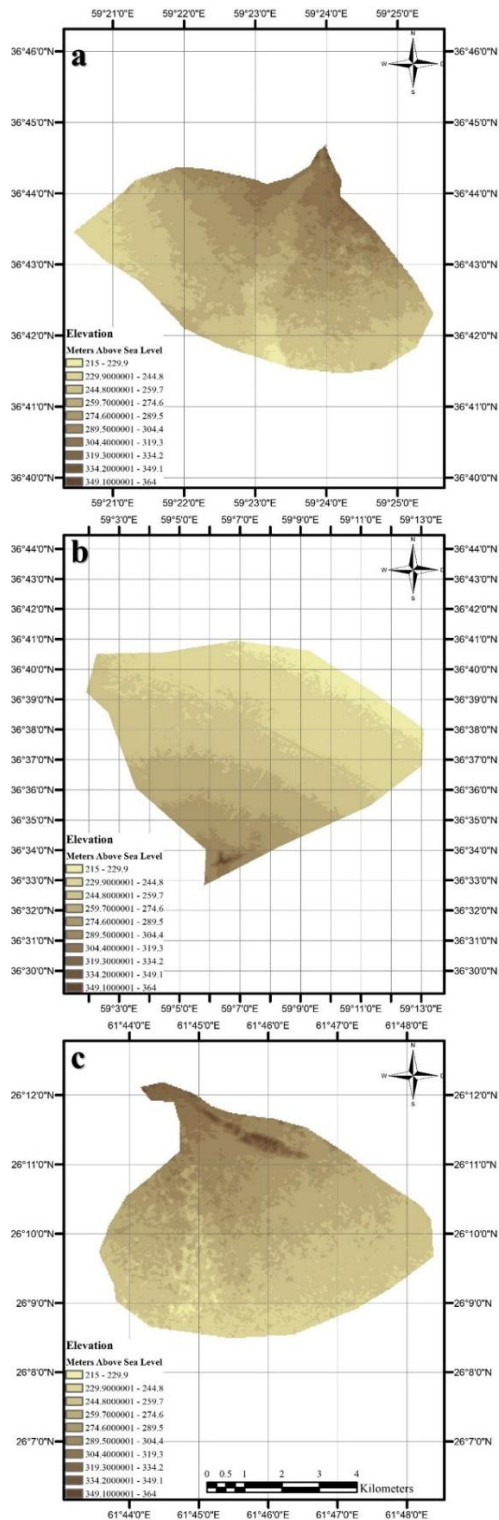
Figure 3. Land elevation from Aster dataset for the: a) Ardak, b) Ferizy, and c) Sarbaz fans.
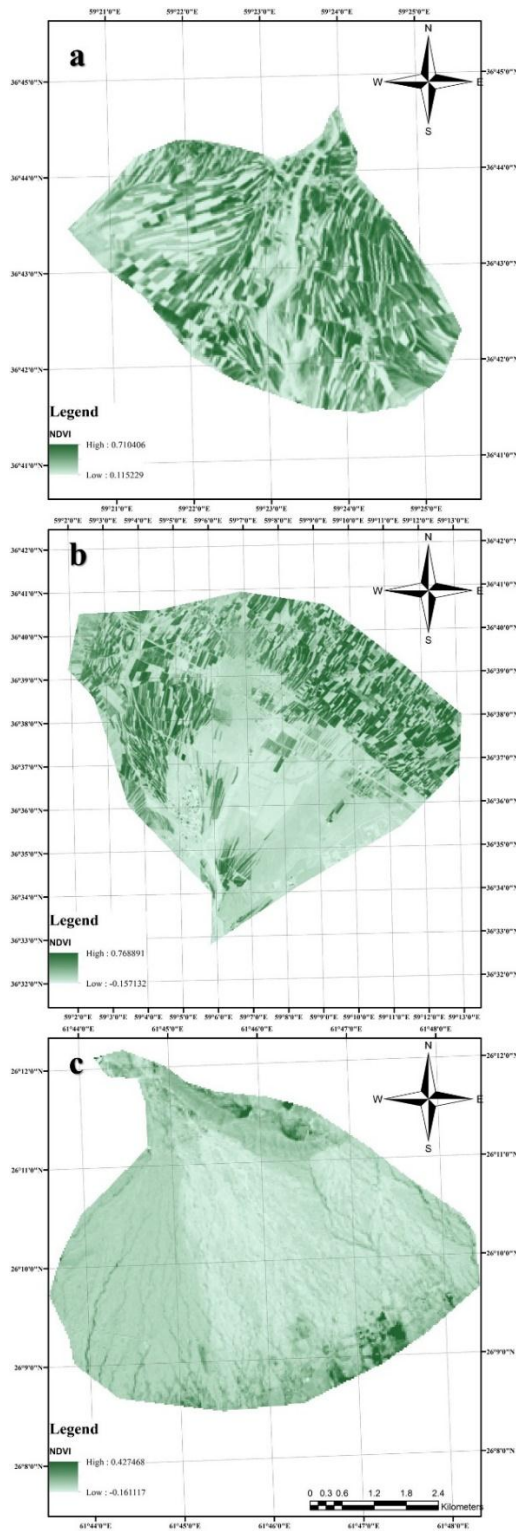
Figure 4. Calculated NDVI for the: a) Ardak, b) Ferizy, and c) Sarbaz fans.
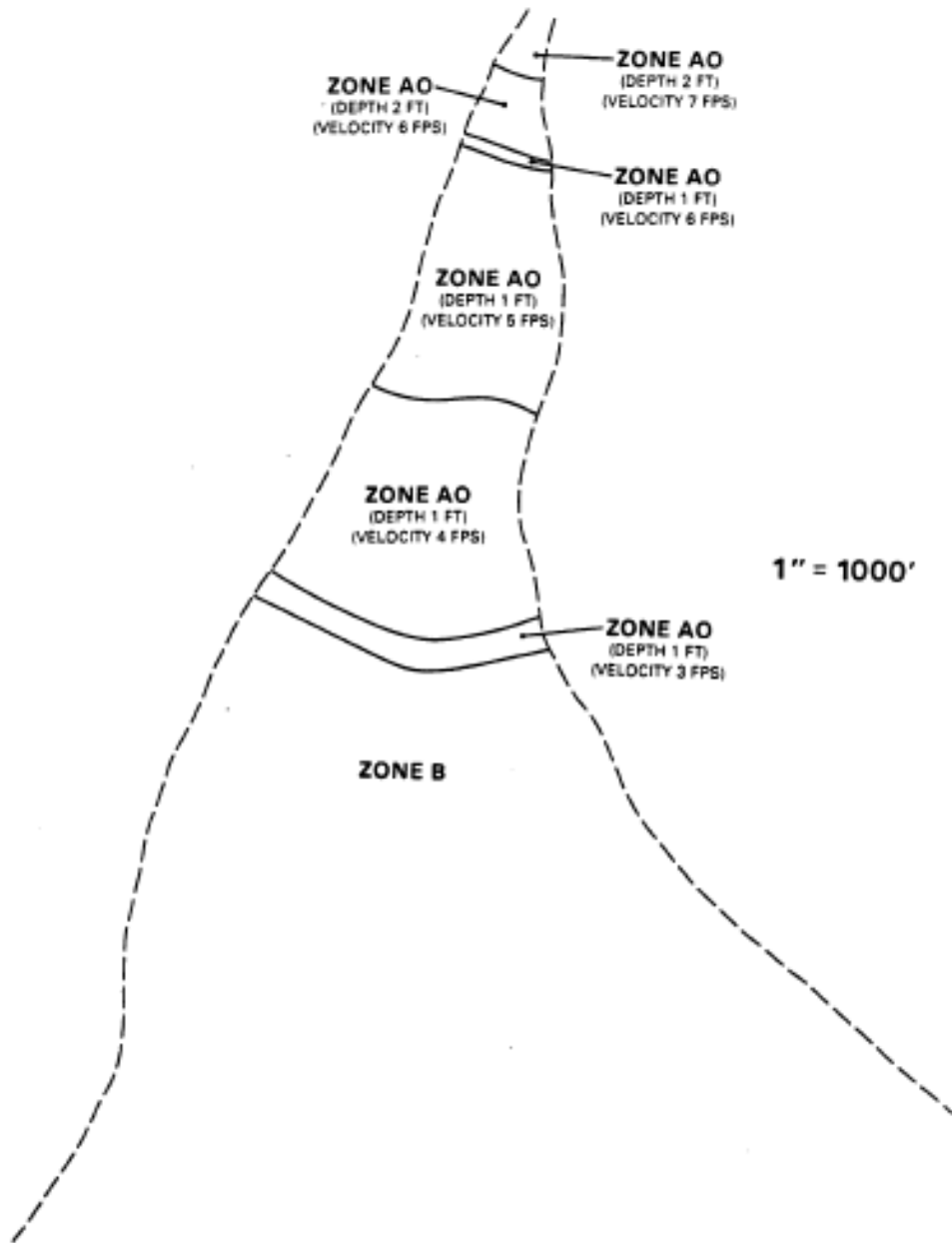
Figure 5. Examples of AO zones according to depth and velocity in FAN model (Federal Emergency Management Agency and Federal Insurance Administration, 1990)**.**
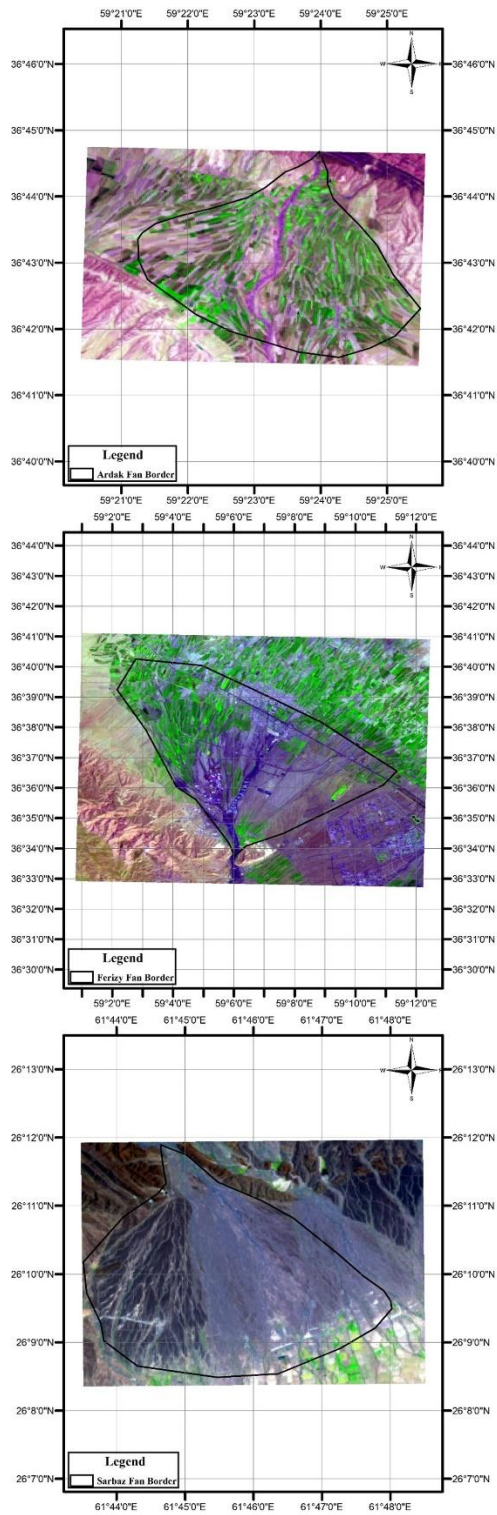
Figure 6. Arial images of the a) Ardak, b) Ferizy, and c) Sarbaz fans.
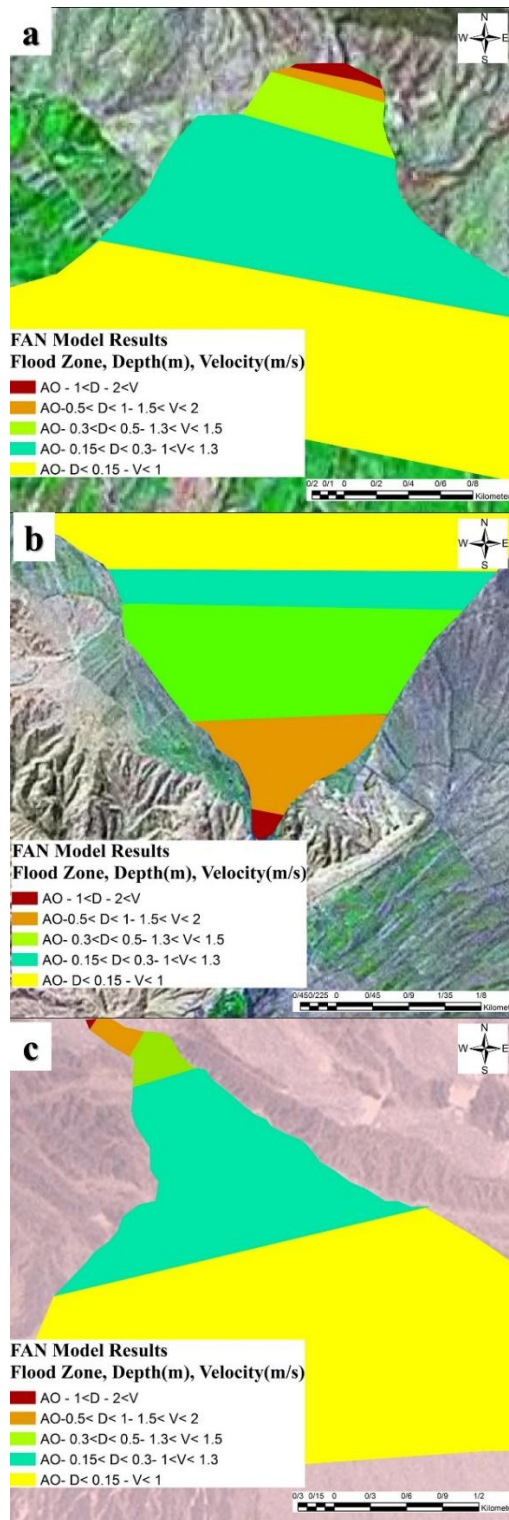
Figure 7. Flood depth and velocity results of FAN model for the: A) Ardak, B) Ferizy, and C) Sarbaz fans.
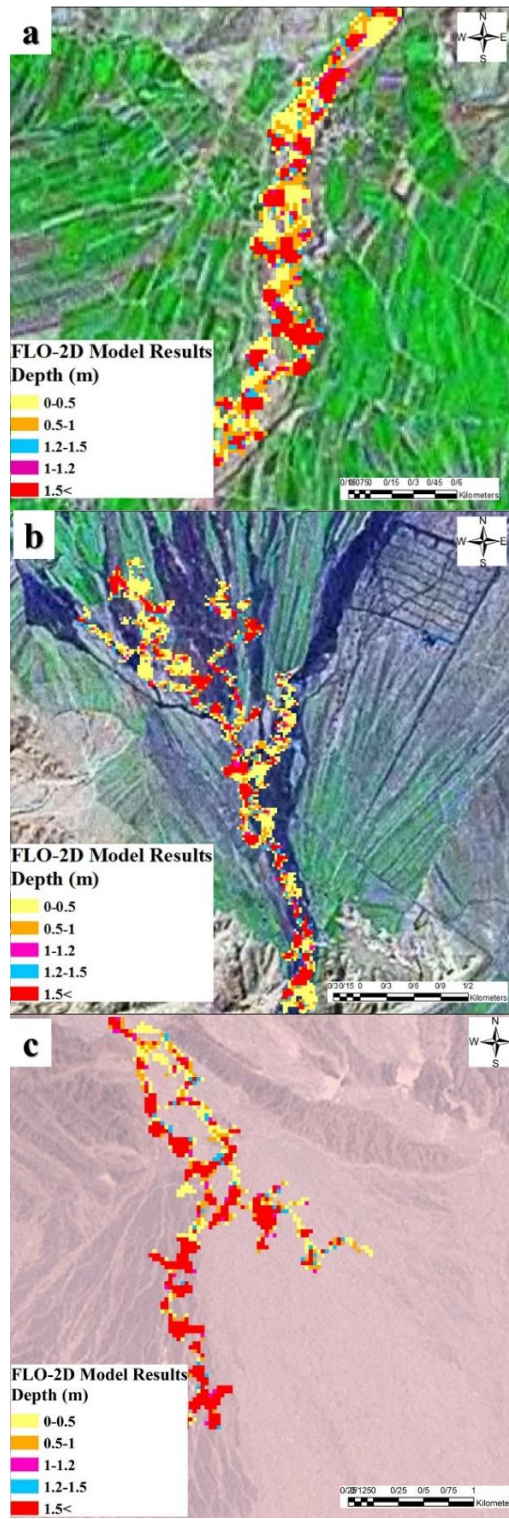
Figure 8. Flood depths results of FLO-2D model for the: A) Ferizy, B) Ardak and, C) Sarbaz fans.
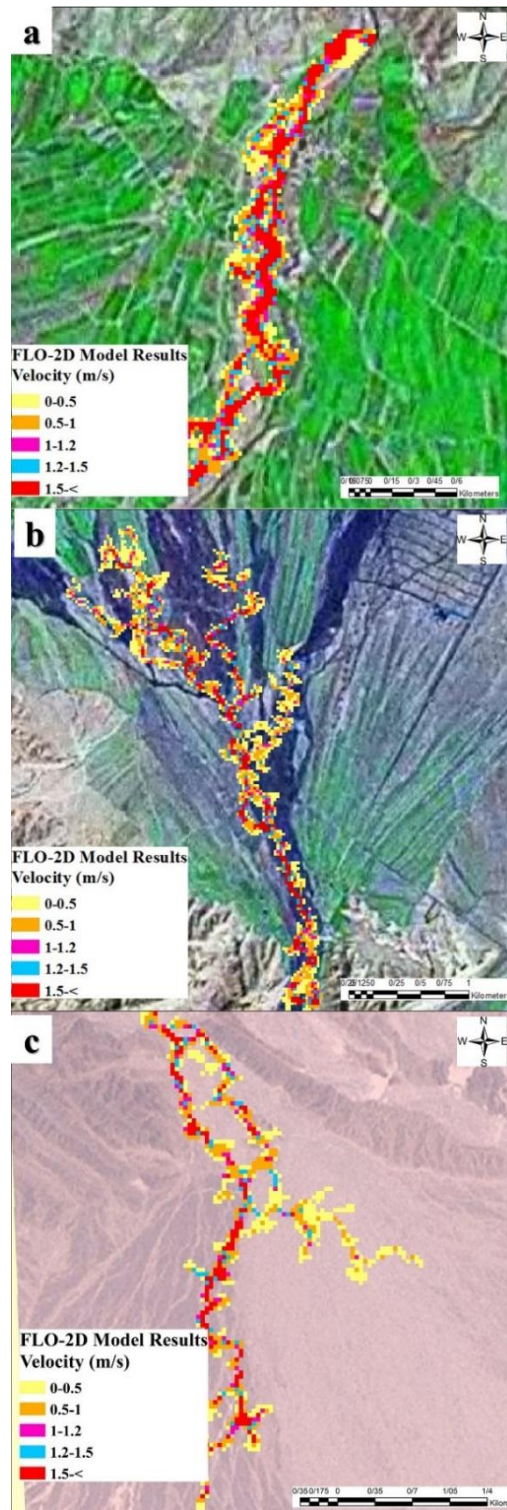
Figure 9. Flood velocities results of FLO-2D model for the: A) Ferizy, B) Ardak and, C) Sarbaz fans.
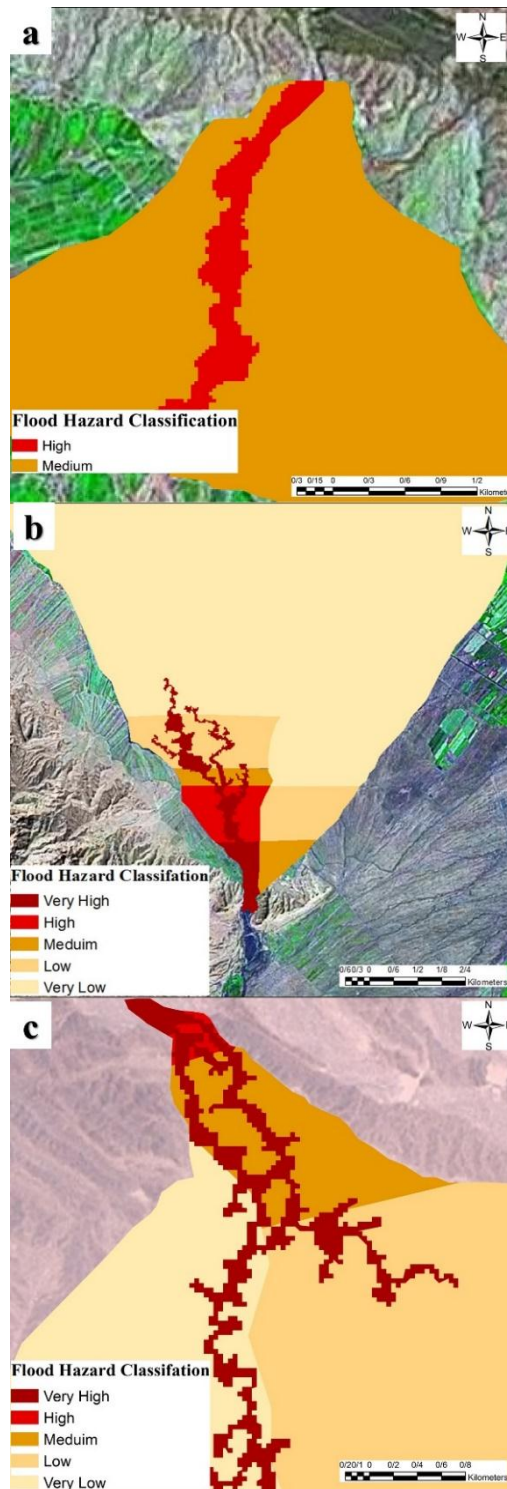
Figure 10. The final integrated results of FAN model, FLO-2D model and the geomorphological approach for the: A) Ferizy, B) Ardak and, C) Sarbaz fans.