Using Self-Organizing Maps for Alluvial Fan Classification

Abdollah Seif¹, Marzieh Mokarram¹*, Dinesh Sathyamoorthy²

¹Department of Geographic Sciences and Planning, University of Isfahan, Iran
²Science & Technology Research Institute for Defence (STRIDE), Ministry of Defence, Malaysia

Abstract. Morphometry research used geographic information system (GIS) to explore alluvial fan morphology for determination of fans location and fast and accurate analysis. The aim of this study is to classify alluvial fans formed by high-gradient braided streams and torrents that discharge into the Oshtrankook altitudes in the Lorestan province, Iran. The morphology of the fans and their watershed is quantitatively described through estimated morphometric parameters. For relationships between geomorphological features of the fans and their drainage basins, self-organizing maps (SOM) were used. In SOM, according to both qualitative data and morphometric variables, the clustering tendency of alluvial fans was investigated using 15 alluvial fans parameters. The results of the analysis showed that several morphologically different fan types were recognized based on their geomorphological characteristics in the study area. A strong positive relationship was found between the drainage basin area and size of the fan with a simple power function. In addition, the relationship between fan slope and drainage area was found to be negative and moderately strong with a simple power function.

Keywords: Alluvial fans; morphometry; self-organizing maps (SOM); component layers; power function.

1. INTRODUCTION

Alluvial fans are created on steep high power channels where reduced stream power and serve as a transitional environment between a degrading upland area and adjacent lowland (Harvey, 1997). The morphology of a fan resembles a cone segment with concave slopes that typically range from less than 25° at the apex to less than 1° at the toe (Mwasiagi, 2011). The analysis of the main controlling factors on past and present fan processes (debris flows and stream flows) is a major concern in order to distinguish between the two dominant sedimentary processes on alluvial fan formation and evolution (Vandine, 1996). Alluvial fans occur in any climatic environment, such as temperate mountain areas (Giles, 2010), humid temperate (Kochel, 1990) and humid tropical environments (Kesel and Spicer, 1985). Several studies have explored the relationship between the size of fans and their contributing basins to understand the mechanisms of fan construction (Church and Mark, 1980). Other studies on fan-basin morphometric focus on differentiation between debris flow and fluvial dominated fans (De Scally and Owens, 2004, Giles, 2010).

Alluvial fan morphometry has been studied since the early 1960s, with a number well-researched relationships developed, such as a drainage basin area to alluvial fan area. Denny (1965) and Hooke (1968) have described classic alluvial fan form process variables using morphometry. More recent morphometry research conducted by Whipple and Dunne (1992) and Volker et al. (2007) used geography information system (GIS) to explore alluvial fan morphology for determination of fans location and fast and accurate analysis. Volker et al. (2007) investigated formative surface processes using morphometry to identify formative surface processes generated by alluvial fan flows. Fan morphometry typically evaluates a number of alluvial fan control variables to demonstrate the impact of each of these variables on fans. They used topographic maps, aerial photographs and derived equations, but were seldom paired up with a field analysis of landforms (Bobbins, 2011).

Self-organizing maps (SOM) (Kohonen, 1995) have been applied as a clustering and projection algorithm for high dimensional data. Modeling utilizing SOM has recently been applied to a wide variety of geomorphology fields. It was employed to cluster volcanic ash arising from different fragmentation mechanisms (Ersoya et al., 2007), assess sediment quality, and define mortality index on different sampling sites (Tsakovski et al., 2009).
addition, Ferentinou and Sakellariou (2005, 2007) applied SOM in order to rate slope stability controlling variables in natural slopes, while Ferentinou et al. (2010) used SOM to classify marine sediments. Karymbalis et al. (2011) also used SOM to investigate the clustering tendency of alluvial fans.

The aim of this study is to perform the classification of alluvial fans, located in the Oshtorankoo altitudes in the Lorestan province, Iran, according to their morphological features, using morphometry and SOM. The investigation will use 15 morphometric variables for each fan as described in Table 1.

Table 1: Morphometric parameters of the fan deltas and their corresponding drainage basins measured for this study (Karymbalis et al., 2007).

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Morphometric parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_b$</td>
<td>Drainage basin area</td>
</tr>
<tr>
<td>$P_b$</td>
<td>Perimeter of the drainage basin</td>
</tr>
<tr>
<td>$\sum L_c$</td>
<td>Total length of 20 m contour lines within the drainage basin</td>
</tr>
<tr>
<td>$C_b$</td>
<td>Basin crest</td>
</tr>
<tr>
<td>$R_b$</td>
<td>Basin relief</td>
</tr>
<tr>
<td>$L_c$</td>
<td>Total length of the channels within the drainage basin</td>
</tr>
<tr>
<td>$A_{pf}$</td>
<td>Fan apex</td>
</tr>
<tr>
<td>$D_b$</td>
<td>Drainage basin density</td>
</tr>
<tr>
<td>$S_b$</td>
<td>Drainage basin slope ($S_b = e \sum L_c/A_b$, where $e$ is the equidistance)</td>
</tr>
<tr>
<td>$Cir_b$</td>
<td>Drainage basin circularity ($Cir_b = 4\pi A_b/P_b^2$)</td>
</tr>
<tr>
<td>$M$</td>
<td>Melton’s ruggedness number ($M = R_b A_b^{0.5}$)</td>
</tr>
<tr>
<td>$L_f$</td>
<td>Fan length</td>
</tr>
<tr>
<td>$A_f$</td>
<td>Fan area</td>
</tr>
<tr>
<td>$S_f$</td>
<td>Fan slope</td>
</tr>
<tr>
<td>$P_f$</td>
<td>Fan concavity</td>
</tr>
</tbody>
</table>

2. MATERIALS AND METHODS

2.1. Study area

The study area is the Oshtorankoo altitudes in the Lorestan province, Iran. This area is located at 33° 9' to 33° 22' N and 49° 12' to 49° 23' E with an area of 3,260.62 km\(^2\) (Figure 1). The lowest and highest elevations in this area are 885 and 4,049 m respectively. Rainfall displays high inter-annual and seasonal variability, with the annual long-term precipitation of the study area being 425 mm.

This study is based on quantitative and qualitative data depicting the morphology and morphometry of fans and their catchments derived from fieldwork. In order to determine the role of the fluvial sediment supply for the evolution of the fan deltas, the correlation between geomorphological features of the drainage basins and features of their fan deltas was estimated.

Drainage networks were delineated from aerial photograph interpretation and topographic maps with a scale of 1:50,000. The same maps, with 20 m contour lines, were used for the measurement of the morphometric parameters of the drainage basins.

In the study area, there are several sub-basins, with each having an alluvial fan (Figure 2). Their respective measured morphometric parameters are shown in Table 2. Maximum, minimum and mean elevations were calculated for each drainage basin using zonal statistics with the mapped basins and filled DEM as inputs.
Fig. 1: Location of the study area.

Table 2: Morphometric parameters measured for the alluvial fans.

<table>
<thead>
<tr>
<th>Fan</th>
<th>$A_b$ (km$^2$)</th>
<th>$P_b$ (km)</th>
<th>$\Sigma L_c$ (km)</th>
<th>$C_b$</th>
<th>$R_b$</th>
<th>$L_c$ (km)</th>
<th>$A_{f}$</th>
<th>$P_{f}$</th>
<th>$S_{f}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>23.66</td>
<td>21.03</td>
<td>530.07</td>
<td>3006</td>
<td>1159</td>
<td>22.15</td>
<td>2006</td>
<td>0.94</td>
<td>0.45</td>
</tr>
<tr>
<td>2</td>
<td>43.61</td>
<td>27.09</td>
<td>1140.38</td>
<td>3509</td>
<td>1750</td>
<td>34.46</td>
<td>2509</td>
<td>0.79</td>
<td>0.52</td>
</tr>
<tr>
<td>3</td>
<td>32.90</td>
<td>23.46</td>
<td>601.72</td>
<td>2644</td>
<td>947</td>
<td>32.38</td>
<td>1644</td>
<td>0.98</td>
<td>0.37</td>
</tr>
<tr>
<td>4</td>
<td>6.09</td>
<td>10.64</td>
<td>113.97</td>
<td>2086</td>
<td>666</td>
<td>5.58</td>
<td>1086</td>
<td>0.92</td>
<td>0.37</td>
</tr>
<tr>
<td>5</td>
<td>20.26</td>
<td>19.50</td>
<td>389.26</td>
<td>2774</td>
<td>1310</td>
<td>18.37</td>
<td>1774</td>
<td>0.91</td>
<td>0.38</td>
</tr>
<tr>
<td>6</td>
<td>9.26</td>
<td>13.53</td>
<td>135.61</td>
<td>2362</td>
<td>718</td>
<td>12.05</td>
<td>1362</td>
<td>1.30</td>
<td>0.29</td>
</tr>
<tr>
<td>7</td>
<td>13.52</td>
<td>14.38</td>
<td>255.82</td>
<td>2893</td>
<td>1255</td>
<td>14.37</td>
<td>1893</td>
<td>1.06</td>
<td>0.38</td>
</tr>
<tr>
<td>8</td>
<td>18.74</td>
<td>18.90</td>
<td>374.16</td>
<td>2844</td>
<td>1522</td>
<td>19.42</td>
<td>1844</td>
<td>1.04</td>
<td>0.40</td>
</tr>
<tr>
<td>9</td>
<td>25.54</td>
<td>20.03</td>
<td>593.39</td>
<td>3200</td>
<td>1843</td>
<td>20.21</td>
<td>2200</td>
<td>0.79</td>
<td>0.46</td>
</tr>
</tbody>
</table>

2.2. SOM

Artificial neural networks (ANNs) are non-linear mapping structures based on the function of the human brain, and are powerful tools for modelling when the underlying data relationship is unknown. ANNs can identify and learn correlated patterns between input data sets and corresponding target values, after which can be used to predict the outcome of new independent input data. ANNs imitate the learning process of the human brain and complex data even if the data is imprecise and hence, are ideally suited for the modeling of alluvial fan data, which are known to be complex and often non-linear. ANNs have great capacity in predictive modeling, whereby all the parameters describing the unknown situation can be presented to the trained ANNs (Dhubkarya et al., 2010).

SOM are unsupervised ANNs formed from neurons located on a regular, usually two-dimensional regular planar array grid (Figure 3). It is based on unsupervised learning, which means that no human intervention is needed during the learning and little needs to be known about the characteristics of the input data. SOM offers a solution to use a number of visualizations linked together (Buza et al., 1991). When several
visualizations are linked together, scanning through them is very efficient because they are interpreted in a similar way. The U-matrix produced from SOM visualizes distances between neighboring map units and thus shows the cluster structure of the map. Samples within the same cluster will be the most similar according to the variables considered.

Fig. 2: The sub-basins in the study area.
Fig. 3: The structure of a SOM network: (a) Selection of a node and adaptation of neighboring nodes to the input data. The SOM grid can be (b) hexagonal or (c) rectangular. The black object indicates the node that was selected as the best match for the input pattern (Dykes, 2005).

3. RESULTS AND DISCUSSIONS

3.1. SOM

SOM was applied for the study area to describe the alluvial fan morphometry. The visualization in Figure 4 consists of 16 hexagonal grids, with the U-matrix in the upper left, along with the 15 component layers (one layer for each morphometric parameter examined in this study).

Fig. 4: SOM visualization through U-matrix (top left) and 15 component layers (one layer for each morphometric parameter examined).
Using Self-Organizing Maps for Alluvial Fan Classification

Based on the clusters for relationship between drainage basins and alluvial fans, it is found that:
(a) Drainage basin area $A_b$ is correlated with fan area $A_f$.
(b) Fan slope $S_f$ and drainage basin area $A_b$ are inversely correlated.

Analysis of each cluster is then carried out to extract the rules that best describe each cluster by comparison of the component layers. The rules to predict the generations of alluvial fans are extracted by mapping the clusters presented in Figure 4 using the input morphometric parameters (component layers) in Figure 5. Using the SOM method, the fans in the study area are divided into two groups (Figure 6). The characteristics of each group of fans are provided in the Table 3.

![Comparison of clusters](image)

**Fig. 5:** Different visualizations of the clusters obtained from the classification of the morphological variation through SOM: (a) Color code. (b) Principal component projection. (c) Label map with the names of the alluvial fans.

**Fig. 6:** The two groups of fans in the study area.

**Table 3:** Characteristics of each group of fans in the study area

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Group 1</th>
<th>Group 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan area $A_f (\text{km}^2)$</td>
<td>0.19</td>
<td>0.43</td>
</tr>
<tr>
<td>Fan concavity $P_f$</td>
<td>1.9</td>
<td>3</td>
</tr>
<tr>
<td>Fan length $L_f$</td>
<td>0.95</td>
<td>1.5</td>
</tr>
<tr>
<td>Fan slope $S_f$</td>
<td>0.36</td>
<td>0.33</td>
</tr>
</tbody>
</table>
3.2. Morphometric relationships

The correlations between the geomorphic features of the studied fans and drainage basins include relationships between drainage basin area and fan area, drainage basin area and fan slope.

3.2.1. Drainage Area $A_b$ and Fan Area $A_f$

Bull (1962) was the first to describe quantitatively that as drainage basin area increases, the size of the alluvial fan also increases. He quantified the relationship with a simple power function of the form:

$$A_f = cA_b^k$$  \hspace{1cm} (1)

where $A_f$ is alluvial fan area, $A_b$ is drainage basin area and $c$ is an empirical derived coefficient representing the area of an alluvial fan with a drainage basin area of 1.0. The exponent $k$ is the slope of the regression line and measures the rate of change in the fan area with increasing drainage basin area. By representing the relationship between these two parameters (Figure 7), it becomes clear that the data fits into a single exponential function:

$$A_f = 0.21A_b^{0.1096}$$  \hspace{1cm} (2)

with a high correlation coefficient of 0.83, so there is a strong positive relation between $A_b$ and $A_f$.

The coefficient $c$, which according to Harvey (1997) ranges from 0.1 to 2.2, has the value of 0.21 for the study area, similar with the value calculated for the coast of Gulf of Corinth, Greece (Karymbalis et al., 2011). In the literature, the different values of $c$ and $k$ for humid and sub humid area fans have been reported (Crosta and Frattini, 2004). Table 4 includes values of $c$ and $k$ in the power law relationships between $A_b$ and $A_f$ from research works in various morphoclimatic environments. The value of the exponent for the study area agrees with the typical value for arid regions (about 0.9) (Hooke, 1968) and 0.88 (Karymbalis et al., 2011), and is higher than those derived from humid (0.58) and polar (0.65) regions. This value shows that the fans increase little in extension when the drainage area increases.

3.2.2. Drainage Area $A_b$ and Fan Slope $S_f$

The relationship between the drainage basin area $A_b$ and fan gradient $S_f$ was investigated by Hooke (1968) and Harvey et al. (1999). This relation is quantified with a simple power function of the form:

$$S_f = cA_b^k$$  \hspace{1cm} (3)

The coefficient $k$ is negative, indicating that increase of $A_b$ results in decrease of $S_f$. In the study area, this relationship (Figure 8) can fit into the following function:

$$S_f = 1.0142A_b^{-0.377}$$  \hspace{1cm} (4)

The value of the exponent $k(-0.377)$ falls within the range of values of -0.40 to 0, as given by Harvey (1997). In the coast of Gulf of Corinth, Greece, the calculated values of $c$ and $k$ are 0.14 and -0.45 respectively (Karymbalis et al., 2011).
Table 4: Values of coefficient $c$ and exponent $k$ in the power law relationship $(A_f = c A_b^k)$ between drainage area and fan area from previous research works performed in various environments

<table>
<thead>
<tr>
<th>Location</th>
<th>$c$</th>
<th>$k$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dellwood, North Carolina, USA</td>
<td>0.23</td>
<td>0.53</td>
<td>Mills (1982)</td>
</tr>
<tr>
<td>Roan Mountain, North Carolina, USA</td>
<td>0.38</td>
<td>0.76</td>
<td>Mills (1983)</td>
</tr>
<tr>
<td>General River Valley, Costa Rica</td>
<td>0.92</td>
<td>1.01</td>
<td>Kesel and Spicer (1985)</td>
</tr>
<tr>
<td>Banff, Alberta, Canada, fluvial fans, debris-flow fans</td>
<td>0.48</td>
<td>0.32</td>
<td>Kostaschuk et al. (1986)</td>
</tr>
<tr>
<td>single-group of fans</td>
<td>0.17</td>
<td>0.48</td>
<td>Kostaschuk et al. (1986)</td>
</tr>
<tr>
<td>Japan</td>
<td>0.15</td>
<td>0.77</td>
<td>Giles (2010)</td>
</tr>
<tr>
<td>Central Alps, Northen Italy</td>
<td>0.29</td>
<td>0.33</td>
<td>Crosta and Frattini (2004)</td>
</tr>
<tr>
<td>Gulf of Corinth, Greece</td>
<td>0.13</td>
<td>0.88</td>
<td>Karymbalis et al. (2011)</td>
</tr>
</tbody>
</table>

The values of exponent $k$ from previous studies are 1.00 (Karymbalis et al., 2011) and hence, Church and Mark (1980) postulated that a general linear relationship exists for $S_f$ versus $M$. For the study area, the value of $k$ (0.26) indicates that the fan slope increases more rapidly than the ruggedness of the basin. According to De Scally and Owens (2004) and Karymbalis et al. (2011), debris-flow fans are supplied by basins with a higher value of $M$ while the fans are steeper, smaller and less concave. This relationship provides an initial assessment of debris-flow potential for the broader study area, but this needs to be supported by field investigation of debris flows and sediment supply conditions in the basin.

4. CONCLUSION

The aim of this study is to determine the effectiveness of SOM as a clustering tool in the field of applied geomorphology. In this research, the geomorphological characteristics of alluvial fans in the Oshtorankoooh altitudes were investigated. Qualitative observations, quantitative geomorphological analysis and application of SOM led to the definition of two main types of fans with different morphological features and the identification of certain correlation schemes between the studied parameters. Comparison of the geomorphological map and SOM showed that the applied methodology is a promising method for the mapping of drainage network channels. This method could be applied as a generic tool of alluvial fan classifier to larger datasets, in order to assess and interpret dominant formation processes through the study of multiple morphometric features describing alluvial fans and corresponding drainage basins. SOM provides an efficient scalable tool for the analysis of geomorphometric features as meaningful landform elements, leading to better understanding complex geomorphological systems.

REFERENCES


Northern Italy. Earth Surface Processes and Landforms 29, 267-293.


Abdollah Seif received the B.A. degree in Geomorphology Science from University of Isfahan in 1986 to 1990 and M.A. degrees in Geomorphology Science from University of Isfahan in 1991 to 1994 and the PhD degree in Geomorphology from University of Isfahan in 2005. He is currently faculty member at the University of Isfahan. He is interested in the research field of GIS and RS, Geomorphology, Quaternary environments.

Marzieh Mokarram received the B.Sc. degree in natural source engineering, Rangeland and Watershed from Faculty of Rangelands and Watershed Management, Shahid Chamran University, GPA 18.04 from 20 (Top student with the 1st honor) in 2003 to 2007 and M.Sc. degrees in Remote Sensing (RS) & Geographic Information System (GIS) from Department of Remote Sensing & GIS, Shahid Chamran University-Ahwaz, GPA 18.44 from 20 (Top student with the 1st honor) in 2008 and 2010, and she has started her PhD in Geomorphology from University of Isfahan in 2011. She is interested in the research field of GIS & RS.