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Curve Estimation Modeling between Area and Volume of Landslides in Tajan River Basin, North of Iran

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ABSTRACT Determining landslide size could be a difficult and expensive task. In this research, size parameters of 142 landslides recognized in Tajan River Basin, northern Iran, have been assessed. The dataset was prepared through the extensive field surveys and using the satellite imagery available via Google Earth. Dependence between landslides area (A-m^2), volume (V-m^3), and depth (D-m) was appointed by the Pearson correlation coefficient (r) at 0.05 and 0.01 levels. Then, the relation between the area and volume variables has been investigated using 10 curve estimation (CE) models. Coefficient of determination (R^2), F statistic, and *RMSE* were calculated to compare the models with each other. Results showed that the power law fit the data better than other CE models. Although, the quadratic and cubic relationships have represented high R^2 and low *RMSE*, they have resulted negative estimated volumes, and also their F statistic is less than its value in power law. To achieve a better result, the estimated volumes were compared with the observed ones using paired test. Results indicated that the estimated volumes were in conformity with the observed ones and there was no statistically significant difference between them (R^2=0.801, *sig*=0.633). Although, the estimated depths were significantly different from the observed ones, the mean depth was estimated 5.5 m which was close to mean of the actual depths (5.53 m).

Key words: *Coefficient of determination, Depth, Pearson correlation coefficient, Power model*

1 INTRODUCTION

Landslides occur due to various triggering mechanisms and are influenced by susceptibility factors such as susceptible geology, steep slopes, uneven topography, changeable climatic and microclimatic conditions, rainfall, earthquake and vegetation degradation, and cause considerable damages (Crozier, 1986; Turner and Schuster, 1996; Gerrard and Gardner, 2002; Wobus *et al.*, 2003; Hasegawa *et al.*, 2009). They generate large amount of sediment in mountainous watersheds; however, quantifying the downstream delivery of landslide-derived sediment remains a challenge (*e.g.* Tsai *et al.*, 2013).

This phenomenon is one of the main natural

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catastrophic events in Iran that could happen any time and makes great economic and public losses annually; as annual economic losses of landslide in Iran have been estimated to be approximately 600 Million $US excluding the loss of non-retrievable resources (Ajalloeian *et al.*, 2013). Regarding the database of landslides in Iran and annual report prepared by Mass Erosion and Landslide Stabilization Group (MELSG) of Iran (2007), the economic losses of landslides was estimated to be about 12,700 million $US from 1982 by the end of 2007 in the country (MELSG of Iran, 2007; 2012; Hagh'shenas, 2009). MELSG of Iran (2012) has reported about 188 persons killed due to landslide occurrence; roads and railroad network damages were estimated 307.67 km totally (forest roads: 3 km, railroads: 6 km, main roads: 252.67 km and rural roads: 46 km) during a 25-year period, from 1982 to 2007.

Thus, it is important to recognize the landslides number and size (area, volume, and depth) in vulnerable regions to estimate the landslide susceptibility, hazard and risk assessment and mitigation (*e.g.* Guzzetti *et al.*, 1999; Cardinali *et al.*, 2002; Malamud *et al.*, 2004, Reichenbach *et al.*, 2005), and to assess the landslides contribution to erosion and sediment yield (*e.g.* Hovius *et al.*, 1997, 2000; Martin *et al.*, 2002; Guthrie and Evans, 2004b; Lavé and Burbank, 2004; Chuang *et al.*, 2009; Tsai *et al.*, 2013). The statistics of the number, density and area of landslides can be calculated for different periods, if landslide inventory maps are available in digital form (Guzzetti *et al.*, 2005, 2006; Imaizumi and Sidle, 2007; Galli *et al.*, 2008).

Estimating the volume of slope failures is a difficult, expensive and challenging task which needs data collection on the surface and sub-surface geometry of the slope, especially for a large population of landslides in an area (Malamud *et al.*, 2004; Guzzetti *et al.*, 2009). At present, it can be achieved only through a thoughtful implementation of the empirical relationships to connect the volume of single landslides to other geometrical parameters of the failures, specially measured landslide area so that (Simonett, 1967; Rice *et al.*, 1969; Innes, 1983; Hovius *et al.*, 1997, Guthrie and Evans, 2004a; Korup, 2005; ten Brink *et al.*, 2006; Imaizumi and Sidle, 2007; Guzzetti *et al.*, 2008, 2009; Imaizumi *et al.*, 2008).

The relation between landslide area (m^2) and volume (m^3) was investigated by many researchers all over the world (*e.g.* Korup, 2005; ten Brink *et al.*, 2006; Imaizumi and Sidle, 2007; Guzzetti *et al.*, 2008, 2009; Imaizumi *et al.*, 2008). Tsai *et al.* (2013) estimated Landslide erosion and sediment delivery to the Shihmen Reservoir watershed in Taiwan using empirical landslide frequency–area and volume–area relationships, empirical landslide runout models, and the Hydrological Simulation Program- FORTRAN (HSPF). They found that just a small percentage of the landslide material was transported to downstream and the sediment delivery in the fluvial system is mainly limited regarding the model simulations. The imbalance between sediment supply and transportation capacity has resulted in a significant quantity of landslide material remaining in the upstream regions of the watershed.

Guthrie and Evans (2004a) found the relation $V=0.1549\times A^{1.0905}$ by considering 124 debris slides in the west coast of Vancouver Island, British Columbia. Korup (2005) studied 23 large landslides in the Western Southern Alps, New Zealand, and established that $V=0.02\times A^{1.95}$ with *A* in km^2 and *V* in km^3. Imaizumi and Sidle (2007) measured the volume of 51 shallow landslide scars in the Miyagawa catchment, central Japan, and obtained that $V=0.39\times A^{1.31}$. Imaizumi *et al.*

used geometry of 11 landslides and determined that $V=0.19\times A^{1.19}$. Guzzetti *et al.* (2008), found the relationship $V=0.0844\times A^{1.4324}$ using a preliminary listing of 539 landslides worldwide. Guzzetti *et al.* (2009) showed that $V=0.074\times A^{1.45}$ for 677 landslides of the slide type selected from a worldwide dataset and used the relation in the Collazzone area, central Italy.

A general review of landslide geometrical characteristics in Iran provides few numbers of international authentic papers on the subject; so that, there are no papers considering the relation between landslides size characteristics, area-volume relation mainly, so far. Omidvar and Kavian (2011) represented the relationship $V=0.974\times A^{1.176}$ (R^2=0.823), for 442 landslides in the range of ≈123 $m^2 \leq A \leq \approx 1085E03$ m^2 in Mazandaran province (the province mapped in Figure 1) northern Iran, at the regional scale and published the result in Persian.

The main purposes of this research are to present a detailed geometric attributes of 142 landslides inventory of Tajan River Basin, north of Iran and assess their volume-area at the basin scale. The main difference between the present study and the previous publications is that it indicates the results of comparison 10 curve estimation models between area and volume with each other. Finally, a relationship to estimate volume value will be proposed for the landslide in the study area.

2 MATERIALS AND METHODS

2.1 Study Area

The study area, a part of Tajan River Basin, is located in the Mazandaran province, north of Iran and south of Caspian Sea, between UTM coordinate 680119E and 725053E, and 3986371N and 4041448N, covering approximately 1,300 km^2 (Figure 1). The altitude of the area ranges from 78 to 3,105 AMSL (m) and the slope angel ranges from 0 to 79 degree based on a 20 m×20 m digital elevation model (DEM) within the study area. Annual mean rainfall of the area is almost 700 mm calculated from data set of 27 rain-gauge stations inside (8 gauges) and outside (19 gauges) the area. Regarding the geological map of Iran, 1:100,000 series, sheets 6662 (Pol-e-Sefid) and 6762 (Kiasar) (GSI, 1997) lithology of the area is covered 42.96% by $M_{2,3}^{m,s,l}$ group which is a Miocene formation, including marl, limy sandstone and siltstone, silty marl, sandy limestone, mudstone and minor conglomerate, and 15.96% by $K_2^{l,m}$ group whose geological age is the Late Cretaceous, including cream-light green-grey glauconitic marly limestone, limy marl, silty marl and marl. The major landuse of the study area is forest which includes high and medium density forests plus mixed forest/orchard and covers nearly 73% of the area. The total length of major faults in the area is 58.17 km (GSI 1997). This area is one of the rainiest regions and frequently hit by severe rainstorms every year that usually trigger a large number of landslides due to its geologic, geomorphologic, and climatic settings, which result in serious economic losses and casualties. This research was conducted to investigate area, volume, and depth parameters of 142 recorded landslides in the area.

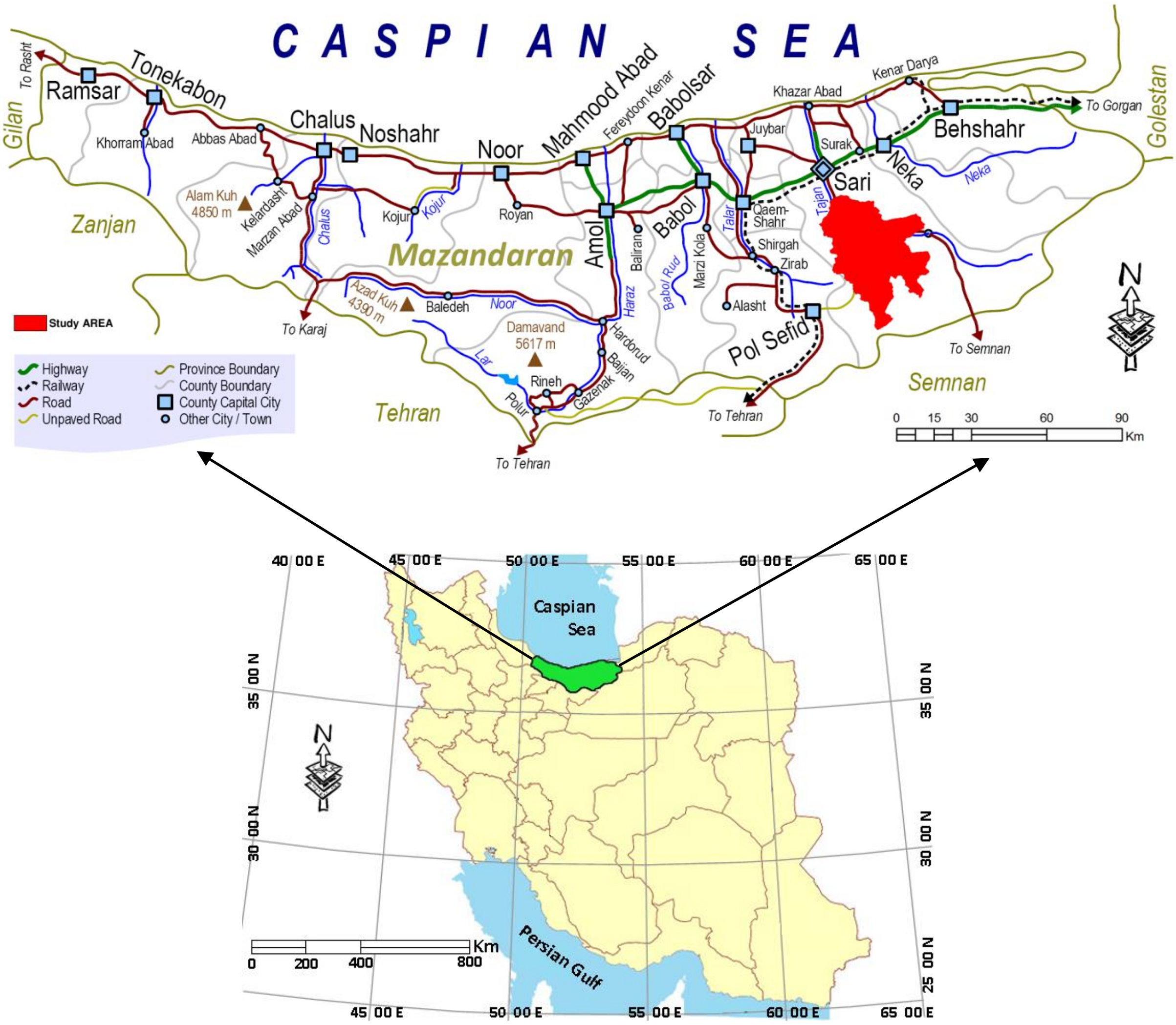

Figure 1 Location of the study area (colored) in Mazandaran Province (in north of Iran)

2.2 Method

A total of 142 landslides were recognized and mapped at 1:25,000-scale, and the required data including location, area, volume and depth of existing landslides were collected through the extensive local field surveys as well as being confirmed by the satellite imagery available via Google Earth (Figure 2).

The area of the individual landslides was obtained multiplying length by width, assuming a rectangular shape for the failure (*e.g.* Innes, 1983; Larsen and Torres Sanchez, 1998; Guzzetti *et al.*, 2009). In the same way, landslide volume was calculated multiplying landslide area by the average soil depth, determined in the field for each particular landslide (*e.g.* Larsen and Torres Sanchez, 1998; Martin *et al.*, 2002; Guzzetti *et al.*, 2009). In next step, the data have been imported to SPSS package (SPSS, Ver. 16) to appoint the correlation between landslides area, volume, and depth using correlation matrix at the 0.05 and 0.01 levels.

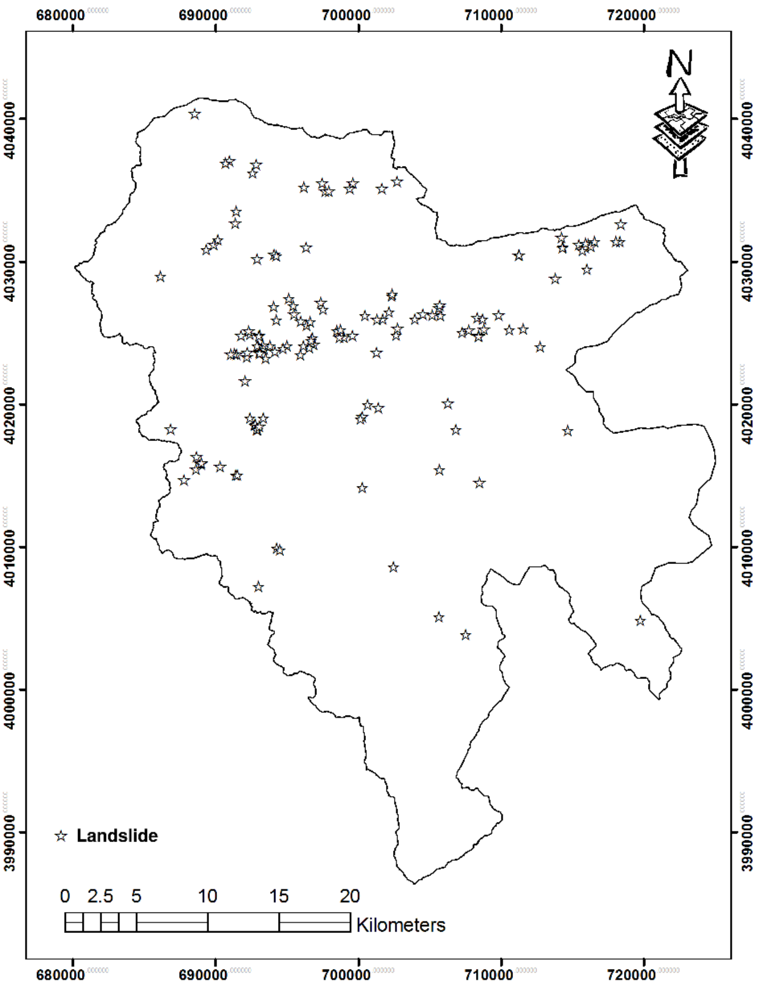

Figure 2 Spatial distribution of 142 individual landslides in the study area

Dependence between the variables was appointed by the Pearson correlation coefficient (*r*) (Pearson, 1896) at the 0.05 and 0.01 levels (Equation 1).

$$r = \frac{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)}{\sqrt{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2}\sqrt{\sum_{i=1}^{n}\left(Y_i - \overline{Y}\right)^2}} \qquad (1)$$

Where X_i, Y_i, $\overline{X}$, $\overline{Y}$ and n are each observed data, estimated data equivalent to that of observed one, mean of total observed data, mean of total estimated data and number of data, respectively.

In that case, the relation between area and volume has been investigated using 10 curve estimation models (CEM) such as Linear, Logarithmic, Inverse, Quadratic (degree 2 polynomial), Cubic (degree 3 polynomial), Compound, Power, S Curve, Growth and Exponential between landslides area (m^2) and volume (m^3) as independent and dependent variables, respectively (Table 1, Pallant, 2007; Chatterjee and Hadi, 2006).

Table 1 General equation of curve estimation models used in this research (Chatterjee and Hadi, 2006; Pallant, 2007)

Model Type	General equation
Linear	$y = a + b_1 x$
Logarithmic	$y = a + b_1 \ln x$
Inverse	$y = a + {b_1}/{x}$
Quadratic	$y = a + b_1 x + b_2 x^2$
Cubic	$y = a + b_1 x + b_2 x^2 + b_3 x^3$
Compound	$y = ab_1^x$ or $\ln y = \ln a + \ln(b_1)x$
Power	$y = ax^{b_1}$ or $\ln y = \ln a + b_1 \ln x$
S curve	$y = e^{a + \left({b_1}/{x}\right)}$ or $\ln y = a + {b_1}/{x}$
Growth	$y = e^{a + b_1 x}$ or $\ln y = a + b_1 x$
Exponential	$y = ae^{b_1 x}$ or $\ln y = \ln a + b_1 x$

Coefficient of determination (R^2), F statistic and *RMSE* (Equation 2, Kim *et al*., 2008) were calculated to compare the models with together.

$$RMSE = \sqrt{\sum (O_i - E_i)^2 / n} \quad (2)$$

Where, O_i, E_i and n are each observed data, estimated data equivalent to that of observed one and number of data, respectively.

Regarding the final area-volume model, the depth of landslides has been estimated and then, the predicted depths have been compared with the actual ones measured through the field surveys, using paired samples test at the 0.01 level.

3 RESULTS

Statistical parameters of 142 landslides in the study area have been shown in Table 2. The area of smallest and largest landslides is 180 m^2 and 900,000 m^2, respectively.

Table 3 presents the result of correlation matrix between area, volume, and depth at the 0.05 and 0.01 levels. As it shows there is significant correlation between these parameters at the mentioned levels.

The results obtained using CE models and the results of comparing between the models with together were shown in Figure 3 and Table 4, respectively. Dependent and independent variables are volume and area of landslides, respectively.

Table 2 Statistical parameters of landslides size in the study area (N=142)

Statistic of Parameter	**Area (m^2)**	**Depth (m)**	**Volume (m^3)**
Standard Error of Mean	6703.896	0.44	63746.82
Standard Deviation	79886.143	5.26	759631.06
Skewness	9.68	2.74	5.75
Standard Error of Skewness	0.2	0.2	0.2
Kurtosis	104.79	9.5	37.1
Standard Error of Kurtosis	0.4	0.4	0.4
Minimum	180	0.6	160
Maximum	900000	35	6300000
Sum	3241293	785.1	31156046

Table 3 Correlation matrix among area, volume and depth of landslides in the study area at 0.05 and 0.01 levels

Variable	**Area (m^2)**	**Depth (m)**	**Volume (m^3)**
Area (m^2)	1	0.219**	0.847**
Depth (m)	0.219**	1	0.578**
Volume (m^3)	0.847**	0.578**	1

** Correlation is significant at the 0.01 level.

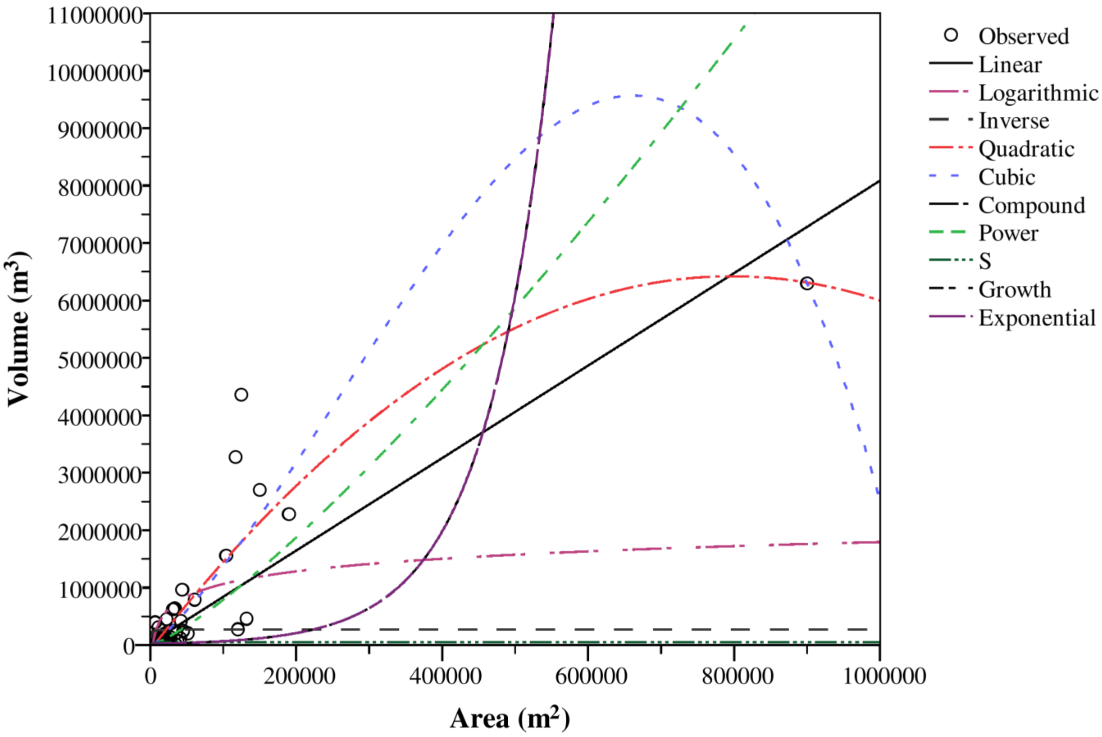

Figure 3 Scatter plot of the area-volume curve estimation models for the landslides of the study area

Table 4 Comparison of curve estimation models between volume and area of study landslides

Model	**R^2**	**F**	**RMSE**
Linear	0.72	357.15	402716.4
Logarithmic	0.33	69.56	619428.3
Inverse	0.02	2.65	749940.8
Quadratic	0.8	281.99	337560.9
Cubic	0.81	191.42	334156.4
Compound	0.22	39.83	45327369.9
Power	0.82	627.61	639723.7
S curve	0.38	84.8	775014.2
Growth	0.22	39.83	45327369.9
Exponential	0.22	39.83	45327369.9

4 DISCUSSION

Results (Table 4) indicated that the power law fit the data better than other CE models because of R^2=0.82, *F*=627.61 (*sig*=0.000) and *RMSE*=639,723.7.

Although quadratic and cubic relationships have represented R^2= (0.8; 0.81) and *RMSE*= (337,560.9; 334,156.4), respectively, they have resulted negative values of estimated volumes and also *F* statistic of them has been resulted less than its value in power law relationship. Hence, the power law has been confirmed as model of the best fit.

For better inspection of the power law relation, the scatter of the empirical data was shown in log–log coordinates (Figure 4).

Standard errors of skewness and kurtosis shown in Table 2 represent that frequency distribution of landslides in the study area follows a normal distribution. Figure 5 indicates frequency distribution of landslides in different classes of their areas (m^2) and volumes (m^3) and confirms that it follows nearly a normal distribution related to areas and volumes, as well.

Frequency distribution above can be characterized as bimodal that can be related to two different types of landslides in the study area.

On the plots compiled in non-logarithmic scale (Figures 3) it is clear that only one event has an area of about 0.9 km^2, which is more than 4 times larger than the largest of others.

Since the power law, quadratic and cubic models showed high value of R^2 (Table 4), these models have been reconstructed by excluding the largest size from the dataset as outlier data. Results show that R^2 decreased slightly in power law from 0.8157 to 0.8055, while it decreased significantly in quadratic and cubic models from 0.8 and 0.81 to 0.6385 and 0.6719, respectively (Figure 6 and Figure 7).

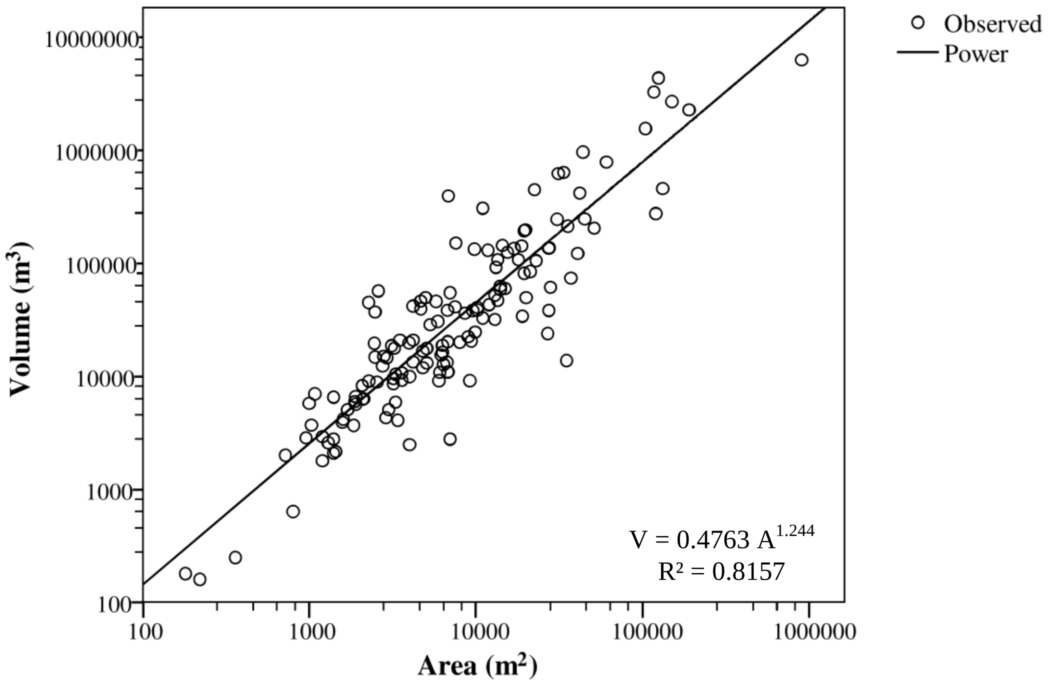

Figure 4 Logarithmic coordinate of the power law relationship between area (*A*) m^2 and volume (*V*) m^3 of the landslides in the study area

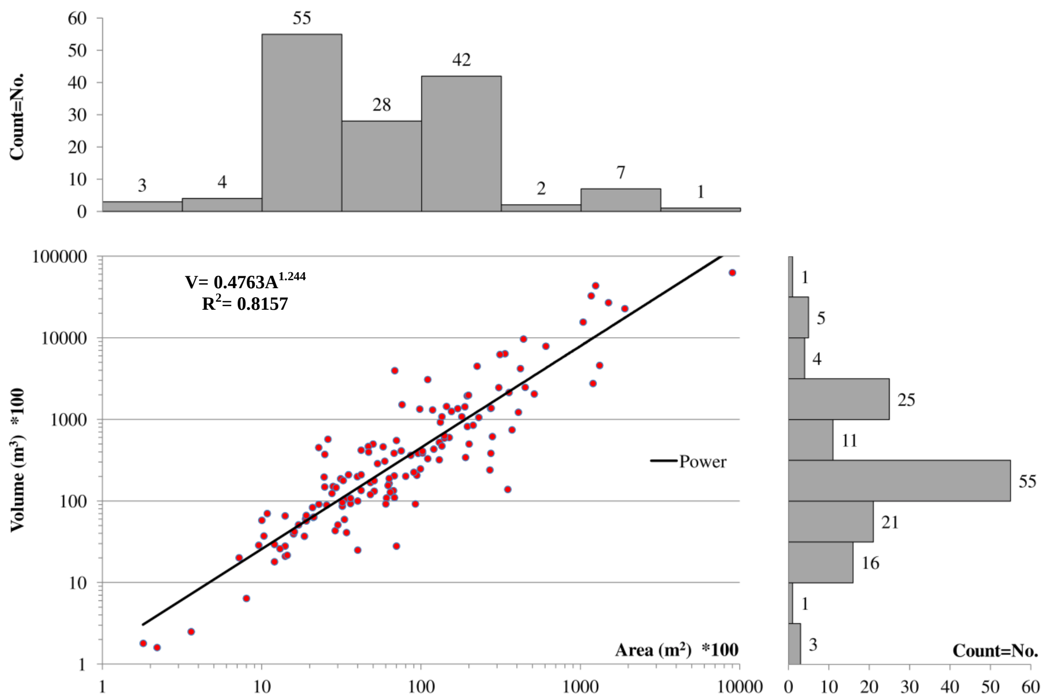

Figure 5 Frequency distribution of the landslides follows nearly a normal distribution related to their areas and volumes. Gray columns show the landslides frequency in different classes of the areas and volumes

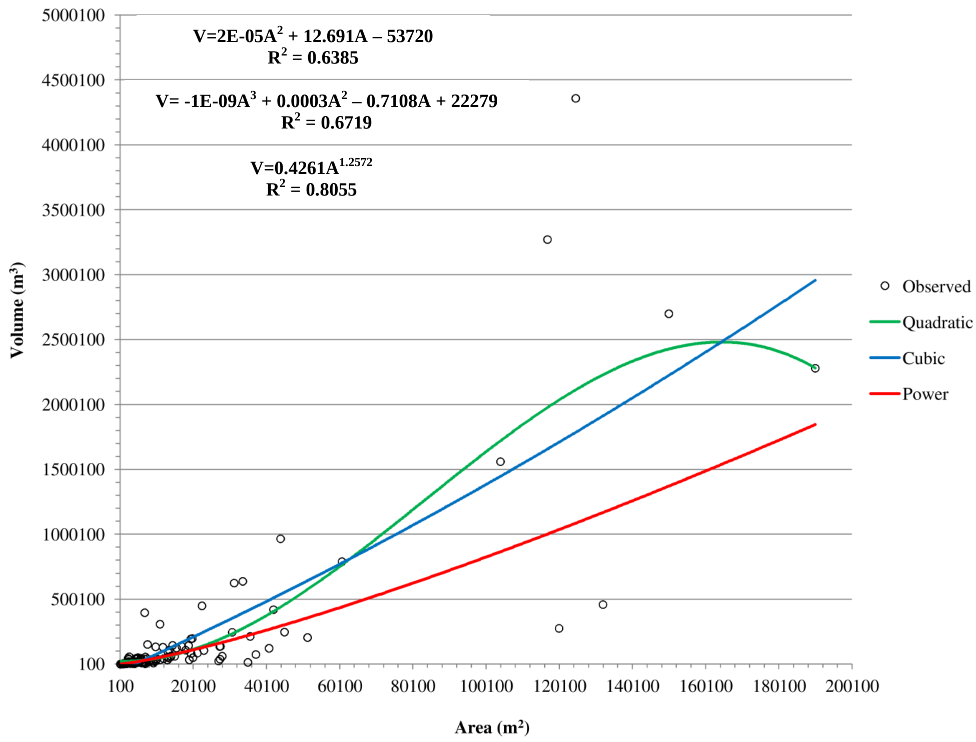

Figure 6 Area-volume power law, quadratic, and cubic models after excluding the largest data

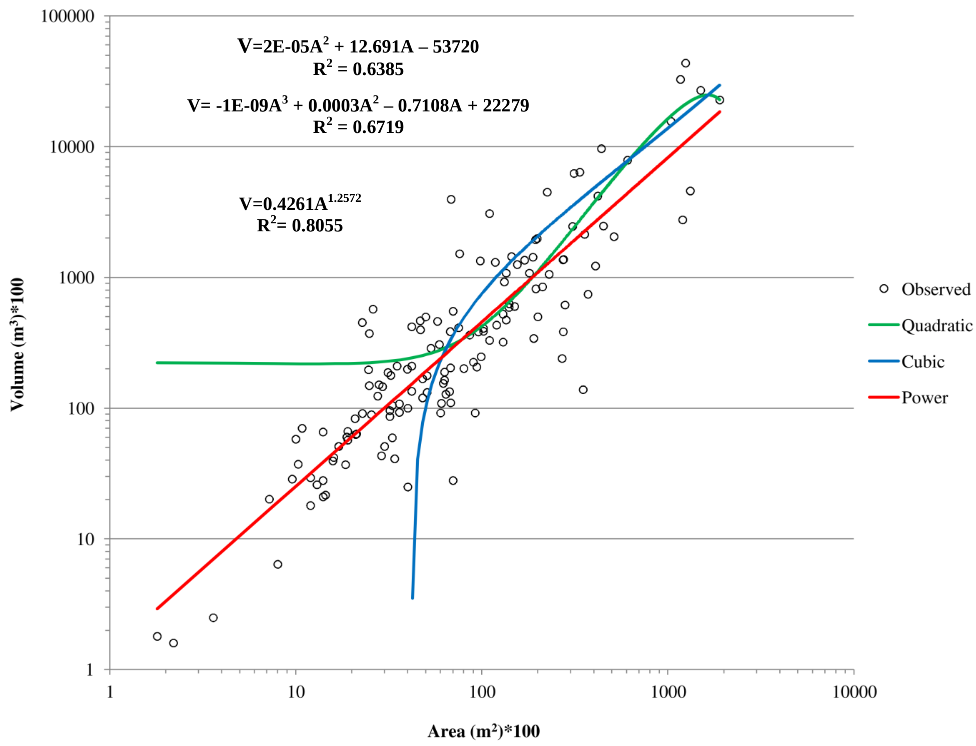

Figure 7 Logarithmic coordinate of the area-volume CE models after excluding the largest data

In fact, we are not allowed to exclude the landslide occurring in the area as an outlier data because it is a reality, and the data of this large landslide are real, hence, it is important to consider all data in various sizes for determination of risk. If we remove the mentioned landslide from the dataset, then, we decrease the susceptibility, hazard, and risk levels in hazardous and risky areas for subsequent researches in landslide zonation assessment and evaluation while the area-volume relationship will not consider the reality which is another thing.

In order to achieve a better result, the power law relationship has been applied to estimate the volumes and then estimated values compared with the observed ones using paired test. Results indicated that the estimated volumes are in conformity with the observed ones and there is no statistically significant difference between them (R=0.801, sig=0.633), (Table 5). 95% confidence interval of the difference indicated that the mean of estimated volumes is less than the mean of the observed ones ($-79178.77 \leq \mu_d \leq 129673.44$).

In this step, the mean of actual area was calculated and then based on the final model (power law), the average of estimated volume obtained. Hence, the average depth of 5.5 m was estimated that is close to the mean of the observed one (5.53 m, Table 2).

Also, values of the estimated depths were compared with the observed ones using paired test. Results indicated that the estimated depths are in disagreement with the observed ones and they are significantly different (R=0.48, sig=0.004), (Table 6). 95% confidence interval of the difference indicated that the mean of the estimated depths is less (in this case a little bit) than the mean of the observed ones ($0.37 \leq \mu_d \leq 1.9$).

Table 5 Results of paired samples correlation and test between the observed and estimated volume of landslides

N	Correlation	Sig.	95% Confidence Interval of the Difference		t	df	Sig.
			Lower	Upper			
142	0.801	0.000	-79178.765	129673.443	0.478	141	0.633

Table 6 Results of paired samples correlation and test between the observed and estimated depth

N	Correlation	Sig.	95% Confidence Interval of the Difference		t	df	Sig.
			Lower	Upper			
142	0.48	0.000	0.369	1.931	2.912	141	0.004

5 CONCLUSION

Adopting the statistical area-volume relationship of landslides would be useful for estimating the volume and depth of a landslide due to difficulties in preparing required data on the surface and sub-surface of the slope (Malamud *et al.*, 2004; Guzzetti *et al.*, 2008; 2009), for erosion and sediment yield assessments (Chuang *et al.*, 2009; Tsai *et al.*, 2013), and for managing the risky and susceptible slopes as well.

A practical relationship to connect landslide area (m^2) to landslide volume (m^3) was achieved from a dataset catalogue of 142 landslides and fitted to the observed data in Tajan River Basin, north of Iran. The relationship is an equation of the form $V=\rho A^{\alpha}$ and is in the same form with relationships published by Simonett, 1967; Rice *et al.*, 1969; Innes, 1983; Guthrie and Evans, 2004a; Korup, 2005; ten Brink *et al.*, 2006; Imaizumi and Sidle, 2007; Guzzetti *et al.*, 2008, 2009; Imaizumi *et al.*, 2008; Omidvar and Kavian, 2011.

Guzzetti *et al.* (2009) concluded that the relationship is chiefly geometrical, and not controlled significantly by geomorphological or mechanical properties of the mass movement types. In other word, landslides occurred in various physiographic and climatic environments and were caused by different triggers indicate that the relationship between volume and area is chiefly independent of the physiographical setting. They mentioned that it suggested a self-similar behavior of the dependency between landslide area and volume. Their conclusion refers to fractal behavior of natural phenomena like landslides.

Regarding to the depth, it is acceptable estimation just for calculating the mean statistic of the collective data and not suitable for the depth estimation of each landslide based on the obtained volume- area relationship since according to the depth importance in determination landslide vulnerability and risk, even low differences in depth could be significant. Therefore, it is better to assess the CE relationships between depth and area or other geomorphometry parameters of landslides that could be measured on the surface of the failure to estimate depth of landslides.

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مدل‌سازی برآورد منحنی بین سطح و حجم زمین‌لغزش در حوزه آبخیز تجن، شمال ایران

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چکیده تخمین اندازه زمین‌لغزش به دلیل جمع‌آوری داده طی عملیات ژئومتریِ سطحی و زیرسطحیِ دامنه گسیختگی، کاری مشکل و هزینه‌بر است. در این تحقیق، ویژگی‌های اندازه ۱۴۲ زمین‌لغزش شناسایی‌شده در حوزه آبخیز تجن واقع در شمال ایران، مورد بررسی قرار گرفته است. مجموعه داده طی بررسی میدانی گسترده و استفاده از تصاویر ماهواره‌ای قابل دسترس از طریق Google Earth فراهم شد. همبستگی بین متغیرهای سطح و حجم توسط ضریب همبستگی پیرسون در سطوح ۵ و ۱ درصد تعیین و سپس رابطه بین سطح و حجم توسط ۱۰ مدل برآورد منحنی بررسی شد. ضریب تبیین، آماره *F* و *RMSE* به‌منظور مقایسه مدل‌ها محاسبه شدند. نتایج نشان داد که مدل توانی نسبت به سایر مدل‌های برآورد منحنی، برازش بهتری بر داده‌ها داشته است. اگرچه روابط چندجمله‌ای‌های درجه دوم و سوم مقدار R^2 بالا و *RMSE* پایینی را نشان داده‌اند ولی حجم‌های برآوردی منفی را نتیجه داده‌اند و نیز آماره *F* آن‌ها پایین‌تر از مقدار آن در مدل توانی بوده است. به‌منظور دستیابی به نتیجه بهتر، حجم‌های برآوردی و مشاهده‌شده توسط آزمون مقایسه زوجی مورد مقایسه قرار گرفتند. نتایج نشان داد که مقادیر حجم تخمینی از مقادیر مشاهده‌شده پیروی نموده، اختلاف آماری معنی‌داری بین آن‌ها وجود ندارد (*sig*=۰/۶۳۳، R^2=۰/۸۰۱). اگرچه عمق‌های تخمینی به‌طور معنی‌داری با عمق‌های مشاهده‌شده در منطقه دارای اختلاف هستند، ولی عمق میانگین تخمین شده (۵/۵ متر) نزدیک عمق میانگین مشاهده شده (۵/۵۳ متر) می‌باشد.

کلمات کلیدی: ضریب تبیین، ضریب همبستگی پیرسون، عمق، مدل توانی