



A modified equation for the downstream dilution of stream sediment anomalies



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ABSTRACT

Mixing stream sediments originating from mineralization surface with eroded materials from background areas leads to downstream dilution in metal content of mineralization-sourced sediments. This phenomenon has a negative effect on delineation of anomalous catchment basins. In order to eliminate the dilution effect from the chemical analysis of stream sediments data, Hawkes (1976) proposed the equation " $C_m A_m = A_a(C_a - C_b) + C_b A_m$ " through which he calculated the metal concentration at the mineralization surface. Hawkes's equation was a great advancement in interpretation of stream sediment geochemical datasets.

However, Hawkes makes some simplifying assumptions to derive his formula from the mass balance equation including the hypothesis that the total sediment produced at a basin surface is delivered to the basin outlet. By this approach, an equation is obtained in which a linear relation is set between the sediment delivery and the area size of the basin. Some of the Hawkes's assumptions are inevitable, but the aforementioned one is not in general true. In the present research, a new equation is derived by employing the concept of sediment delivery ratio (SDR) and its introduction into the mass balance equation, used by Hawkes (1976). SDR that represents the gap between the gross erosion in a catchment basin and the amount of sediment delivered at the basin outlet is negatively related to the basin size, and, as the basin size increases, the rate of deposition at the basin outlet decreases.

SDR plays the main role in our work to attain a modified formula in which the dilution is related to the basin size by a power function. The modified equation " $C_m A_m^{1+n} = C_a A_a^{1+n} - C_b (A_a - A_m)^{1+n}$ " is a general form of Hawkes's equation where power equals 1 ($n = 0$) corresponds to Hawkes's equation. The new equation was applied to test the data presented by Hawkes, and it emerged that, in his study, $n = 0$ delivers closer results to the reality in the first case study, but $n = -0.25$ and -0.5 delivers closer Cu values to the actual value in the second case. Similarly, more acceptable results were achieved for Mo if $n = -0.25$ in the second case. Additionally, the sample catchment basin was tested on the stream sediment dataset in the west of Iran, where orogenic gold occurrences were recognized to exist. Employing the modified equation with those three n values has resulted in repositioning of some catchment basins in terms of their favorability.

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1. Introduction

Stream sediment samples and their chemical contents have been employed in mineral exploration for decades. They are mainly collected in reconnaissance stages of mineral exploration programs in order to restrict the exploration region to a smaller number of catchment basins which can be further investigated by rock or soil sampling. These types of samples are assumed to be representative of upstream and, in turn, the whole basin from which they originate. So, elevations in the metal concentration of samples might be attributed to background differences between catchment basins or to potential mineralization occurrences inside the basin(s).

Since the 1970s, different geochemical aspects of stream sediment samples have been studied and scrutinized by many researchers such as Hawkes (1976), Rose *et al.* (1976), Stendal (1978), Bonham-Carter

et al. (1987), Fletcher (1997), Cohen *et al.* (1999), Moon (1999), Spadoni (2006), Carranza (2009), and Abdolmaleki *et al.* (2014). The studies range from sampling to using analytical techniques and consequently processing of the results. As a central stage, interpretation of results has been the focal point for these studies a considerable number of which deal with formulation to calculate the background values for catchment basins and to delineate anomalous ones. One of the most important factors taken into account in calculation and delineation of anomalous catchment basins is dilution correction.

1.1. Dilution phenomenon

The erosion of materials from different sources and their migration through drainage systems leads to deposition of stream sediments at the outlet of catchment basins whose chemical composition is affected by the chemical contents of parent rocks. However, if a basin comprises mineralization, the sediments in the outlet are expected to be originating partly from mineralized areas and partly from non-mineralized

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areas (collectively named background). Usually, due to the much larger coverage area of background than that of mineralization, a considerable proportion of stream sediments are made up of background sourced materials. Consequently, mixing sediments originating from a mineralization surface having high metal content with sediments sourced from the rest of the basin, during their transportation as well as deposition at the basin outlet, results in the weakening of the metal contents of stream sediment samples. This phenomenon is called 'dilution' and has a negative effect on the delineation of favorable catchment basins where mineralization exists. Therefore, it is required to remove the dilution effect from the chemical composition of stream sediment samples.

The highly cited research on dilution phenomenon is the work conducted by Hawkes (1976). Part of the significance of the study is based on his formulation regarding the dilution effect. In fact, Hawkes's formula has to do with the total mass of sediments at the sampling point coming from two origins as background and mineralization. He employed the mass balance equation to connect the total mass of sediments produced at the basin outlet to each of these two sources. Hawkes's formula has extensively been used in the literature to eliminate the dilution effect of background on the metal content of sediments originating from mineralization (Bonham-Carter and Goodfellow, 1986; Carranza and Hale, 1997; Carranza, 2004; Carranza, 2009; Abdolmaleki et al., 2014).

However, Hawkes made some simplifying assumptions in order to derive his equation which may lead to deviation of results from the reality. The aim of the present research is to consider sedimentation processes, controlling parameters, and factors of sedimentation in a catchment basin. By taking these parameters into account, instead of simplifying the formulation, a formula with more parameters can be derived, from which the results gets closer to the reality. In this research, we have proven that the existing dilution correction formula is not completely correct. So, we have derived a new equation to modify the metal contents of stream sediment samples suffering from the dilution phenomenon. The existing and newly modified equations are applied to the dataset presented by Hawkes (1976) and also to the stream sediment geochemical data from an area in Iran comprising Au mineralization. Moreover, a statistical test is conducted on the values resulting from both equations to assess the difference between their results.

2. Erosion and sediment transportation in a catchment basin

There is an extensive body of research in sedimentological, hydrological and geomorphological literature carried out on defining parameters and investigating mechanisms of erosion and transportation of materials in drainage basins (Ferro and Minacoiilli, 1995; Lu et al., 2006; Dong et al., 2013). Also, a large number of papers in these fields deal with mathematical modeling of erosion and quantification of sediment transport in catchment basins. On the other hand, geochemical literature on stream sediment samples for mineral exploration purposes has not properly considered these parameters and formulations for interpretations of geochemical data. In the present study, we concentrate on some important definitions and parameters related to sediment transport in a catchment basin that will later be employed to derive the modified downstream dilution equation.

- Soil erosion is usually referred to as soil or earth surface destruction by water (Zachar, 1982). The Universal Soil Loss Equation (USLE), developed by Wischmeier and Smith (1978), takes into account a variety of factors (Morgan, 2005) based on field measurement of soil erosion through which soil loss for a given area can be calculated. Gross erosion in a catchment basin (E) is equal to the total mass of eroded materials from different sources expressed as $\text{tonne km}^{-2} \text{ year}^{-1}$ (Wischmeier and Smith, 1978).
- Sediment Yield (SY) and Sediment Delivery Ratio (SDR): sediments eroded from the parent materials in a drainage system are transported downstream mainly by runoff waters; however, this movement is

limited by water velocity (Wischmeier and Smith, 1978). Deposition of the eroded materials occurs continuously once migration of the detached materials is started, and, as a consequence, not all the eroded materials are delivered to the outlet of the catchment basin. In other words, there is a gap between the gross erosion in the basin and the amount of sediments delivered to the outlet of the basin. The total amount of the eroded materials in a watershed which is delivered to the basin outlet is called 'sediment yield' (SY) (Toy et al., 2002). SY is normalized to unit area and stated as $\text{tonne km}^{-2} \text{ year}^{-1}$. The ratio of sediment yield to gross erosion of a catchment basin, above its outlet, is known as 'sediment delivery ratio' (SDR) of that drainage basin (Wischmeier and Smith, 1978; Ferro and Minacoiilli, 1995; Zhou and Wu, 2008; Dong et al., 2013). This is an important parameter in estimating the total amount of sediments that is deposited at the outlet of a watershed every year and can be calculated by the following equation:

$$SDR = \frac{SY}{E}. \quad (1)$$

However, many factors control SDR , such as climate, soil properties, drainage area, stream length and land use (Ferro and Minacoiilli, 1995; De Boer and Crosby, 1996; Lu et al., 2006). Amongst these factors, drainage area has specifically been paid attention to, and its relationship to sediment yield is studied in greater details. In most cases, it is documented that SDR is inversely related to the basin size and, as the basin size increases, SDR decreases (Ferro and Minacoiilli, 1995; Ferro, 1997). The general form of the equation for SDR and basin size is:

$$SDR = KA^n \quad (2)$$

where A is the area size of the basin in km^2 , and K and n are empirical parameters. In fact, SDR is linked to basin size by a power function and not a simple linear one (Ferro and Minacoiilli, 1995; Lu et al., 2006). Different studies have shown that n can vary between -0.01 to -0.25, but lower values of n down to -0.7 have also been reported (Ferro and Minacoiilli, 1995; Lu et al., 2006). Fig. 1 displays examples of SDR curves against catchment basin area in different regions (Lu et al., 2006).

3. Modification of Hawkes's downstream dilution equation

In this section, the aforementioned factors and equations are taken into account in order to create a new equation for removing the dilution

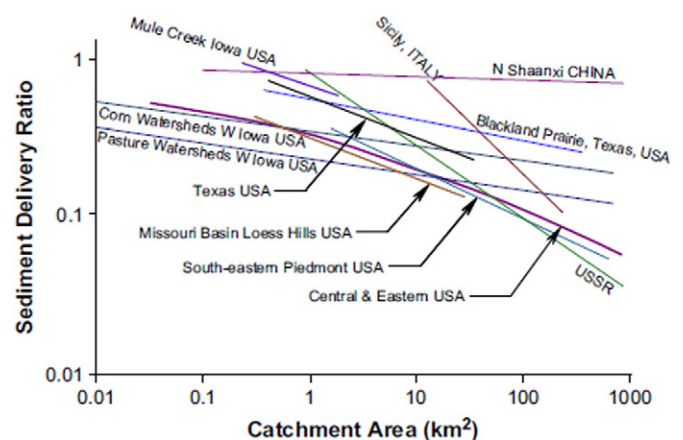


Fig. 1. Relationship between SDR and area size of a basin in different regions (Lu et al., 2006).

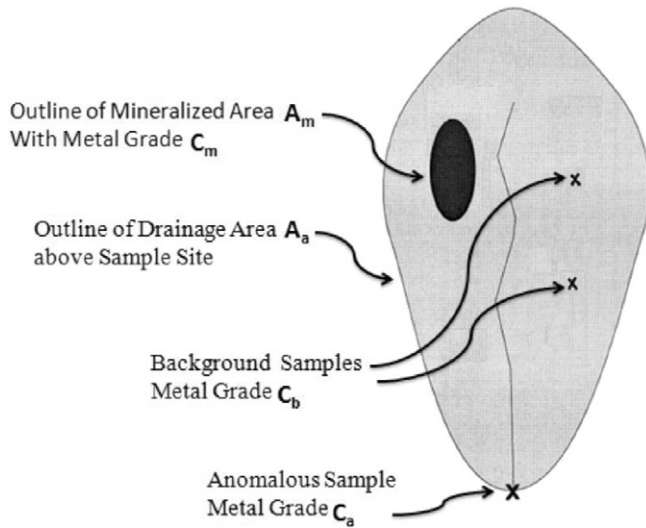


Fig. 2. An idealized situation displaying a catchment basin, mineralization and background.

effect from the chemical composition of stream sediment samples. Fig. 2 depicts an idealized situation where mineralization has been located inside a catchment basin. The following notations will be used in this paper:

b	background
m	mineralization
A_b	area of background in km^2
A_m	area of mineralization in km^2
A_a	total area of catchment basin containing mineralization in km^2
C_b	metal concentration in background in g tonne^{-1}
C_m	metal concentration in mineralization in g tonne^{-1}
C_a	metal concentration at the catchment basin outlet containing mineralization in g tonne^{-1}
M_{sb}	mass of sediment at the catchment basin outlet originating from background in tonne
M_{sm}	mass of sediment at the catchment basin outlet originating from mineralization in tonne
M_{sa}	total mass of sediment at the catchment basin outlet in tonne
M_{mb}	mass of metal at the catchment basin outlet originating from background in tonne
M_{mm}	mass of metal at the catchment basin outlet originating from mineralization in tonne
M_{ma}	total mass of metal at the catchment basin outlet in tonne
SDR_b	sediment delivery ratio of background area
SDR_m	sediment delivery ratio of mineralization area
SDR_a	sediment delivery ratio of whole catchment basin area containing mineralization
E	erosion rate in $\text{tonne km}^{-2} \text{year}^{-1}$

3.1. Hawkes's equation for downstream dilution

In order to calculate the total mass of sediments at a catchment basin outlet, Hawkes used the following formula (it should be noted that unit value for time period, i.e. year=1, has been used in the present work):

$$M_{sa} = EA_a. \quad (3)$$

So, the mass of metal at the outlet would be:

$$M_{ma} = C_a M_{sa} = EC_a A_a. \quad (4)$$

This amount of mass can be divided into two sources: metal originating from mineralization (Eq. (5)) and metal originating from background (Eq. (6)).

$$M_{mm} = C_m M_{sm} = EC_m A_m. \quad (5)$$

$$M_{mb} = C_b M_{sb} = EC_b A_b. \quad (6)$$

Therefore, the total metal at the outlet is equal to the metal from mineralization plus the metal from background (Eq. (7)).

$$M_{ma} = EC_a A_a = M_{mm} + M_{mb} = EC_m A_m + EC_b A_b. \quad (7)$$

So, E is cleared from both sides of Eq. (7), with the following result:

$$C_a A_a = C_m A_m + C_b A_b. \quad (8)$$

where $A_a = A_m + A_b$ or $A_b = A_a - A_m$

$$C_a A_a = C_m A_m + C_b (A_a - A_m). \quad (9)$$

The above equation relates the areas of the whole catchment basin, mineralization and background to different values of metal grades by a linear function.

By rearranging the terms, Hawkes derived the flowing formula for dilution:

$$C_m A_m = A_a (C_a - C_b) + C_b A_m. \quad (10)$$

As commonly $A_m \ll A_a$, Eq. (10) can also be written in following form:

$$C_m A_m \cong (C_a - C_b) A_a. \quad (11)$$

So, C_m will be:

$$C_m \cong (C_a - C_b) \frac{A_a}{A_m}. \quad (12)$$

If 0.01 km^2 is assumed for a mineralization surface (Carranza and Hale, 1997), C_m is equal to:

$$C_m \cong (100 A_a) (C_a - C_b). \quad (13)$$

3.2. Modified equation for downstream dilution

If a catchment basin is divided into v morphological units, the total mass of the sediments delivered at the basin outlet by employing the sediment delivery ratio can be calculated by the following equation:

$$M_{sa} = \sum_{u=1}^v \text{SDR}_u A_u E_u. \quad (14)$$

where SDR_u , A_u and E_u are the sediment delivery ratio, area and erosion rate of u th morphological unit, respectively. Consequently, through Eq. (4), the following formula can be assumed for the metal content of the element of interest at the basin outlet:

$$M_{ma} = \sum_{u=1}^v \text{SDR}_u A_u E_u C_u. \quad (15)$$

In our case, rather than morphological units, we deal with two geochemical units: mineralization unit and background unit. Here, we assume an equal value for erosion rate of mineralization, background and the whole basin area. So, both sides of Eq. (15) are expanded

based on SDR to deliver the following relationship:

$$SDR_a A_a EC_a = SDR_m A_m EC_m + SDR_b A_b EC_b. \quad (16)$$

On the other hand, SDR is a function of unit area based on Eq. (2). Then we can have the following equation:

$$k A_a^n A_a EC_a = k A_m^n A_m EC_m + k A_b^n A_b EC_b. \quad (17)$$

Assuming that k is the same for all the units, Eq. (17) can be rewritten in the following form:

$$C_a A_a^{1+n} = C_m A_m^{1+n} + C_b A_b^{1+n}. \quad (18)$$

where $A_a = A_m + A_b$ or $A_b = A_a - A_m$.

$$C_a A_a^{1+n} = C_m A_m^{1+n} + C_b (A_a - A_m)^{1+n}. \quad (19)$$

By rearranging this equation to have mineralization parameters on one side, we will have:

$$C_m A_m^{1+n} = C_a A_a^{1+n} - C_b (A_a - A_m)^{1+n}. \quad (20)$$

Eq. (20) is called 'the modified equation for downstream dilution of stream sediment geochemical data'. Unlike Hawkes's equation (Eq. (10)), this equation relates the metal content at the basin outlet to the mineralization grade and its area and also the background grade and its area by a power function. However, in a special case where $n = 0$, the modified equation is equal to Hawkes's equation (Eq. (10)).

If $A_m \ll A_a$, the above formula can be written as:

$$C_m A_m^{1+n} \cong (C_a - C_b) A_a^{1+n}. \quad (21)$$

So, C_m will be:

$$C_m \cong (C_a - C_b) \left(\frac{A_a}{A_m} \right)^{1+n}. \quad (22)$$

if a surface area of 0.01 km² is assumed for a mineralization, C_m will be equal to:

$$C_m \cong (100 A_a)^{1+n} (C_a - C_b). \quad (23)$$

This is revised equation allowing the estimation of the concentration or tenor of mineralization in a catchment to be estimated taking SDR into account, and will be applied to case studies in the following.

4. Case studies

In order to evaluate the validity and applicability of the modified equation, the existing and modified equations are both applied to the data presented by Hawkes a the stream sediment geochemical data obtained in part of Iran comprising proven gold mineralization indices. The next sections present the results obtained through employing these equations for the selected cases.

4.1. Hawkes's data

The data from three porphyry copper deposits investigated by Hawkes (1976) including Cerro Colorado (in Panama), Casino (in Canada) and Chaucha (in Ecuador) are used to apply the modified equation, i.e. Eq. (20), to the downstream dilution of stream sediment data as presented in Table 1. In this table, the three values are given for n , namely 0, -0.25 and -0.5, as in Eq. (20), where $n = 0$ corresponds to the results obtained by Hawkes.

For Cerro Colorado deposit, Hawkes's equation (i.e. linear relationship between downstream dilution and catchment basin area) has delivered closer values for concentration of mineralization in origin but they deviate largely if n is replaced by values smaller than 0.

However, for Casino deposit in which 2000 ppm is set as a cut-off contour, $n = -0.25$ and -0.5 return closer values to 2000 ppm. It should be mentioned that the value of 2000 ppm is considered by Hawkes as the boundary for mineralization, and higher concentrations could be found inside the boundary. In addition, concentration of MoS₂ in rocks was reported to be more than 100 ppm, and we converted it to Mo value, which became equal to or more than 60 ppm of Mo element. The results of employing the modified equation, especially for $n = -0.25$, show that C_m approaches to 60 ppm. Similarly, for Chaucha deposit, the estimated metal concentration at mineralization gets close to 1000 ppm where $n = -0.25$.

4.2. Stream sediment data from orogenic gold mineralization area, west of Iran

An area in the west of Iran has been found to contain proven gold mineralization and selected for studying the stream sediment samples

Table 1
Data presented by Hawkes (1976) to predict concentration at mineralization. These data are used to evaluate the modified equation based on Eq. (20). In this table, $n = 0$ corresponds to Hawkes's results, and $n = -0.25$ and -0.5 columns display new results.

Deposit name	Sample number	Element	Distance below deposit (km)	A _a (km ²)	A _m (km ²)	C _a (ppm)	C _b (ppm)	Tenor of source, C _m (ppm)			Actual
								Computed			
								n=0	n=-0.25	n=-0.5	
Cerro Colorado, Panama	1	Cu	47	300	1.5	160	115	9115	2416	640	7500 (ore)
	2		6	48	1.5	195	115	2675	1113	463	
	3		4	45	1.5	350	115	7165	3049	1298	
	4		2.5	16.5	1.5	650	115	6000	3279	1792	
	5		1	10.6	1.5	1308	115	8546	5225	3194	
Casino, Yukon	1	Cu	13	80.5	0.35	122	54	15694	4027	1033	2000+ (rock)
	2		10	39.4	0.35	306	54	28422	8722	2676	
	3		5	20.2	0.35	780	54	41955	15217	5519	
	4		1.6	2.34	0.35	1000	54	6379	3959	2457	
	1		Mo	13	80.5	0.35	2	1	231	59	
2	10	39.4		0.35	6	1	564	173	53		
3	5	20.2		0.35	6	1	290	105	38		
4	1.6	2.34		0.35	150	1	997	620	385		
Chaucha, Ecuador	1	Cu	45	900	4	69	40	6565	1692	436	1000+ (soil)
	2		4.5	356	4	300	40	23180	7544	2455	

collected in this region. The area is favorable for orogenic gold mineralization and is located on a 1:50000 Mirdeh geological map sheet.

4.2.1. Geological settings, sampling method and analysis

Mirdeh1:50000 geology map is located in the southwest of Saqqez 1:100000 map sheet, between longitudes 46° and 46° 15' E and latitudes 36° and 36° 15' N (Fig. 3). The symbols used for different lithology units are described in Appendix (Table A1). The area is favorable for orogenic gold mineralization, and detailed exploration activities have been done in some parts of it.

The oldest rock units in the region are mainly Precambrian metamorphic rocks consisting of gneiss and granite-gneiss, schist and gneiss, mica-schist, meta-rhyolites and metavolcanic units which are mainly expanded in the center, west and northwest of the area. Shale and sandstone rock units cover the southwestern part of the region that has undergone low-grade metamorphism. These units also contain thick sequences of green tuffs. The area contains formations from Permian with red sandstones overlaid by thick gray limestone layers. Jurassic-aged units are sequences of shale and thin-layered gray-green sandstones which are located over dolomite rocks dating back to Triassic or older. However, volcano-sedimentary Cretaceous entities are widely spread over the area in the southern and the northeastern parts. Lithologically, they are made up of alternations of shale, silt, limestone, dolomitic limestone, marble, tuff and

andesite, andesitic breccia and shale metamorphosed to schist and slate. In addition to the above units, plutonic igneous rocks are granite and gneissic granite which are the oldest intrusive bodies and cut through Precambrian metamorphic units in some parts of the region. Amphibole rich diorite-gabbros cut through Precambrian metamorphic rocks, and sill-shaped basic bodies intrude northwesterly into Cretaceous clastic-carbonate rock formations. Moreover, Quaternary deposits are spread in some parts of the area (Geological survey of Iran, 2002).

Five gold indices known as Qarehchar, Qabaqlujeh, Kervian, Hamzehqarenein and Qolqolah were recognized through stream sediment sampling and later geochemically explored in detail in order to delineate their exact positions. These mineralized zones are positioned in the southwestern part of the map (Fig. 3) and mainly represent orogenic type deposits associated with quartz veins (Aliyari et al., 2012; Geological survey of Iran, 2008).

In this research, 299 stream sediment samples were used. The samples were smaller than 40 mesh in size and covered an area of 617 km². Au and W were employed in the present research. The fire assay technique was used for Au analysis, and W was analyzed by ICP (Alizadeh-Dinabad et al., 2013). Duplicate analyses (30 pairs) were employed to control the quality of the laboratory analysis through the method proposed by Thompson and Howarth (1976). They displayed precision of the analysis to be better than

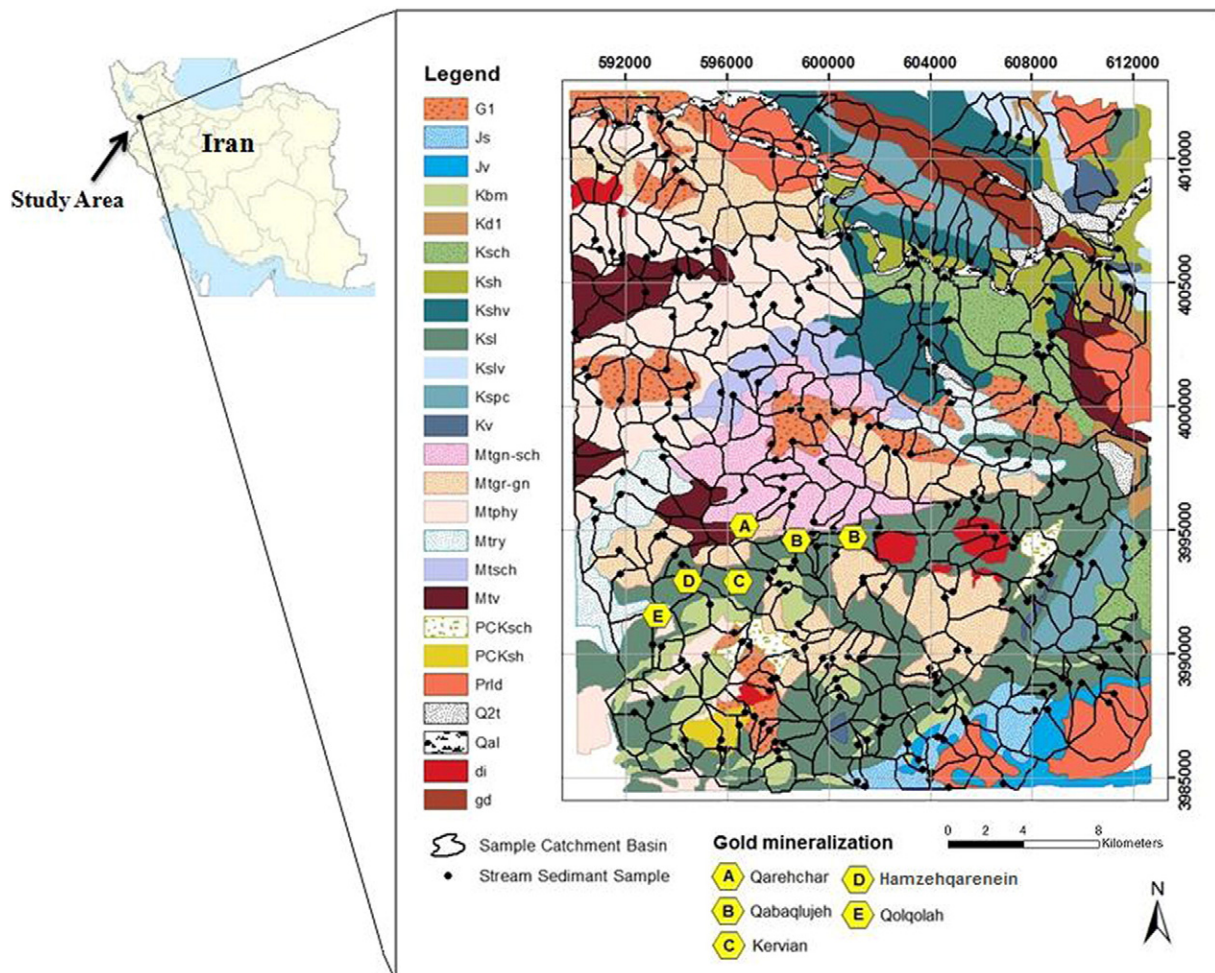


Fig. 3. Lithologic map of the study area (adopted from Saqqez 1:100,000 scale geological map, Geological Survey of Iran), stream sediment sampling points, their catchment basins and position of known gold indices.

Table 2
Summary statistics for Au and W in stream sediments of the study area.

Element	Mean	Min	Median	Max	StDev.
Au (ppb)	6.62	0.08	1.42	739.26	44.36
W (ppm)	3.47	2.3	3	11.6	1.36

± 10%. A statistical summary of the above elements is given in Table 2.

4.2.2. Estimation of background values

A major part of the variation in the geochemical dataset can be due to the lithologic variation regardless of presence or absence of any mineralizing source. Therefore, the variation that is due to the changes in the background content of elements of interest has to be eliminated prior to delineation of anomalous catchment basins. One of the widely used methods to estimate the background concentration of each lithologic unit for every element is the weighted average method that takes into account the area of lithologic units in every sample catchment basin (Bonham-Carter et al, 1987; Carranza and Hale, 1997; Carranza, 2009). In the present research, this technique is employed to calculate the background content of Au for each lithologic unit in the study area.

If A_{ij} is the area of the j th ($j=1, 2, \dots, p$) lithologic unit in the sample catchment basin i ($i=1, 2, \dots, q$) and C_i represents the metal concentration of the sample at the basin outlet, the following equation delivers the weighted average element concentration M_j ($j=1, 2, \dots, p$) for the j th lithologic in which the sum term in the denominator is the total area of lithology j (Carranza, 2009).

$$M_j = \frac{\sum_{i=1}^q C_i A_{ij}}{\sum_{i=1}^q A_{ij}} \quad (24)$$

The local background concentration of the element (C'_i) at the basin outlet due to lithology can be estimated by Eq. (25) (Carranza, 2009):

$$C'_i = \frac{\sum_{j=1}^p M_j A_{ij}}{\sum_{j=1}^p A_{ij}} \quad (25)$$

where $\sum_{j=1}^p A_{ij}$ in the denominator is equal to the total area of the i th sample catchment basin.

4.2.3. Dilution correction of residuals

The residual value ($C_i - C'_i$) for every catchment basin can take a positive or negative value to be interpreted as enrichment or depletion respectively. As enrichment of elements is taken into account in exploration; only positive values are further processed for dilution.

In order to calculate the corrected residual values for downstream dilution, Eq. (23) may be used. As there was no known n at hand, three arbitrary equidistant n values including $n = 0$, -0.25 and -0.5 were considered for the study area. The power of catchment basin area ($1 + n$), thus, becomes less than 1 (except for $n = 0$), resulting in dampening of the growing rate of residuals by the basin size.

4.2.4. Statistical and fractal analysis of results

In order to evaluate whether or not the results of applying Hawkes's and the modified formulas are statistically different from each other, Sign test and Wilcoxon signed-rank test (Reimann et al., 2008) were run on the results of dilution corrected values of Au resulting from Eq. (23). The results of applying $n = 0$ (corresponding to Hawkes's equation) and $n = -0.25$ and also $n = 0$

Table 3
Statistical analysis of dilution corrected residuals of Au by non-parametric Sign test and Wilcoxon signed-rank test using Hawkes's and modified equations.

		Sample 1: $n=0$	Sample 1: $n=0$
		Sample 2: $n=-0.25$	Sample 2: $n=-0.5$
Sign test	N+	120	120
	Expected value	60	60
	Variance (N+)	30	30
	p-value (two-tailed)	<0.0001	<0.0001
Wilcoxon signed-rank test	alpha	0.05	0.05
	V	7260	7260
	Expected value	3630	3630
	Variance (V)	145805	145805
	p-value (Two-tailed)	<0.0001	<0.0001
	alpha	0.05	0.05

and $n = -0.5$ are compared. In these tests, the null and alternative hypotheses are as follows:

H₀: The two samples follow the same distribution.

H_a: The distributions of the two samples are different.

The results of Sign test and Wilcoxon signed-rank test are presented in Table 3. As it can be seen, both tests have proven that the results of applying the power function to correct the residual values significantly ($\alpha=0.05$) differ from the linear formula ($n = 0$).

In the present research, W is also used as a pathfinder element as it is reported to be associated with Au (Geological survey of Iran, 2008). Furthermore, comparison has been made between the maps produced from different dilution correction values. The comparison actually draws upon the results of applying the above three n values (Fig. 4). Fractal analysis is used in order to delineate the classes inside the dataset and highlight the promising zones. Different thresholds of Au and W are determined using the concentration-area fractal technique (the corresponding plots are presented in Appendix, Fig. A1). As the fractal analysis is not the main point of this paper, details about this method are not given here but can be found in textbooks and other papers (e.g. Cheng, et al., 1994; Carranza, 2009 and Geranian et al., 2013). Moreover, positions of the known gold occurrences have been taken into account to evaluate models efficiency (Fig. 4).

A considerable part of the area is differentiated as non-promising zones after removing the lithological effect from the stream sediment samples. Consequently, target catchments are limited to those catchments basins labeled as anomaly or higher. Similarly, W displays clusters of high-ranking anomalies in this part of the map although discrepancies exist between the spatial distributions of concentration of these two elements (Fig. 4).

In spite of overall consistency in the general trending of anomalous Au basins between maps generated by using different n values, there are variations in basins in terms of their anomaly ranking classes. Some basins gain higher anomaly ranks for $n = -0.25$ and -0.5 compared to $n = 0$. On the other hand, some basins appear in lower classes. To have a closer look, six catchment basins were selected, and their IDs were marked in Fig. 4. Table 4 reveals the figures about these catchment basins and the changes in their importance in terms of favorability based on Au fractal analysis. Catchment 241, in spite of its large area size, did not show changes in terms of favorability by variation in the n value, remaining as a background, which can be attributed to its low residual value. On the contrary, catchment 100 varied from anomaly to high anomaly and then to very high anomaly as a result of dampening the area size effect in dilution correction. Considering the relatively small area size of this catchment, it can be inferred that applying different n values must have lowered the position of larger catchment basins, pushing

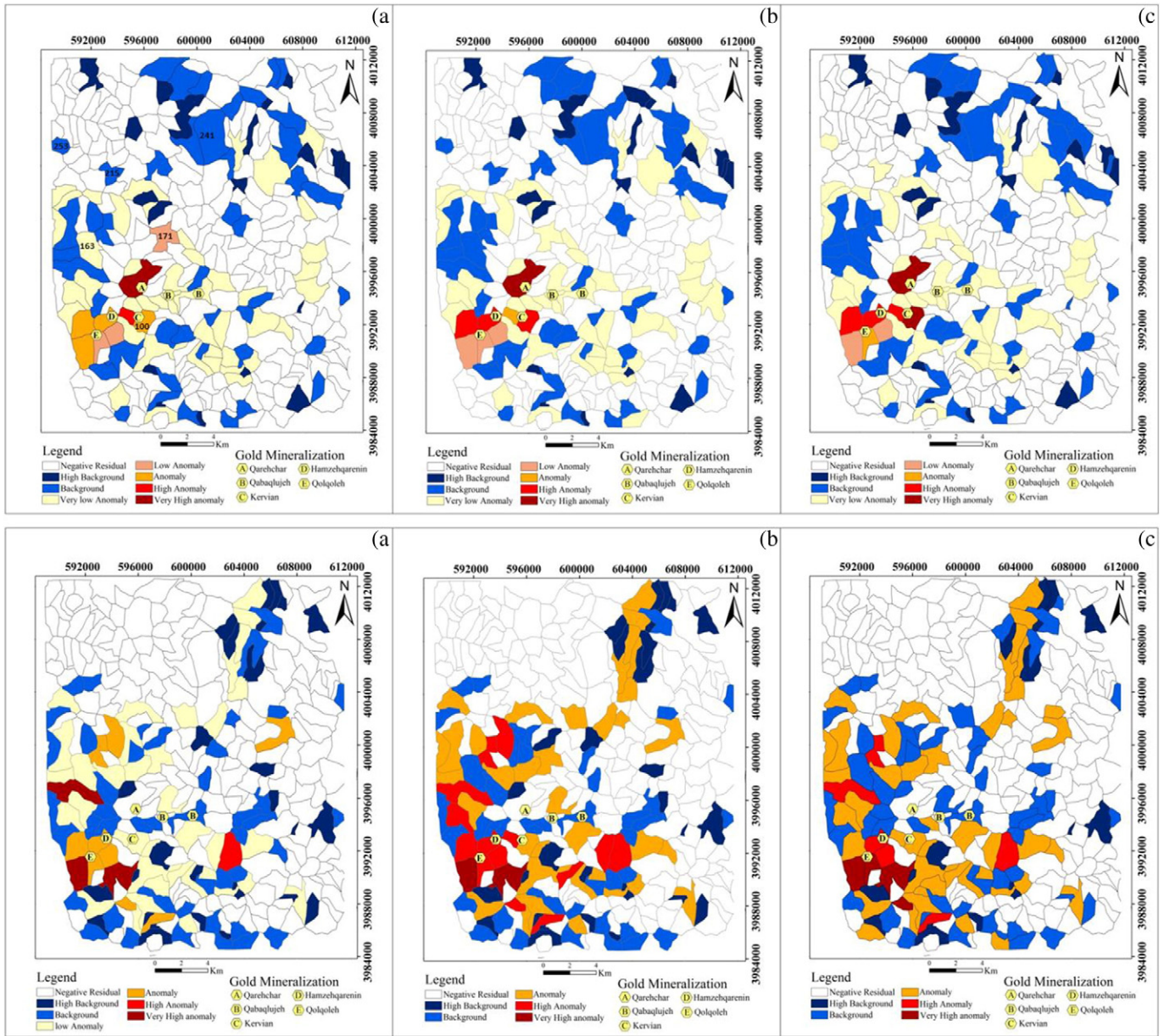


Fig. 4. Anomaly delineation for Au and W through fractal analysis of dilution corrected residuals, a) $n = 0$, b) $n = -0.25$ and c) $n = -0.5$ in the study area. The numbers in some of the catchments, on the top left map, represent the selected catchment basins IDs.

catchment 100 to higher ranks. Also, as it is understood from Table 4 and Fig. 4, catchment 171 has a lower position after using a nonlinear relationship on its residual value.

Sample catchment basin approach was successfully used to delineate the proven Au occurrences situated in the southwest of the area

mainly in the metamorphosed units apart from “B” mineralization. The catchments adjacent to this mineralization were classified as ‘low anomaly’. This issue could have arisen due to the position of this index that is located downstream of a larger catchment basin. In other words, dilution from upper catchments may have caused

Table 4
Figures for six selected catchment basins and their ranks based on fractal analysis of Au values.

Catchment ID	Area (km ²)	Y _i (ppb)	Y _i (ppb)	Residual (ppb)	Ranking of dilution corrected values of residuals		
					$n = 0$	$n = -0.25$	$n = -0.5$
171	2.84	19.34	2.17	17.17	Low Anomaly	Very Low Anomaly	Very Low Anomaly
253	1.32	3.66	1.85	1.81	Background	Background	Very Low Anomaly
215	1.74	3.06	1.67	1.39	Background	Background	Very low Anomaly
241	7.62	1.22	1.06	0.16	Background	Background	Background
0.85	2.04	2.89	3.79	163	Very low Anomaly	Background	Background
100	1.96	123.5	3.10	120.41	Anomaly	High Anomaly	Very High Anomaly

considerable dilution to the samples at lower elevations. Other Au indices that are relatively located in upper catchments basins are differentiated acceptably by the technique.

5. Discussion and conclusion

Many factors control the delivery process of eroded materials from a catchment basin surface to its outlet. If a basin is divided into different morphological units, it would be possible to calculate the amount of sediments that can be delivered at the basin outlet from every unit. However, this is not practical in mineral exploration as the position of mineralization is unknown. So, not every developed model can be used for the sediment delivery of a catchment basin in stream sediment geochemical exploration.

Sediment delivery ratio is one of the parameters in sedimentological studies that can be used to calculate the amount of dilution arising from background materials over mineralization sourced sediments. The issue of using this ratio has been overlooked in geochemical literature for the calculation of the downstream dilution of geochemical anomalies and, consequently, applying an equation in which a linear relationship is set between dilution and catchment basin size of each sample may lead to a considerable deviation from the reality. In general, SDR shows a negative power relationship with basin size; therefore, the closer step to the reality of dilution corrected values of residuals may be taken if the effect of the sample catchment basin size is dampened by a power less than 1. This could also help to prevent generation of outlier data where catchment basins become large, as noticed by Moon (1999). In order to deter-

mine the exact “ n ” value to which the basin size should be powered, it is required to have sedimentological data for the study area through field measurement of the sediment yield. Three suggestions are made to find the “ n ” value: first, to obtain “ n ” from previous completed works if available; second, to hire an “ n ” value from studies on similar trains; and third, taking $n = -0.2$ (García, 2008).

The proposed new equation for the downstream dilution of stream sediment anomalies is the generic form of Hawkes's equation in which $n = 0$ delivers an equation identical to Hawkes's equation. It is evident from Hawkes's study (Table 1) that, where basins become smaller and smaller, the estimated concentration of the existing formula and that of the modified one get closer to each other.

However, if the sampling is carried out in a way that catchment basins are generated with almost equal sizes, the differences between the results achieved by Hawkes's and the modified equations become negligible. This can be understood from the second case study in this paper.

In situations where the sampling density in a study area is not evenly distributed, the resulting sample catchment basins would have different area sizes. Then, application of the modified equation is recommended for removing the dilution effect from positive residuals.

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Appendix A

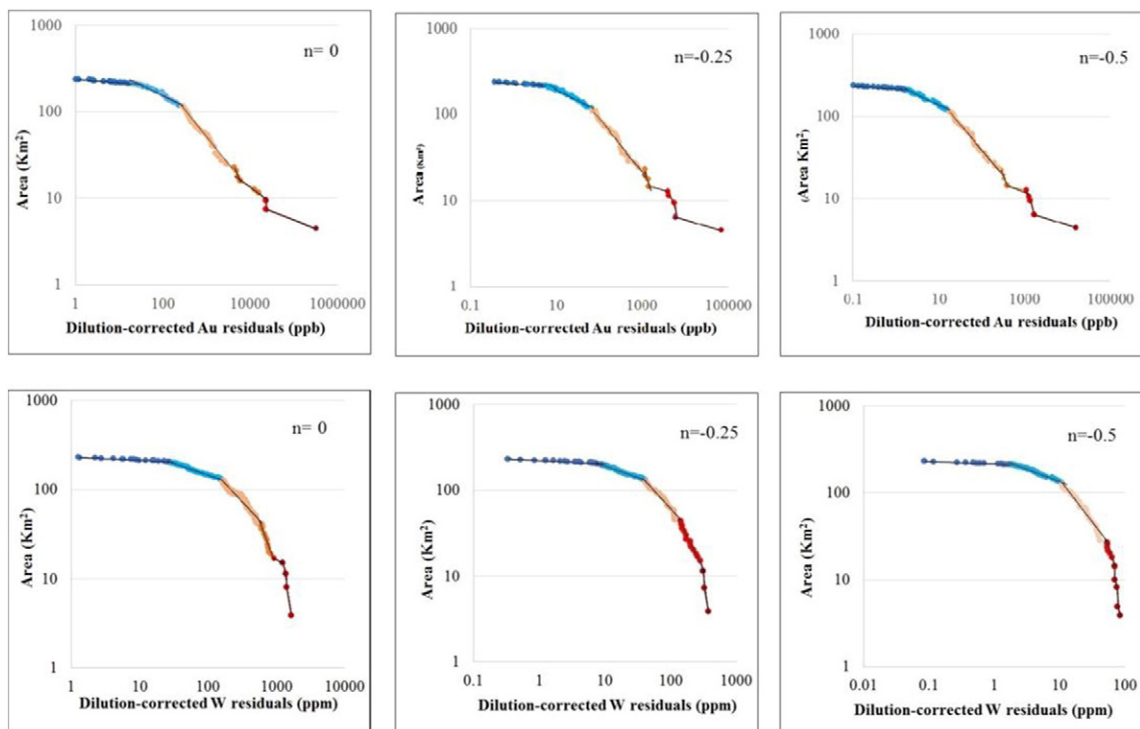


Fig. A1. Concentration–Area plots of fractal analysis of Au and W for different n values.

Table A1

Description of lithology notations used in Fig. 3.

Symbol	Description
G1	Pink quartz – feldspathic foliated granite
Js	Green – grey tuffaceous shale, sandstone, micro conglomerate and shale
Jv	Epidotized and cloritized andesitic – basaltic lava
Kbm	Light, grey marmorized dolomite and limestone
Kd1	Dark to light grey dolomite and limestone
Ksch	Dark grey schist, slate, metasilts and sandstone
Ksh	Thin bedded grey penfield shale slate and schist stone
Kshv	Alteration of volcanic rocks and black shale
Ksl	Alternation of grey shale, shaley limestone, limestone, metamorphosed
Kslv	Alternation of limestone and volcanic rocks (andesitic lavas and tuffs)
Kspc	Grey green tuff, tuffaceous sandstone
Kv	Grey to green andesitic lavas and volcanic breccias
Mtgn-sch	Alternation of light quartzofeldspathic gneiss and mica schist
Mtgr-gn	Quartzofeldspathic gneiss and granite – gneiss
Mtphy	Green slate, phyllite and quartzite
Mtry	Metarhyolite : green rhyolitic gneiss and schist
Mtsch	Grey mica schist and quartzite schist
Mtv	Meta volcanite : chlorite – epidote schist; quartz chlorite – epidote schist
PCKsch	Schist, slate, phyllite, meta tuff and sandstone
PCKsh	Greenish grey slaty shale and siltstone
Prlid	Grey crystallized limestone, dolomitic limestone
Q2t	Young terraces (silt, clay, sand)
Qal	Recent alluvium
di	Hornblende metadiorite
gd	Micro diorite and gabbro

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