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A modified equation for the downstream dilution of stream sediment anomalies

Ahmad Reza Mokhtari *, Sima Garousi Nezhad

Department of Mining Engineering, Isfahan University of Technology, Isfahan 8415683111, Iran

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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 "$C_mA_m = A_a(C_a - C_b) + C_bA_m$" 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 "$C_mA_m^{1+n} = C_aA_a^{1+n} - C_b(A_a - A_m)^{1+n}$" 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.

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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* Corresponding author.
E-mail address: ar.mokhtari@cc.iut.ac.ir (A.R. Mokhtari).

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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 Minacaoilli, 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 tonne km^{-2} $year^{-1}$ (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 tonne km^{-2} $year^{-1}$. 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 Minacaoilli, 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:

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

However, many factors control SDR, such as climate, soil properties, drainage area, stream length and land use (Ferro and Minacaoilli, 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 Minacaoilli, 1995; Ferro, 1997). The general form of the equation for SDR and basin size is:

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

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 Minacaoilli, 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 Minacaoilli, 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

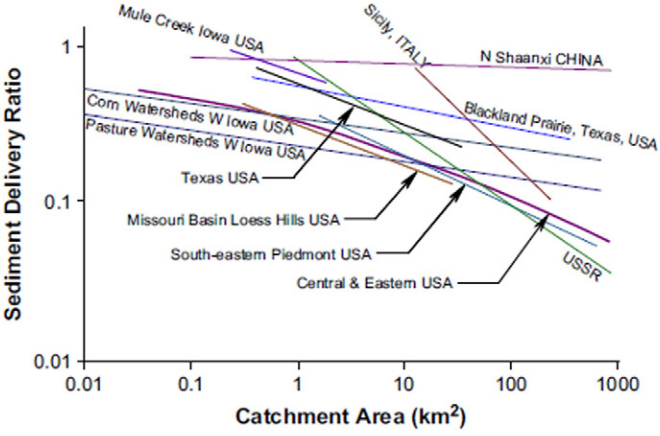

Fig. 1. Relationship between SDR and area size of a basin in different regions (Lu et al., 2006).