Full Length Research Paper

Effective discharge for suspended sediment transportation in Ghohruod watershed

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Soil erosion and sediment transport is a phenomenon that happens due to rainfall and water flow on the ground surface in different regions and scales. Different flow values have different effects on this process, so that any change in flow results in suspended sediment content change. Therefore, different flow performance and dominant flow determination (effective discharge) data are necessary for designation and implementation of proper soil erosion and sediment yield control projects along with watershed management. The main objective of present study was to estimate effective discharge for suspended sediment transportation in Ghohruod watershed in Iran with an area of 9091.34 ha. Suspended sediment and flow discharge data for a period of 20 years were applied. After preparing suitable sediment rating carves and data augmentation, the average daily discharge in each statistical year was calculated. Then, discharge values during the period were divided into same intervals. Discharge frequency and cumulative suspended sediment determined for each specific discharge class was plotted as histogram. Effective discharge and its frequency were determined by sediment-discharge histogram scrutinizing. Results demonstrated that effective discharge for the study station was in low flow class and equal to 0.125 m³/s with 46 days frequency and 21.8% flow duration.

Key words: Effective discharge, sediment transport, suspended sediment, sediment rating curve, Ghohruod watershed, Iran.

INTRODUCTION

In many developing countries sustainable land and water resources management are threatened by soil erosion and sediment related problems (Walling et al., 2001). Awareness of affecting factors on erosion process and sediment yield is very necessary to reduce the inside and outside soil erosion hazards and to right natural resources management. Rivers show very different behaviors in different situations of soil erosion. Alluvial rivers construct their own geometries to transport the water and sediment supplied from the drainage basin (Gomez et al., 2007) and discharges with different value have numerous effects, especially in long term, including flow magnitude (volume) and frequency (Esmaeili and Mahdavi, 2002). Hence, flows value and their frequency are very important factors in sediment transport process. Leopold (1994) believes that small flows have abundant frequency but don’t have enough power to transport large amount of sediment. Meanwhile, great flows have great sediment transport power and low probability.

Therefore effective discharge is a flow with mediocre discharge between small and large flows and it was originally defined as a discharge or a range of discharges that are able to transport the largest portion of sediment load in the long-term (Wolman and Miller, 1960; Lenzi et al., 2006; Ma et al., 2010). Effective discharge values are routinely used to characterize the geomorphic impact/work that different flows have on streams and watersheds (Crowder and Knapp, 2005). Therefore, information on effective discharge is very necessary for each region to designate and implement proper soil erosion and sediment yield control projects.

Many researches focused on determination of effective discharge and its role in soil and water resources
management. Wolman and Miller (1960) wrote one of the preeminent discussions associated with effective discharge and dominant discharge theory. They argued that over long period of time smaller more frequent flows, but not infrequent catastrophic flows (e.g., 100- and 500-year floods) carry the most sediment within streams. Pickup and Warner (1976) found that in Cumberland watershed in Australia, effective discharge values were significantly different. Comprehensive researches have been done on effective discharge in different places around the world (Nash, 1994; Emmett and Wolman, 2001; Esmaeili and Mahdavi, 2002; Simon et al., 2004; Crowder and Knapp, 2005; Lenzi et al., 2006; Feiznia et al., 2006; Schmidt and Morche, 2006; Gomez et al., 2007; Ma et al., 2010).

The results of all studies in different ecosystems entirely highlight the importance of magnitude and power flows role in suspended sediment transport process and emphasize on comprehensive researches in this field. Therefore, the intention of this study was determination of effective discharge for suspended sediment transportation in Gohroud watershed.

MATERIALS AND METHODS

Study area

The present study took place in the Gohroud watershed with an area of 9091.34 ha, located in Esfahan Province (Figure 1).
Elevations vary from 1759 to 3041.5 with an average of 2400.25 m above mean sea level. The watershed is deeply incised with a dominant gradient of 30 to 60%. Maximum, minimum and mean annual precipitation in this watershed is 228.1, 199.2 and 209.2 mm, respectively. Mean annual temperature is 10.2°C with maximum and minimum monthly temperature of -9.1 and 30.3°C in December and May, respectively. The region including the study site has semi-arid and cold with dry season in summer at the lower part (with the elevation lower than 2400 m), while humid and cold with very hot and dry season in summer at the upper areas of the watershed (with the elevation more than 2400 m) based on Köppen climate classification.

Date collection

Data of the nearest station as Gabrabad station was used. To achieve this research, necessary suspended sediment and discharge data was collected from Isfahan Water Regional Company during a twenty-year period (1986 to 2006). It depends on river condition, in some months there wasn’t any data and there was missed data for some month.

Data analysis

After preparing data, missed data augmentation was calculated by using of sediment rating curves. Different statistical models were applied for the study, including both linear and nonlinear models using ordinary and transformed data, viz. square root, inverse square root and their combination. This has the general expression (Sadeghi et al., 2008; Sadeghi and Saeidi, 2010):

\[ \text{SSC} = f(Q) + \eta \]  

(1)

Where SSC represents the suspended sediment concentration (g L\(^{-1}\)), Q is corresponding water discharge (m\(^3\) s\(^{-1}\)), and \(\eta\) is a residual error between observation and prediction. Different statistical criteria, namely, correlation coefficient (\(r\)), significant level of \(p\) value, standard error of estimate (SE), relative and absolute error of estimation (RE), coefficient of efficiency (CE) and root mean of square error (RMSE), were calculated using Equations 2 to 6 to evaluate the fitness, soundness and reasonability of the regression models (Sadeghi et al., 2008; Sadeghi and Saeidi, 2010) where \(N\) is the number of samples (\(i = 1,2,\ldots\)):

\[ r = \sqrt{1 - \frac{\sum_{i=1}^{n} (SSC_o - SSC_E)^2}{\sum_{i=1}^{n} (SSC_o - SSC_A)^2}} \]  

(2)

\[ SE = \frac{\sum_{i=1}^{n} (SSC_o - SSC_E)^2}{N(N-1)} \]  

(3)

\[ RE = \frac{(SSC_o - SSC_E)}{SSC_o} \times 100 \]  

(4)

\[ \text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (SSC_o - SSC_E)^2}{N}} \]  

(6)

Where \(SSC_o, SSC_E\) and \(N\) are observed SSC, estimated SSC and number of observations in data set, respectively. The model with higher \(r\) and smaller other criteria (\(p\) value, SE, RE and RMSE) was supposed as the best performing model (Sadeghi et al., 2008, Sadeghi and Saeidi, 2010).

Effective discharge calculation

The range of discharges is subdivided into a number of arithmetic and equal-size intervals, referred to as "intervals of stream discharge" (Benson and Thomas, 1966) or "class intervals" (Biedenharn et al., 1999; Crowder and Knapp, 2005).

As noted in previous studies, the choice of the size of class interval (CI) or the number of flow discharge classes (\(N\)) has generally been empirical (Pickup and Warner, 1976; Lenzi et al., 2006). Typically, Yevjevich (1972) stated that the class interval of flow discharge should not be larger than \(S/4\), where \(S\) is the standard deviation of flow discharge for the sample concerned, and that the number of classes should be between 10 and 25, depending on the sample size (Ma et al. 2010). For simplicity, the effective discharge value is considered to be the midpoint of that interval. For simplicity by using the midpoint of discharge value of each class and the best selected sediment rating curve, an estimate is made of the average sediment load that the discharges carry within each class interval. The total suspended sediment load transported by each class interval was estimated by multiplying the class interval’s average suspended sediment load by the number of flow days occurring within that class interval. Finally, the suspended sediment loads in all corresponding classes were calculated and plotted in a histogram against the representative discharges. The flow discharge corresponding to the peak of suspended load in the histogram is then determined as effective discharge (Crowder and Knapp, 2005; Ma et al., 2010).

RESULTS AND DISCUSSIONS

Fitting the SSC–Q relationship

For computing of suspended sediment amounts, 4 common regression equations as linear, logarithmic, power and exponential were fitted to the dataset. The results of application of different types of regression fitting procedures established for the entire data collected at study area are summarized in Table 1.

The results of the SSC–Q relationship analysis (Table 2) show that almost all of models were statistically significant. However, the correlation coefficient between SSC and Q data was low. Based on the result of Table 2, linear and logarithmic models had higher SE, estimation and validation absolute RE than other two models. Linear model had the least RMSE.

High variability of regression coefficients and parameters clearly indicated high variability of SSC–Q relationships. It also emphasized on combined effects of
variability of affecting factors of sediment availability, ecosystem complexity and rainfall characteristics during categorized datasets. Similar findings have also been reported by Sadeghi et al. (2008) through conducting a cause-and-effect analytical study in a reforested watershed in Sadeghi and Saeidi (2010) in educational forest watershed of Tarbiat Modares University in Iran. Low correlation coefficient between SSC and Q data indicated the poor association between discharge and SSC.

This finding agrees with the results reported by Sorriso-Valvo et al. (1995) in connection with poor correlation between annual average discharge and SSC from the forested north facing slopes in a small Calabrian watershed, Schmidt and Morche (2006), (regression correlation of 30 to 80%) in two small mountainous Bavarian Alps watersheds in Germany, Sadeghi et al. (2008), in the Mie watershed, Sadeghi and Saeidi (2010) in educational forest watershed of Tarbiat Modares University in Iran.

According to the equations and rating curves in Table 1, it is also found that, the power function gave a better performance. This agrees with the findings of Asselman (2000), Kao et al. (2005) and Sadeghi et al. (2008), who believed power models are the most common function that relates SSC to water discharge. However, it opposes Asselman (2000), Horowitz (2003), Sadeghi et al. (2006) and Schmidt and Morche (2006), who found that the other types of regression models (e.g. linear, quadratic, cubic, three-parameter power, exponential and quadratic) sometimes performed better than simple power type equations.

Sediment output from the basins was calculated for the individual measuring periods using the rating curves. Results from this study (Table 1) show that sediment rating curve as the power form in follow equation with the

### Table 1. Regression models in relationships between suspended sediment concentration (SSC, g L⁻¹) and discharge (discharge, m³ s⁻¹) in Ghohroud watershed.

<table>
<thead>
<tr>
<th>Row</th>
<th>Model</th>
<th>r</th>
<th>P value</th>
<th>SE</th>
<th>Absolute RE (%)</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Estimation</td>
<td>Validation</td>
</tr>
<tr>
<td></td>
<td>Y=285.825X-30.425</td>
<td>0.91</td>
<td>0</td>
<td>29.44</td>
<td>1152.22</td>
<td>1001.44</td>
</tr>
<tr>
<td>2</td>
<td>Y=41.64LnX+105.94</td>
<td>0.56</td>
<td>0.002</td>
<td>44.11</td>
<td>1921.42</td>
<td>1151.47</td>
</tr>
<tr>
<td>3</td>
<td>Y= 59.01X1.4</td>
<td>0.61</td>
<td>0.001</td>
<td>1.34</td>
<td>176.41</td>
<td>146</td>
</tr>
<tr>
<td>4</td>
<td>Y=0.91e7.276X</td>
<td>0.47</td>
<td>0</td>
<td>1.74</td>
<td>195.64</td>
<td>123.34</td>
</tr>
</tbody>
</table>

### Table 2. Amount and frequency of suspended sediment and discharge.

<table>
<thead>
<tr>
<th>Row</th>
<th>Range</th>
<th>Mean class</th>
<th>Sediment (t/day)</th>
<th>Frequency (day)</th>
<th>Sediment × Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-0.05</td>
<td>0.025</td>
<td>0.33</td>
<td>8</td>
<td>2.62</td>
</tr>
<tr>
<td>2</td>
<td>0.05-0.1</td>
<td>0.075</td>
<td>1.54</td>
<td>90</td>
<td>138.44</td>
</tr>
<tr>
<td>3</td>
<td>0.1-0.15</td>
<td>0.125</td>
<td>3.16</td>
<td>46</td>
<td>145.26</td>
</tr>
<tr>
<td>4</td>
<td>0.15-0.2</td>
<td>0.175</td>
<td>5.07</td>
<td>28</td>
<td>142</td>
</tr>
<tr>
<td>5</td>
<td>0.2-0.25</td>
<td>0.225</td>
<td>7.22</td>
<td>19</td>
<td>137.26</td>
</tr>
<tr>
<td>6</td>
<td>0.25-0.3</td>
<td>0.275</td>
<td>9.58</td>
<td>8</td>
<td>76.67</td>
</tr>
<tr>
<td>7</td>
<td>0.3-0.35</td>
<td>0.325</td>
<td>12.12</td>
<td>2</td>
<td>24.245</td>
</tr>
<tr>
<td>8</td>
<td>0.35-0.40</td>
<td>0.375</td>
<td>14.83</td>
<td>2</td>
<td>29.66</td>
</tr>
<tr>
<td>9</td>
<td>0.4-0.45</td>
<td>0.425</td>
<td>17.7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>0.45-0.50</td>
<td>0.475</td>
<td>20.69</td>
<td>1</td>
<td>20.69</td>
</tr>
<tr>
<td>11</td>
<td>0.5-0.55</td>
<td>0.525</td>
<td>23.82</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>0.55-0.6</td>
<td>0.575</td>
<td>27.07</td>
<td>1</td>
<td>27.073</td>
</tr>
<tr>
<td>13</td>
<td>0.6-0.65</td>
<td>0.625</td>
<td>30.45</td>
<td>2</td>
<td>60.89</td>
</tr>
<tr>
<td>14</td>
<td>0.65-0.7</td>
<td>0.675</td>
<td>33.93</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>0.7-0.75</td>
<td>0.725</td>
<td>37.52</td>
<td>2</td>
<td>75.04</td>
</tr>
<tr>
<td>16</td>
<td>0.75-0.80</td>
<td>0.775</td>
<td>41.22</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>17</td>
<td>0.8-0.85</td>
<td>0.825</td>
<td>45.01</td>
<td>1</td>
<td>45</td>
</tr>
<tr>
<td>18</td>
<td>0.85-0.90</td>
<td>0.875</td>
<td>49</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>19</td>
<td>0.90-0.95</td>
<td>0.925</td>
<td>52.88</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>0.95-1.0</td>
<td>0.975</td>
<td>56.94</td>
<td>1</td>
<td>56.94</td>
</tr>
</tbody>
</table>
correlation coefficient \((r)\) equal to 61.00\% was the best equation to define the suspended sediment and flow discharge data.

\[
Q_s = 59.01 \times Q_w^{1.408}
\]  \hspace{1cm} (1)

**Effective discharge results**

Main aim of this research was estimation of effective discharge. Effective discharge is an important concept in sediment transport process. Effective or dominant discharge is defined as the flow or flow class which performs most work in terms of sediment transport (Wolman and Miller, 1960). This paper follows the original concept of Wolman and Miller in which effective discharge is the water discharge that transports more sediment than any other discharge (Emmett and Wolman, 2001; Crowder and Knapp, 2005; Ma et al. 2010).

The analysis of grouped datasets show that maximum, minimum and standard deviation of flow discharge in studied watershed was equal to 0.962, 0.03 and 0.185, respectively. Hence, based on Yevjevich’s results (1972) the number of class intervals in the present study was 20. Result of the suspended sediment and discharge coupled with their histograms are presented in Table 2, and Figures 2 and 3, respectively.

Coefficient of variation \((C_{vd})\) (the ratio of the standard deviation of all discharges to their mean value; Yevjevich (1972) for this region is 0.185. The value of \(C_{vd}\) indicates that flow variability is notably small in the region. This reflects the relative lower magnitude of extreme flow events in this region. According to results from Table 2 and Figures 2 and 3, in the Ghohroud watershed, effective discharge value is equal to 0.125 m\(^3\)/s with 46 days frequency that has lower magnitude and higher frequency than the other discharge. Based on the S/4 class interval, histograms of suspended sediment transport in the Ghohroud watershed generally have multi-peak forms (Figure 2). In this type, effective discharge is located within the range of low or moderate flows with a notable peak (Figure 2). These events have high flow frequency and small magnitude. The suspended sediment transport in the study watershed is characterized by a bimodal dominant discharge. This finding conforms to those of Miller and Wolman (1960), Richard et al. (1999), Schmidt and Morche (2006) in small high mountain catchment (Reintal) in German and Esmaili and Mahdavi (2002) in Zayandeh-rood Dam basin who find that effective discharge in their study basin is in lower class. These findings are opposes to findings of Ashmore and Day (1988) on streams in the Saskatchewan River basin in Canada, Schmidt and Morche (2006) in Lahnenwiesgraben region in Bavaria, Ma et al. (2010) in China which both extreme and more frequent flow events are defined as effective discharges. However, results from this study differ considerably with some studies performed in other areas, where average effective discharge duration occurs between 0.4\% and
Figure 3. Discharge class frequency histogram.

3% of the time (1.5–16 days year$^{-1}$) (Wolman and Miller, 1960; Pickup and Warner, 1976; Simon et al., 2004). In the other words, result of histograms analysis show that flow with high value carry high suspended sediment content but in a long period, the higher frequency of low and moderate flows have the most important role in sediment transport. This result disagrees with some mentioned researches.

**Conclusion**

The aim of present study was estimation of effective discharge for suspended sediment transportation in Gohroud watershed. Therefore, necessary suspended sediment and discharge data was collected. Sediment rating curve in the form of a power curve was selected as the best equation to define the suspended sediment and flow discharge relations. According to results of this study, effective discharge for suspended sediment transport in Gohroud watershed did not have high recurrence intervals and it shows that mentioned discharge is able to erode river bed and land surface. However, the lower discharges have a lower flow power and higher discharges have a low frequency in compare with the evaluated effective discharge. Therefore lower and higher discharges do not have necessary ability for high suspended sediment content transport. Further extensive studies with accurate, longer and comprehensive hydrological and climatological datasets with regards to temporal variation of effective discharge for the same study area and other watersheds with different conditions are accordingly advised.

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