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# Spatial variation of sediment yield using PSIAC model and reservoir sediment survey

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**ABSTRACT**

One of the most important concerns in arid and semi-arid areas of Iran is water erosion and sediment transport. Several experimental models were used for predicting the erosion severity and sediment yield in a sub-catchment area. These models are often developed for different regions than those in which they are applied. Therefore more field data should be gathered for model calibration and, ultimately, a better evaluation of method should be undertaken. However because of insufficient and less reliable sediment yield data in Iran the objective of this study is to evaluate the output results of PSIAC model in five small catchments, Semnan Province, Iran using reliable sediment yield data deposited in reservoir constructed in the outlet of these catchments. Correlation analysis showed that Upland erosion is closely related to Specific Sediment Yield ($r^2$= 0.86). Comparison of the amount of PSIAC predicted and observed reservoir sediment SSY indicate that model was predicted lower than observed values in one catchment (Amrovan) and higher in four other catchments but these differences are not considerable in catchment scale.

## Introduction

One of the most important concerns in arid and semi-arid areas is water erosion and sediment transport. Soil particle transmission from farm and orchards to other areas causes the fertility of such lands decreases gradually. Moreover, sedimentation in water channels clogs the water ways; it may also transfer pollutants into farm lands and dams, which are used for irrigation and drinking purposes (Sarmadian et al., 2010). Several experimental models were used for predicting the erosion severity and sediment yield in a sub-catchment area. These models are often developed for different regions than those in which they are applied. However, more field data should be gathered for model calibration and, ultimately, a better evaluation of any method should be undertaken. (Sadeghi, 2005). The commonest models now being used are USLE (Mati et al., 2000; Erskine et al., 2002), MUSLE (Modified Universal Soil Loss Equation), WEPP (Water Erosion Prediction Project), RUSLE (Revised Universal Soil Loss Equation) (Millward and Mersey, 1999, 2001; Raghunath, 2002), EPM (Erosion Potential Method) (Refahi and Nematti, 1995; Tangestani, 2001), and PSIAC (Pacific Southwest Inter-Agency Committee) (Nelson and Rasele, 1989;Heydarian, 1996; Clark, 2001). The PSIAC model (PSIAC, 1968) estimates total annual sediment yield, not just sheet and rill erosion (PSIAC, 1968). The procedure was developed for sub-catchments in the western United States greater than 30 km2; however, it has also been applied to smaller basins. Compared to other empirical methods, the PSIAC model considers the greatest number of factors, so the results are more realistic and it is believed to be appropriate for the same environmental conditions in Iran (Sadeghi, 1993; Bagherzadeh, 1993; Jalalian, 1992). The procedure considers nine factors that depend on surface geology, soils, climate, runoff, topography, ground cover, land use, channel erosion, and upland erosion. Each factor is subdivided into different categorical classes, and based on the degree of impact of each factor class; a weighting value will be assigned to each class using the model tables (PSIAC, 1968). However this model cannot be applied directly and must be evaluated firstly. Most of the evaluation had been based on sedimentary station statistics that affected by variation in flow of the River during the study period, and the timing of the collection of suspended sediment samples.

Due to the wide range of discharges and suspended sediment concentrations when samples were collected, sediment concentration were weighted according to the values of discharge and suspended sediment concentration at the time of sampling (cf. Walling et al., 1999; Owens et al., 2002). However because of insufficient and less reliable sediment yield data in Iran the objective of this study is to evaluate the output results of PSIAC model in five small catchments, Semnan Province, Iran using reliable sediment yield data deposited in reservoir constructed in the outlet of these catchments.

## Materials and methods

### Study area

The study area is situated in northernmost Iran and contains five small catchments ranging in size from about 100 to 600 ha, each with a reservoir at its outlet (Fig 1).

The climate is semi-arid, with sparse vegetation. Precipitation is largely in the form of rain during the winter months. Present land use is confined largely to grazing rangeland. The source areas represent a range of geological formations, and should provide a meaningful basis for a general assessment of enrichment of some fingerprint properties in the source and reservoir sediment. Table 1 represents characteristics of study catchments.

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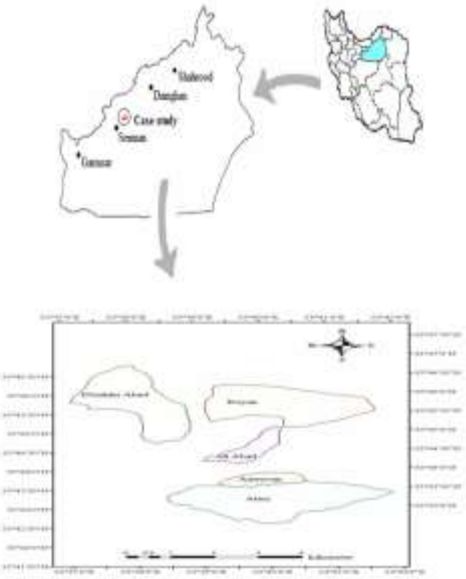


**Fig 1. The location map of the study areas and five small catchments**

### Scoring the factors of PSIAC model

A field campaign by a team with different professional backgrounds was undertaken in each catchment in order to score each model's factors. Derivation of the factors required by the PSIAC model is documented in the literature (PSIAC, 1968). However, the recent development of GIS and remote sensing technologies permits a more accurate estimation of some of the factors. The following sections describe the techniques used to generate the data and to evaluate the erosion factors.

### Surface geology (y1) and soil type (y2)

Geological data were compiled by interpretation of 1:50,000 lithological maps, aerial photographs and field observations. The lithological map was digitized using a Calcomp table digitizer to be used as a GIS layer. Lithological units were re-classified into 10 categories based on their sensitivity to erosion. Soil types were classified and the name of soil series was assigned according to experimental data from field observation and sampling, using the Approximate Seventh Soil Taxonomy (Miller and Donahue, 1999). Data for estimating the coefficient of rock and soil resistance to erosion were obtained by examining 10 representative samples of rock and soils from each unit. The test sites were subjectively examined and evaluated based on the type of lithology, thickness of beds, degree of cementation, and density of fractures and joints. The coefficients of rock and soil resistance to erosion were assigned for each map class using the methodology proposed by Feyznia (1995).

### Climate (y3)

Although it has been suggested that rainfall erosivity has a positive linear relationship with the volume of precipitation (Cook et al., 1985; Renard and Freimund, 1994), recent work suggests that elevation may also influence erosivity (Daly et al., 1994; Mikhailova et al., 1997). Daly et al. (1994) suggest that increases in precipitation can be positively correlated with an increase in elevation over small areas. The PSIAC model considers average climatic conditions and the type of precipitation (PSIAC, 1968).

### Runoff (y4)

The runoff factor was estimated by the PSIAC assessment model using Hydrologic Soil Groups (HSG). The Hydrologic Soil Group of each soil type was evaluated based on the infiltration rate measured in the field, by the use of NRCS (Natural Resources Conservation Service) method. The method used to measure the infiltration rate was by a field test using a cylinder or ring infiltrometer. The field data obtained by the infiltration test was used to generate the HSG layer. According to the PSIAC method, weighting score of the runoff factor ranges between 0 and 10; with 0 for pervious areas (HSG A), and 10 for Hydrologic Soil Groups D, and C (PSIAC, 1968).

### Slope (y5)

Land slopes were calculated using 1:25,000 topographic maps produced by the Agriculture and Natural Resource Research Center, Semnan, Iran. The original digital data in Microstation Design (DGN) format were used to build up a DEM (Digital Elevation Model) of the sub-catchment area. A raster grid cell of 50*50 m was generated and was applied to produce the DEM, from which, slope steepness could be determined. The slopes were reclassified into five categories ranging from 0–5 to >40%.

### Land use (y6) and land cover (y7)

The area was covered mainly by low-to-moderate density pasture and minor dispersed forest. Small changes in land use had occurred between the time of collection of the satellite data and the field surveys. The PSIAC land use and land cover values were estimated for each map class using the model guide tables (PSIAC, 1968). The output data layers were converted into 50*50 cell-size and the format readable by IDRISI software (Eastman, 1997).

### Erosion processes (y8)

The coefficients of observed erosion processes required visual estimation in the field. Visual interpretation of aerial photographs at the scale 1:40,000 and field surveys were carried out to identify the erosion processes. The primary map of erosion processes generated by photo interpretation was controlled by a five-day field survey. The tables of observed erosion process coefficient of PSIAC model were used to determine this factor (PSIAC, 1968). Susceptibility of surface geology to weathering and erosion is also used. Weightings range from 0 for the most resistant formations to 10 for lithologies with highest susceptibility to weathering and erosion. The map layers were rasterized as a 50*50 m cell-size file and input into the IDRISI spatial database.

### Channel erosion (y9)

This factor indicates the rate of erosion from river and drainage channels. The slope steepness, type of bedrock, and the potential energy of floods are the major factors affecting channel erosion. To determine the channel erosion factor it is necessary to prepare a map showing the relationship between the drainage and different rock units and slope classes. The drainage was derived from the 1:25,000 digitised topographic data, which was overlaid on the rock-type and slope-classes data layers. The coverage generated was reclassified based on the slope steepness, rock type, and drainage density. Each map class was then evaluated and weighted using the PSIAC guide tables.

### Measured actual sediment deposition

Sediment deposits in reservoirs were used to assess the total sediment yield from the corresponding catchment using Equation 1 proposed by werstren and poesen (2002). Here, the term total sediment yield (TSY) refers to the mass of sediment that enters the reservoir yearly.

$$TSY = 100 * M / (STE * Y) \qquad (1)$$

Where, TSY= total sediment yield (t year$^{-1}$), M= sediment mass (t), STE=sediment trap efficiency (%), Y =age of the reservoir (years), and

$$M = Sv*dBD \quad (2)$$

Where, Sv = the measured sediment volume in the reservoir ($m^3$), dBD = the area-weighed average dry bulk density of the sediment (g $cm^{-3}$).

Sediment thickness was measured by observing sediment profiles (between 0.7 to 2.8 m deep) in pits along transects, with 40 to 100 pits per reservoir depending on the size and nature of the original bottom surface of the reservoir. Sediment volume was computed by constructing a Digital Elevation Model (DEM) with a resolution of 1 m using TIN interpolation in IDRISI and taking sediment thickness as the z value (Harweayn 2005). The trapping efficiency of the reservoirs was assessed based on one year field monitoring (2008) and interviewing the local farmers about the history of the reservoir. All reservoirs are less than 10 years old and spillage has never occurred for reservoirs since their construction. Dry bulk density (dBD) was determined by the gravimetric method (Harweayn 2005).

**Results and Discussions**

The results of assessment sediment survey are presented in Table 1. Sediment volume is converted to Sediment Mass using dry bulk density (dBD). In this study, the vertical variability of dBD was considered by taking average dBD values obtained from different depths in a profile, while the horizontal variation was accounted by producing a dBD map using Thiessen polygons in IDRISI software. The profile dBD analysis result from pits indicates that dBD varies spatially both within the reservoir and vertically in the profile. For instance, in the case of Atary, 10 pits were sampled and it was found that dBD varies between 1.22 gr $cm^{-3}$ at the inlet and 1.42 gr $cm^{-3}$ near the dam. The results seem to be reasonable because of deeper and more compressed of sediments in near the dam. For the same number of pits (n =10), analysis of vertical variation of dBD was made by analyzing dBD values from cores taken in two regions at two depths (upper and lower) in a profile pit. There exists some variation of dBD between the upper and lower zones, i.e. 1.12 gr $cm^{-3}$ and 1.25 gr $cm^{-3}$, respectively. A similar trend exists in other reservoirs. There is some variation in SSY between catchments: i.e. from 3.57 t $ha^{-1}$ $year^{-1}$ to 0.35 t $ha^{-1}$ $year^{-1}$ for Amrovan and Ali Abad Catchments, respectively. These values are low when compared to the values reported in most semi arid regions of Iran. Several factors may explain this difference: most of the values reported obtained by river sediment statistics especially in periods of high sediment load (winter and sprig) and use not the reservoir sediments. Furthermore, sediment load may increase with catchment size as channel erosion becomes dominant (e.g. Church et al., 1999).

Table 2 show the nine PSIAC factors rated based on the PSIAC Guide Tables for study catchments. The sums of the values for the appropriate characteristics of the nine factors yielded the total score (Pt) and rating class for the catchments, a linear regression then was fitted between Pt and the observed SSY value (Eq. 3) to determine predicted SSY.

$$SSY = 4.119\ Pt + 55.31 \quad (R2 = 0.755) \quad (3)$$

Where, SSY is specific sediment yield (t $ha^{-1}$ $year^{-1}$), Pt is PSIAC total score obtained by summing each individual factor (Table 2).

Results indicate that all of the catchments are located within the moderate SSY (Rating class 3). The highest and lowest amount of PSIAC predicted SSY is related to Amrovan (3.171 t $ha^{-1}$ $y^{-1}$) and Atary (1.74 t $ha^{-1}$ $y^{-1}$) catchments respectively.

Comparison of the amount of PSIAC predicted and observed reservoir sediment SSY indicate that model was predicted lower than observed values in one catchment (Amrovan) and higher in three other catchments (See Tables 1 and 2).

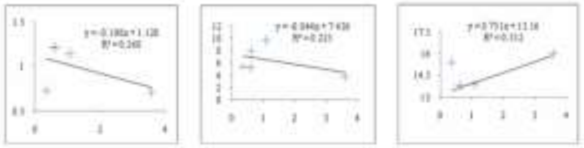
To assess the contribution of the nine PSIAC factors in explaining the variation of SSY between the catchments, linear regression and correlation analysis between observed SSY and the score of each factor was undertaken across the catchments (Figure 2). These relationships are discussed below. The effect of surface geology is important (Fig 2. A), because there are large contrasts in erodibility of geological formations in the catchments. These include highly weathered materials like marl and quaternary deposits (e.g. Amrovan and Royan). Other catchments have a more resistant geology such as azarin rocks (e.g. Ebrahim Abad, Atary). There is some variation in soil conditions (Fig 2. B). in the studied catchments, the effect of soil ranges from low-moderate in areas where there is high to low stone cover to moderate-high in areas where there is a soil that is characterized between medium to single grained textured soils. The erodibility of a soil is influenced by stone cover (e.g. Poesen et al., 1994; Nyssen et al., 2001) and grain size (e.g. Morgan, 1986; Evans, 1980). Climate is not important for explaining variability in SSY (Fig 2. C), the variability of climate between catchments is low; hence rainfall does not have any impact on the variation of SSY. Runoff is also an important variable in explaining SSY variability across the catchments (Fig 2. D). Runoff is affected by other factors (land use, soil and water conservation practices, slope, lithology and soil conditions) (USDA-SCS, 1964). Topography shows a relatively high influence on the variability of specific sediment yield (Fig 2. E); although most of the areas of Amrovan, Ali Abad and Atary catchments are characterized by steep upland slopes (> 20%) in the Ebrahim Abad and Royan there are higher slopes(<20%). The effect of topography may be partly masked by interaction effects. Because stoniness may be expected to increase with slope gradient, the effects of slope steepness and soil cover on erosion may counteract each other (Haregeweyn et al., 2005). The ground cover is well correlated with SSY (Fig 2. F). The impact on SSY variability is strong as some catchments remain tilled and bare for the rainy season (e.g. Amrovan), While others are significantly protected due to the presence of a higher cover. The effect of ground cover in reducing soil erosion has been demonstrated by different cover experiments: e. g. cover related to interception and cover in direct contact with the soil surface such as the effect of crop residues (Morgan, 1986) and stones (Nyssen et al., 2001). In addition to interception, ground cover dissipates the energy of surface runoff by increasing roughness (Morgan, 1986).

Land use is weakly correlated with SSY (Fig 2. G), mainly because there is no major variation of land use across the catchments; more than 90% of the area of most catchments is rangeland. Upland erosion is closely related to SSY (Fig 2. H). in our study catchments, erosion occurs by rill, inter-rill and some gully erosions. Although erosion rates are lower for catchments where shrub land is dominant and stone cover is high (e.g. Ebrahim Abad and Atary catchments) in some catchment such Amrovan the percentage of shrub and stone cover is very lower. Channel erosion is also indicating some variable explaining SSY (Fig 2. I). in our study catchments there are no big channel. However in the Amrovan and Royan there are some small and un- development channels. The sediment production from channels is mainly because of the presence of very erodible parent materials like marl in the case of this catchments and due to the vertic character of clay formations (Nyssen et al., 2000) that are susceptible to piping that ends with bank collapse and active head cuts (e.g. Amrovan). Hence, priority should be given to rehabilitating the channels and the channeled sub catchments when planning soil and water conservation activities in the catchments.

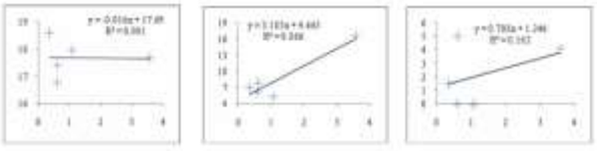
## Conclusion

This study first assessed the spatial variability of SSY in five reservoirs/catchments by measuring the volume and mass of deposited sediment in the reservoirs and also by characterizing the reservoirs and their respective catchments. The sources of errors during SSY analysis (e.g. bulk density, trap efficiency) were fully considered during investigation.

A) Surface geology B) Soil type C) Climate



D) Runoff E) Slope F) Ground cover



G) Land use H) Upland erosion I) Channel erosion and sediment transport

**Figure 2 Relation between each PSIAC scores and observed SSY. Horizontal diagrams are observed SSY (t ha$^{-1}$ y$^{-1}$) and vertical diagrams are individual PSIAC scores.**

The survey shows that SSY varies significantly between catchments, i.e. from 3.57 t ha$^{-1}$ year$^{-1}$ to 0.35 t ha$^{-1}$ year$^{-1}$. The high spatial variability in SSY is mainly associated with differences in lithology, runoff, topography, ground cover and upland erosion. The PSIAC (1968) model was evaluated using the study catchments by a team with different professional backgrounds. From an analysis of the relative roles of the various factors in controlling SSY, the important role of upland erosion was emphasized. Studies of the relationship between known sediment yield (SSY) and the catchment characteristics involving semi-quantitative approaches such as PSIAC could be of substantial benefit in extrapolating data to areas without information in a cheap and quick way. However, it should be kept in mind that such models must be calibrated first if they are to be used beyond the region where they were developed. Moreover, involving experienced and related experts during rating of the individual scores can minimize the subjectivity of the scoring.

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**Table1. The characteristics of each studied catchment.**

| Catchment | Area (ha) | Mean annual rainfall (mm) | Mean slope (%) | Low elevation (m) | High elevation (m) |
|---|---|---|---|---|---|
| Amrovan | 102.35 | 174.5 | 11.4 | 1795 | 1925 |
| Attary | 628.48 | 180.4 | 15.95 | 1750 | 2220 |
| Ali Abad | 121.96 | 176.9 | 16.20 | 1775 | 2093 |
| Ebrahim Abad | 505.64 | 182.9 | 29.31 | 1825 | 2070 |
| Royan | 538.83 | 184 | 23.95 | 1855 | 2070 |

**Table1. Assessment of sediment volume, sediment mass and sediment yield**

| Reservoirs | TSV ($m^3$) | dBD (g $cm^{-3}$) | TSM (t) | Age (year) | TE (%) | TSY (t $year^{-1}$) | Area (ha) | SSY (t $ha^{-1}$ $year^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| Amrovan | 2624.76 | 1.39 | 3651.04 | 10 | 100 | 365.104 | 102.35 | 3.57 |
| Atary | 2676.1 | 1.41 | 3778.65 | 10 | 100 | 377.865 | 627.96 | 0.6 |
| Ali Abad | 1035.89 | 1.35 | 1395.34 | 10 | 100 | 139.534 | 507.81 | 0.35 |
| Ebrahim Abad | 1244.4 | 1.43 | 1786.95 | 10 | 100 | 178.695 | 129.25 | 1.08 |
| Royan | 2363.29 | 1.385 | 3273.15 | 10 | 100 | 327.315 | 538.83 | 0.61 |

TSV: Total sediment volume; dBD: dry bulk density; TSM: Total Sediment Mass; TE: trap efficiency; TSY: Total Sediment Yield.

**Table 2 Scores and coefficient of various PSIAC factors and the amount of predicted SSY in the study catchments.**

| PSIAC factors | Catchments | | | | |
|---|---|---|---|---|---|
| | Amrovan | Atary | Ali Abad | Ebrahim Abad | royan |
| Surface geology (y1) | 5.99 | 5.76 | 5.74 | 5.18 | 5.66 |
| Soil type (y2) | 4.28 | 3.43 | 1.97 | 4.35 | 4.65 |
| Climate (y3) | 1.12 | 1.12 | 1.12 | 1.12 | 1.12 |
| Runoff (y4) | 0.71 | 1.21 | 0.72 | 1.14 | 1.20 |
| Slope (y5) | 3.76 | 5.26 | 5.35 | 9.67 | 7.90 |
| Ground covers (y6) | 16.03 | 13.80 | 15.36 | 13.90 | 11.4 |
| Land use (y7) | 17.67 | 16.77 | 18.58 | 17.95 | 17.41 |
| Upland erosion (y8) | 16.58 | 6.20 | 7.08 | 5.40 | 7.85 |
| Channel erosion and sediment transport (y9) | 4.09 | 0.00 | 1.51 | 0.00 | 5.03 |
| Total score (Pt) | 70.23 | 53.55 | 57.43 | 58.71 | 62.22 |
| Rating class | 3 | 3 | 3 | 3 | 3 |
| Predicted SSY (t ha_1 year_1) | 3.171 | 1.74 | 1.99 | 2.09 | 2.35 |