Using Sediment Deposited in Small Reservoirs to Quantify Sediment Yield in Two Small Catchments of Iran

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Abstract

Sediment deposition in reservoirs is a serious off-site consequence of soil erosion in Semnan Province, Iran. So far insufficient and less reliable sediment yield data have been collected for these regions. The large number of available sediment deposition rates in reservoirs makes the use of reservoir sediments very attractive for regional-scale studies of sediment delivery. This paper however discusses a methodology combination of both source fingerprinting technique and reservoir sediment survey to provide reliable data on sediment yields of geological formation for two small catchments, Iran. The study first assessed the volume and mass of deposited sediment in reservoirs. Secondary a fingerprinting technique have been used to identify the contribution and then specific sediment yield of each geological formation to reservoir sediment. Results indicate that there is some variation in specific sediment yield (SSY) among geological formations in two catchments: i.e. 10.31 t ha-1 year-1 to 0.41 t ha^{-1} year^{-1} and emphasize the importance of Quaternary units and Upper Red formations as the dominant surface source within two catchments. This is the important finding to support design and implementation of sediment control strategies in these catchments.

Keywords: Specific sediment yield, Geological formation, Fingerprinting, Reservoir, Iran

1. Introduction

The construction of reservoirs for water supply or flood control has been a priority for the Government of Iran for the last decade. Siltation of these reservoirs is a serious off-site consequence of soil erosion as it threatens the sustainability of the reservoirs. So far, insufficient and less reliable sediment yield data have been collected systematically for the region. Sediment yield however can be monitored by using measuring sediment deposition rates in lakes, reservoirs or small ponds (e.g. Van den Wall Bake, 1986; Neil and Mazari, 1993; McManus and Duck, 1985; Foster, 1995; White et al., 1996; Verstreaten and Poesen, 1999, 2001c). In many of this reservoir, sediment deposition can be observed. This large number of potentially available sediment yield data makes the use of reservoir sediments very attractive for regional-scale studies of sediment delivery. Although sediments in reservoirs and lakes have been used for decades to assess sediment yield (e.g. Dendy et al., 1973; White et al., 1996), this was mostly done through larger reservoirs or lakes that have more or less uniform hydrologic conditions through time (e.g. water storage at all times), which are also mostly linked to larger catchments. This is in contrast with the many small reservoirs that are linked with smaller catchments (Verstraeten and Poesen, 2000). Furthermore an understanding of the nature and relative importance of the principle sediment sources within a catchment is needed to support the design and implementation of sediment control strategies in catchments (Collins et al., 2001). Resources could be effectively wasted if, for example, control strategies focused on reducing sediment source, when most of the sediment transported through a river system was contributed by another sediment source. Any attempt to identify the primary sediment sources within a catchment or river basin and to assess their relative contributions to the sediment load at the catchment outlet will face a number of important problems (Peart and Walling, 1988; Collins and Walling, 2004). In response to the problems associated with conventional procedure for establishing the primary sediment sources within a catchment, the fingerprinting approach has been increasingly adopted as an alternative and more direct and reliable means of assembling such information. In particular Source fingerprinting techniques provide a relatively simple and cost-effective basis for assembling spatially and temporally integrated data for catchments of different scales (Collins and Walling, 2004; Walling, 2005, Walling et al., 2008). Fingerprinting technique is founded upon the link between the physical and geochemical properties of the sediment and those of its sources. If potential source materials can be distinguished on the basis of their fingerprints, the likely provenance of the

sediment can be established using a comparison of the properties of the sediment with those of the individual potential sources (Walling et al., 2008). The application of this approach comprises two basic steps. These involve: first, the selection of diagnostic properties, which distinguish potential sediment sources, and secondly, a comparison of sediments and catchment source samples using these properties, in order to establish sediment provenance (Walling et al., 2008). Existing research has provided valuable information on the range of properties that can be successfully employed to discriminate potential sediment sources in drainage basin. These have included mineralogy, and color (Grimshaw and Lewin, 1980), mineral magnetism (Caitcheon, 1993), environmental radionuclides (Wallbrink and Murray, 1996), geochemical composition (Foster and Walling, 1994), Organic constituencies (Collins and walling, 2002), acid extractable metals (Collins and Walling, 2002) and particle size (Stone and Saunderson, 1992). This paper however discusses a methodology combination of both source fingerprinting technique and reservoir sediment survey to provide reliable data on sediment yields of geological formation for two small catchments, Iran.

2. Methodology

2.1 The study catchments

This area is located in Semnan Province of Iran (Figure 1) and is including the two catchments: 1. Amrovan catchment: Total area of the Amrovan catchment is 102.35 ha. The Altitudes range from 1795 meter at the catchment outlet to 1925 m in the upstream areas and the catchment slope average is commonly 11.4%. The mean annual precipitation is 174 mm and occurs in winter and spring months generally. The geology is dominated by Quaternary, Hezar-Dareh and Upper Red Formations. All of the catchment area is covered by bush ranges. 2. Royan catchment: The catchment has a total area of 538.83 ha. The climate annual rainfall is 184 mm. Most of the rainfall occurs in winter and spring. The topography of the region mainly consists of highland parts up to 2000 meter and the catchment slope average is commonly 23.95%. The geology is dominated by Quaternary, Hezar-Dareh, Shemshak, Lar and Upper Red Formations. All of the catchment area is covered by bush ranges. The selected reservoirs had been created by constructing earth embankments to harvest seasonal runoff.

2.2 Survey of 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.

$$TSY = 100*M/(STE*Y) \tag{1}$$

Where, TSY= total sediment yield (t year_1), M= sediment mass (t), STE=sediment trap efficiency (%), Y =age of the reservoir (years), and

$$M = Sv*dBD \tag{2}$$

Sv=the measured sediment volume in the reservoir (m3), 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 (see examples in Figure 2). 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) (see Figure 3). 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. 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. Undisturbed representative sediment samples were taken using core rings (volume $1*10^{-4}$ m^3) from 8 to 10 sampling sites per reservoir (near the dam axis, in the middle, side and at the inlet of the reservoir), and at a minimum of two different depths in the profile pit.

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 with point dBD values obtained from all pits in the reservoirs. The map produced by Thiessen Interpolation produced the expected distribution of dBD both along and across the reservoir. A map of the mass of accumulated sediment per unit area was then produced by multiplying the sediment DEM and dBD map layers. Then the total mass of the sediment accumulated over the years was determined by using the "EXTRACT" module in IDRISI.

2.3 Fingerprinting procedure

Field sampling involved the collection of representative samples of both main potential sediment sources identified within each study catchment and the sediments deposited in reservoir dam constructed in the outlet of catchments. Potential sediment sources were categorized surface soils from different geological formations. 10 representative samples were collected from both main geological formation within each study catchment and the sediments deposited in reservoirs. All source material samples were air-dried and subsequently dry-sieved to <63

μm to facilitate direct comparison with sediment samples (Walling et al., 2008). Selection of fingerprint properties for use in the investigation was based on previous experience of source discrimination, as well as being constrained by available analytical facilities and the time available for analytical work. The samples were finally analyzed in the laboratory for 15 properties as a tracer, comprising five groups of fingerprinting properties: Organic constituents (C, N, P), base cations (Na, K, Ca, Mg), acid extractable metals (Cr, Co), clay minerals (Smaktite, colorite, illite, Kaolinite) and two magnetic properties consisting of Low Frequency Magnetic Susceptibility (X_{lf}) and Frequency Dependent Magnetic Susceptibility (X_{fd}). A multivariate mixing model, as described by Collins et al. (1997), was used to estimate the relative contribution of the potential sediment sources to the individual sediment samples collected from each designated catchment. This model assumes that the concentrations of the selected fingerprint properties in any given sample of sediment directly reflect the corresponding concentrations in the original source materials and the relative proportions of sediment contributed by those sources. The amount of sediment yield (SY) for each sediment source was obtained by multiply of each sediment source contribution and total sediment yield (TSY) obtained from total catchment area. SY was finally divided to area of each sediment source to computation of specific sediment yield (SSY) from each sediment source.

3. Results and discussion

3.1 Survey of sediment deposition

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 Amrovan, 10 pits were sampled and it was found that dBD varies between 1.45 gr cm^{-3} at the inlet and 1.16 gr cm^{-3} 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. 1.08 gr cm^{-3} and 1.15 gr cm^{-3}, respectively. A similar trend exists in other reservoirs. In general, associated errors during sediment volume and sediment yield determination are low for two reasons: firstly sufficient precision was obtained both during sediment surface mapping, sediment thickness measurement (with precision of 1 cm) and during sampling for dBD analysis and during DEM generation (1 m by 1 m), and secondary the effect of STE determination in the overall error is very low as all of reservoirs have never spilled since construction.

The results of sediment volume, sediment mass and sediment yield assessment are presented in Table 1. Looking in general at the results presented in Table 1, there is some variation in TSY between catchments: i.e. 365.104 t year^{-1} to 327.315 t year^{-1} for Amrovan and Royan catchments respectively.

3.2 Quantifying sediment yield of geological formation

Table 2 examines the results of relative contribution, sediment yield and specific sediment yield from each sediment source to the reservoir sediment. In the Amrovn catchment the sediment yield from the Upper-Red Formation (156.99 t year^{-1}) is most important, followed in descending order by the Hezar-Dareh Formation (127.78 t year^{-1}) and Quaternary units (80.32 t year^{-1}). These results demonstrate that all parts of the catchment provide significant contributions to the sediment at the reservoir. It is important to recognize that these results relate specifically to relative contributions and that a high relative contribution may not necessarily reflect a high contribution in terms of the actual mass of sediment, therefore it is important to take account of the proportions of the catchment area supplying these contributions and thus the equivalent sediment yields from these areas. Based on the proportions of the catchment occupied by Upper Red, Hezar Dareh and Quaternary formations (i.e., 31.33, 65.23 and 7.79 ha, respectively), the specific sediment yields from these three geological formation may be estimated to be ca. 5.01 t ha^{-1} year^{-1} from Upper Red formation, ca. 1.95 t ha^{-1} year^{-1} from Hezar Dareh formation and ca.10.31 t ha^{-1} year^{-1} from Quaternary units. Therefore Quaternary units and Upper Red formation is more important sediment source in this catchment. In the Royan catchment the sediment yield from Karaj formation represents the dominant sediment source (127.65 t year^{-1}), but that Quaternary units also represent important sources (121.10 t year^{-1}). This two sediment sources overall approximately supplies higher than 75% of the sediments. The increased importance of Karaj formation reflects the existence of large areas occupied by this geological formation and location of this formation close proximity to the channel network. There was insufficient sediment supplied by Shemshak, Upper-Red and Lar formations for their contribution to be detected by the mixing model in this catchment. This reflects both the limited extent of these sources in the catchment and the lack of erosion from such sources. It is again important to take account of the proportions of the catchment area supplying these contributions and thus the equivalent specific sediment yields from this geological formation. Based on the proportions of the catchment occupied by Quaternary units and Upper Red, Karaj, Lar and Shemshak formations (i.e., 121.10, 26.18, 127.65, 19.63 and 32.73 ha, respectively), the specific sediment yields from these geological formation may be estimated to be ca. 0.78 t ha^{-1} year^{-1} from Quaternary units, ca. 0.55 t ha^{-1} year^{-1} from Upper Red formation, ca. 0.54 t ha^{-1} year^{-1} from Karaj formation, ca. 0.41 t ha^{-1} year^{-1} from Lar formation and ca. 0.55 t ha^{-1} year^{-1} from Shemshak formation. In this catchment Quaternary units and Upper red formation again reflect as dominant specific sediment yield, but it is less than that Amrovan catchment.

4. Conclusions

This study has investigated a methodology combination of both source fingerprinting technique and reservoir sediment survey to provide reliable data on sediment yields of geological formation for two small catchments, Iran. The study first assessed the volume and mass of deposited sediment in reservoirs. This methodology requires several operations, such as accurate topographical surveying, measuring the dry sediment bulk density to convert sediment volumes to sediment masses, and assessing the sediment trap efficiency of the pond. The sources of errors (e.g. bulk density, trap efficiency) were fully considered during investigation. In general, associated errors during sediment volume and sediment yield determination are low for two reasons: firstly sufficient precision was obtained both during sediment surface mapping, sediment thickness measurement (with precision of 1 cm) and during sampling for dBD analysis and during DEM generation (1 m by 1 m), and secondary the effect of STE determination in the overall error is very low as all of reservoirs have never spilled since construction.

In order to apply fingerprinting procedure the 15 properties selected comprised five groups of fingerprinting properties, including Organic constituents (C, N, P), base cations (Na, K, Ca, Mg), acid extractable metals (Cr, Co), clay minerals (Smaktite, colorite, illite, Kaolinite) and mineral magnetism (X_{lf}, X_{fd}). A multivariate mixing model was used to estimate the relative contribution of the potential sediment sources and then specific sediment yield of each geological formation to reservoir sediment.

Results indicate that there is some variation in SSY between geological formations in two catchments: i.e. 10.31 t ha-1 year^{-1} to 0.16 t ha-1 year^{-1} (see Table 2). Looking in more detail at the specific sediment yield of the geological formation in two catchments, the results presented emphasize the importance of Quaternary units and Upper Red formations as the dominant source within two catchments. This is the important finding to support the design and implementation of sediment control strategies in these catchments. This finding is also consistent with that obtained for another Iranian river (Hakim khani et al., 2007). These areas should be treated as erosion hazards and catchment management practices should be adopted in these areas to reduce the rate of erosion.

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Table 1. Assessment of sediment volume, sediment mass and sediment yield

Reservoirs	TV (m3)	dBD (g cm^{-3})	TM (t)	Age (year)	TE (%)	TSY (m^3 year^{-1})	TSY (t year^{-1})
Amrovan	2624.76	1.39	3651.04	10	100	262.476	365.104
Royan	2363.29	1.385	3273.15	10	100	236.329	327.315

TV: total volume; dBD: dry bulk density; TM: total mass; TE: trap efficiency; TSY: total sediment yield.

Table 2. Mean contributions of each sediment sources to the sediment samples.

| Catchment	Sediment sources	Contribution (%)	SY (t year^{-1})	Area (ha)	SSY (t ha^{-1}year^{-1})
Amrovan	Quaternary units	22.00	80.32	7.79	10.31
	Hezar-Dareh Formation	35.00	127.78	65.23	1.95
	Upper-Red Formation	43.00	156.99	31.33	5.01
Royan	Quaternary units	37.00	121.10	154.58	0.78
	Upper-Red Formation	8.00	26.18	47.02	0.55
	Karaj Formation	39.00	127.65	233.65	0.54
	Lar Formation	6.00	19.63	47.72	0.41
	Shemshak Formation	10.00	32.73	59.48	0.55
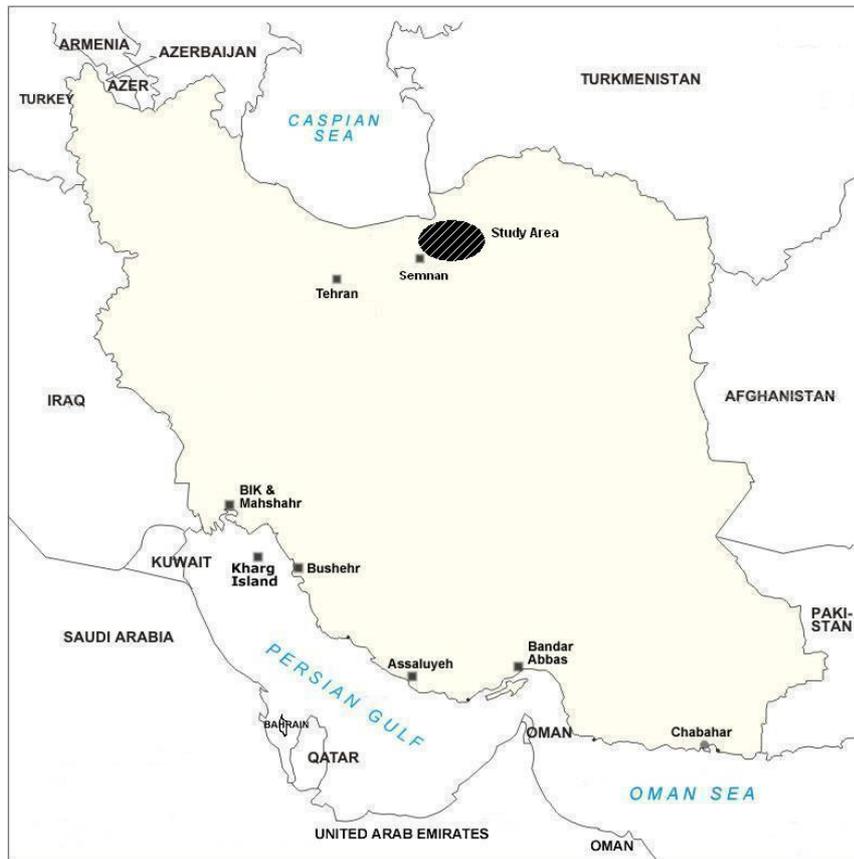
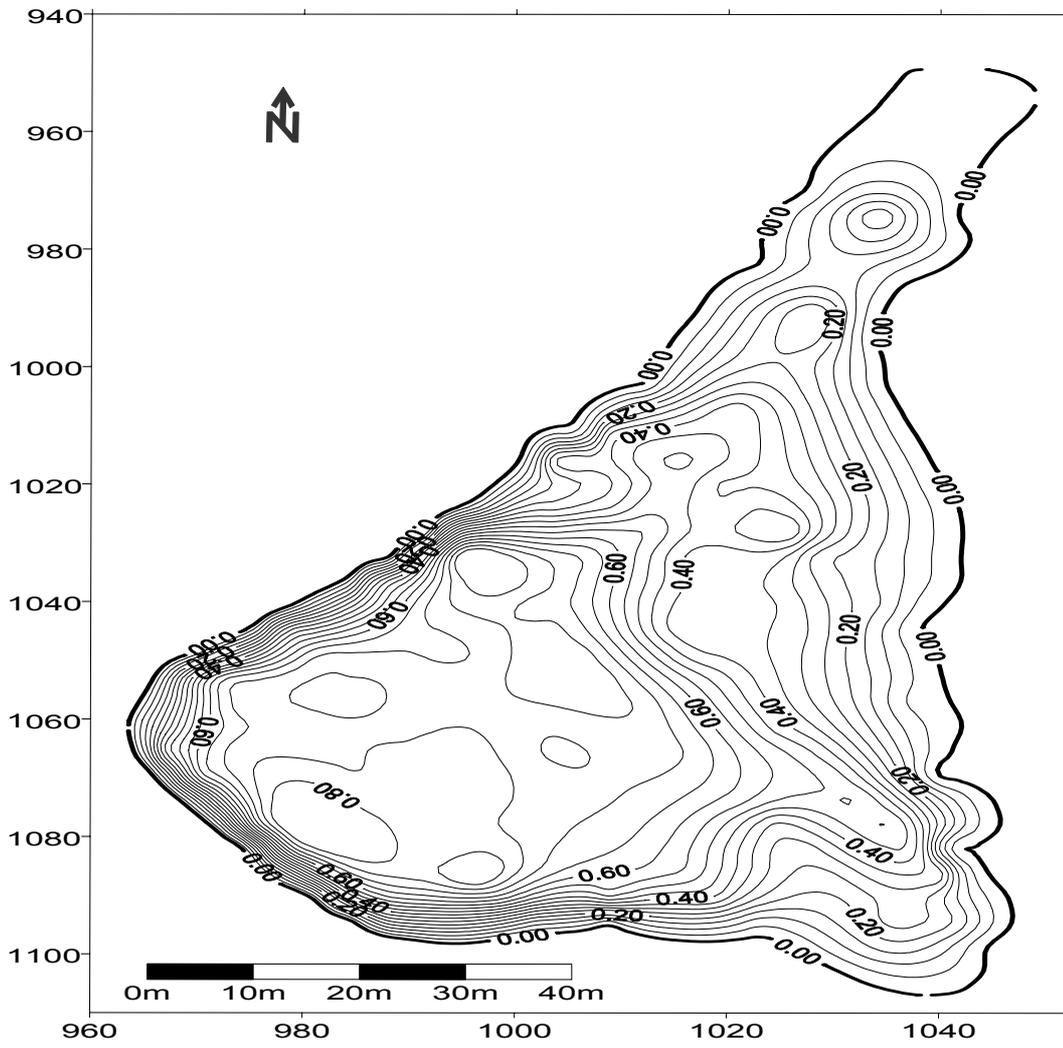Figure 1. location map of study area

Figure 2. Examples of the profile pits

Figure 3. Topographic mapping at Amrovan reservoir