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Evaluation of Reservoir Sediment Load under Climate Change

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ABSTRACT: Reservoir dams are often under threat from sedimentation initiated and accumulated in the upstream basin. Reservoir sedimentation reduces the efficiency and the designed expected life of the reservoir while endangering hydroelectric and water supply systems. From a hydrological perspective, sediment load specifically affected by climate change considerations are particularly important at basin scale studies. Here, the EPM model has been utilized to determine the annual sediment volume in the basin under study for its appropriate responses to climate variations. To assess the effects of climate change the HadCM3 climate model data have been utilized under the A2 and B2 scenarios sought as most appropriate scenarios for the basin under consideration. The SDSM model has been used next for downscaling and the results were formatted as input into the EPM model. A series of possible future variations were considered. Available daily precipitation and temperature data for the period 1971-1985 were used for model calibration and verification of model performance was achieved using the data for the period 1986-2000. Results indicate a reduction of 13.6 % and 13.8 % in the annual sediment volume for the period 2041-2055 under the circulation scenarios A2 and B2 respectively compared to the base values for the period 1986-2000.

Keywords: Reservoir sedimentation, Climate change, EPM, HadCM3, SDSM

1 INTRODUCTION

The construction of dams blocks the flow of sediment downstream. Although reservoir sedimentation as a possible water resource issue can be seen either as a problem of quality or quantity, the scope of this study focuses on sedimentation quantity. While the rate of sedimentation varies for each reservoir, eventually all reservoirs develop a reduced water storage capacity due to the exchange of storage space for sediment. Diminished storage capacity results in reduced availability of water for irrigation and decreased ability to produce hydroelectric power. Furthermore, the high volume of sediment causes abrasion of hydropower equipment and other dam components. Therefore, to make a more accurate economic prediction for a planned dam, prediction of reservoir sedimentation rate is necessary.

The rate of sedimentation in reservoirs varies with sediment production on the watershed, the rate of transportation in streams and the proportion of a river's total sediment load captured by dam, known as its "Trap Efficiency". The rate of erosion and consequent sediment flows are influenced by weather conditions. Based on both the trends in the observed meteorological and hydrological data during the recent past and on the results of climate models for different greenhouse gas emission scenarios, the general consensus is that “climate change” will affect weather patterns in significant ways. As an increasing number of studies have shown, many countries, including Iran, will be affected by climate change (Zohrabia et al., 2014; Kousari et al., 2013; Ghorbani et al., 2013; Rahmani et al., 2013; Zarghamia et al., 2011). Therefore, it is expected that climate change will influence the rate of sedimentation in reservoirs.

Climate change impact assessments require data of spatial and temporal resolutions that are not currently available from the output of General Circulation Models (GCMs). According to Hostetler's study (1994), hydrological models are most realistic at the watershed scale. Conversely, atmospheric models are primarily concerned with dynamics at the planetary scale. In other words, there is a gap between mesoscale atmospheric predictor variables and regional scale hydrometeorology. Statistical downscaling methods are utilized to address this issue. These methods have been used in literature to link the outputs of climate models with the requirements of hydrological impact modelers. As a result, in order to consider climate change impacts on reservoir sedimentation rate, initially the impact of climate change on meteorological parameters in small scale should be investigated.

Reservoir sedimentation rate depends on the sediment delivery rate to the reservoir and Trap Efficiency. Various empirical models are generated for estimating these two parameters. Choosing the best model is based on the quality and quantity of available data and validity of results.

Research has been conducted on the influence of climate change on sediment production. Lu et al. (2013) presented a quantitative estimate of changes in sediment loads in response to climate change in eight large Chinese rivers. They concluded that over the past decades, precipitation change coupled with rising temperatures has played a significant role in influencing the sediment delivery dynamics. Mouri et al. (2013) assessed future changes in suspended sediment yield in Japan. The results indicated that suspended sediment generation will increase by the 2090s. Gomez et al. showed that depending on the climate change scenario, suspended sediment discharge may either decline or increase in Waipaoa River in the 21st century.

2 MATERIALS AND METHOD

2.1 *Study Area and Data used*

The Hasanjoun watershed, as a sub-watershed of Taleghan river basin, was selected for the case study. The case watershed is located in the northwest of Tehran and lies within 50˚39′ to 50˚47′ E longitude and 36° 19′ to 36° 12′ N latitude. The elevation in the catchment varies from 1780m to 4042m. The main topography of the catchment is mountains and hills, and the elevation decreases from the north to the south. There is a reservoir dam in the south of the basin which is used for agriculture, municipal supplies and hydroelectric power generation.

Available weather stations data in Hasanjoun watershed are not fully sufficient for climate change studies because the short period of observed records. It was therefore necessary to use data from Zidasht station too, located marginally outside the watershed (Latitude: 36° 13' Longitude: 50° 41').

According to the Ministry of Agriculture of Iran’s report (2001), the Hasanjoun watershed is composed of six completely independent sub-watersheds termed H_1, H_2, H_3, H_4, H_5, H_6 and one internal sub-watershed called H_{int} (Table 1). All watershed creeks join together and form the main channel in H_{int} sub-watershed. Watershed segmentation is based on slope and stream density, and the required accuracy of the study.

Table 1. characteristics of the hydrologic units

Hydrologic Unit	Average elevation (m)	Perimeter (km)	Area (km2)
H1	2628	7.85	3.163
H2	2965	21.50	23.53
H3	3157	20.60	19.959
H4	2896	21.47	19.486
H5	2427	5.75	1.868
H6	2367	21.17	11.066
H – int	2075	28.43	14.347
Total	2775	48.04	93.418

2.2 *General Circulation Model (GCM)*

A General Circulation Model (GCM), is a mathematical climate model, first developed by Manabe and Wetherald (1975), representing physical processes in the atmosphere, ocean, cryosphere, and land surface based on the Navier–Stokes equations on a rotating sphere with thermodynamic terms for various energy sources. GCMs depict the climate using a three dimensional grid over the globe, typically having a horizontal resolution of between 250 and 600 km, 10 to 20 vertical layers in the atmosphere and sometimes as many as 30 layers in the oceans.

HadCM3 model, used in this study, is a GCM developed at the Hadley Centre and described by Gordon et al. (1999). The atmospheric component of the model has 19 levels with a horizontal resolution of 2.5 degrees of latitude by 3.75 degrees of longitude, which produces a global grid of 96×73 grid cells.

This is equivalent to a surface resolution of about 417 km×278 km at the Equator, reducing to 295 km×278 km at 45 degrees of latitude.

The Intergovernmental Panel on Climate Change (IPCC) has prepared a series of standard scenarios of greenhouse gas and sulfate aerosol emissions for use in the GCMs. These scenarios are classified in four storylines named A1, A2, B1and B2, based on different assumptions about social, economic, technological, demographic, and environmental change (Nakicenovic et al., 2000). The A2 and B2 scenarios are most commonly used emission scenarios in climate change assessment (Hannah, 2010).

2.3 *Statistical Downscaling Model (SDSM)*

Statistical Downscaling Model (SDSM) is a tool for assessing local climate change impacts. SDSM uses a multi-regression method to link large-scale climate variables provided by GCMs (predictors) with station-scale climate variables provided by daily meteorological data (predictands). Full technical details, including model validation and usage, are described by Wilby et al. (2002). In summary this model reduces the task of statistically downscaling daily weather series into seven discrete steps:

1) Quality control and data transformation;
2) Screening of predictor variables;
3) Model calibration;
4) Weather generation (using observed predictors);
5) Statistical analyses;
6) Graphing model output;
7) Scenario generation (using climate model predictors).

2.4 *Erosion Potential Method (EPM)*

Lack of information for preparing erosion maps for quantitative and qualitative evaluation of sedimentation rates is a major obstacle in the watershed management plans in Iran. Therefore, numerous studies focus on suggesting models that give accurate results for the climatic conditions of Iran. Some of these studies suggest using the "Erosion Potential Method" (EPM) in regions with limited data (Tangestani, 2006; Amiri and Tabatabaie, 2009; Koupeima et al., 2011).

The EPM model was introduced for the first time by Gaverlovic in River Stream International Conference (1988). Gaverlovic based EPM model on erosion measurements during 40 years in former Yugoslavia. Sediment estimation in this model is based on six factors that depend on surface geology and soils, topographic features, land use, and climatic factors (including annual precipitation, and average annual temperature). The coefficient of erosion intensity (Z) is calculated by the following equation:

$$Z = Y.Xa(\psi + I^{0.5}) \tag{1}$$

Where, Y is the rock and soil susceptibility coefficient, Xa is the land use coefficient, ψ is the coefficient value for the observed erosion processes and I is the average land slope in percent(Gavrilovic, 1988). Erosion severity is classified into five different groups. For instance, Areas with Z>1.0 have "severe erosion" and those with Z< 0.19 have a "very slight erosion".

Specific Erosion is estimated by the following equation:

$$W_{sp} = T.H.\pi.Z^{1.5} \tag{2}$$

where, W_{sp} is the average annual specific production of sediments (m^3/km^2/year), H is the height of annual rainfall (mm), Z is the coefficient of erosion and T is the temperature coefficient which is calculated as:

$$T = \left(\frac{t}{10} + 0.1\right)^{0.5} \tag{3}$$

where "t" is the average annual temperature (degrees Celsius).

In the EPM model, the amount of sediment delivered to the reservoir is linearly proportional to the amount of soil eroded. Sediment delivery ratio (Ru) is estimated by the following equation:

$$Ru = \frac{4(O.D)^{0.5}}{L+10} \tag{4}$$

where, O is the circumference of the watershed (km), D is the difference between medium altitude and catchment outlet altitude (km) and L is the watershed length (km). Specific Sediment Yield (SSY) is estimated as

$$SSW = W_{SP}.Ru \tag{5}$$

It should be noted that SSW corresponds to suspended sediment load.

2.5 *Trap Efficiency (TE)*

Trap Efficiency (TE) is the ratio of sediment retained within the reservoir to the sediment inflow to the reservoir. The Trap efficiency is formulated as follows:

$$TE = \frac{(S_{inflow} - S_{outflow})}{S_{inflow}} = \frac{S_{settled}}{S_{inflow}} \tag{6}$$

where S_{inflow} is the sediment mass entering the reservoir, $S_{outflow}$ is the sediment mass that flow out of the reservoir, $S_{settled}$ is the sediment mass that settle in the reservoir.

It is very difficult to evaluate the TE in a simple manner because of the many parameters which influence the sedimentation process. As a general approach, empirical formulae are used. These methods simplify the sedimentation process and do not consider some of the affecting factors. Nevertheless these formulae are very useful in studies of reservoir sedimentation. In this study, the method that was described by Brown has been used. It is widely used to empirically determine the Trap Efficiency. Brown developed a curve that relates TE to capacity-watershed area ratio based on data from 15 reservoirs:

$$TE = 100(1 - \frac{1}{1+D\frac{C}{W}}) \tag{7}$$

where C is the reservoir storage capacity expressed in acres/feet, W is the catchment area (mile^2) and values of D range from 0.046 to 1, with a mean value of 0.1, and they are dependent on the characteristics of a reservoir. The TE of Taleghan dam reservoir has been estimated 32 percent for the purposes of this time by using equation 6. It should be noted that this value will change over time due to decrease in reservoir capacity.

Based on Brown's curve, climate change will have no effect on TE because it is independent of climate conditions. Consequently, evaluation of climate change effects on this factor is not necessary. Therefore in order to evaluate the climate change impacts on reservoir sedimentation rate, focus is merely made, in this study, on sediment delivered to the reservoir.

3 RESULTS

3.1 *Downscaling*

In order to predict future climate, appropriate predictors should be selected. Parameters given in the table (2) showed best correlation with daily rainfall and daily temperature data. These parameters have been derived by using monthly analysis and partial correlation. January 1, 1971 to December 31, 1985 was selected as the calibration period, and January 1, 1986 to December 31, 2001 as the validation period. Observed (or NCEP re–analysis) atmospheric predictor variables was used for calibration and validation. Total monthly precipitations and average monthly temperature have been shown in Figure (1). There is good agreement between the observed data and the model results in the validation period.

Predictors that were selected in the previous step were used in the next step to downscale the local variables for the future climate. In order to produce ensembles of synthetic daily weather series data supplied by the HadCM3, driven by the two emission scenarios (A2 and B2) for the prediction period (January 1, 2041 to December 31, 2055) were used. 20 time series of precipitation and temperature for the prediction period was generated.

Table 2. Large-scale atmospheric predictor variables used to downscale daily temperature and Predict and

Predictand	Predictors (NCEP re-analysis)	Partial r
Precipitation	Meridional velocity component	0.25
	Divergence	0.22
	Near surface specific humidity	0.23
Temperature	Mean sea level pressure	0.71
	500 hPa geopotential height	0.75
	Mean regional temperature at 2 m	0.46

The partial correlation coefficient (r) shows the explanatory power that is specific to each predictor. All are significant at the p= 0.01 level.

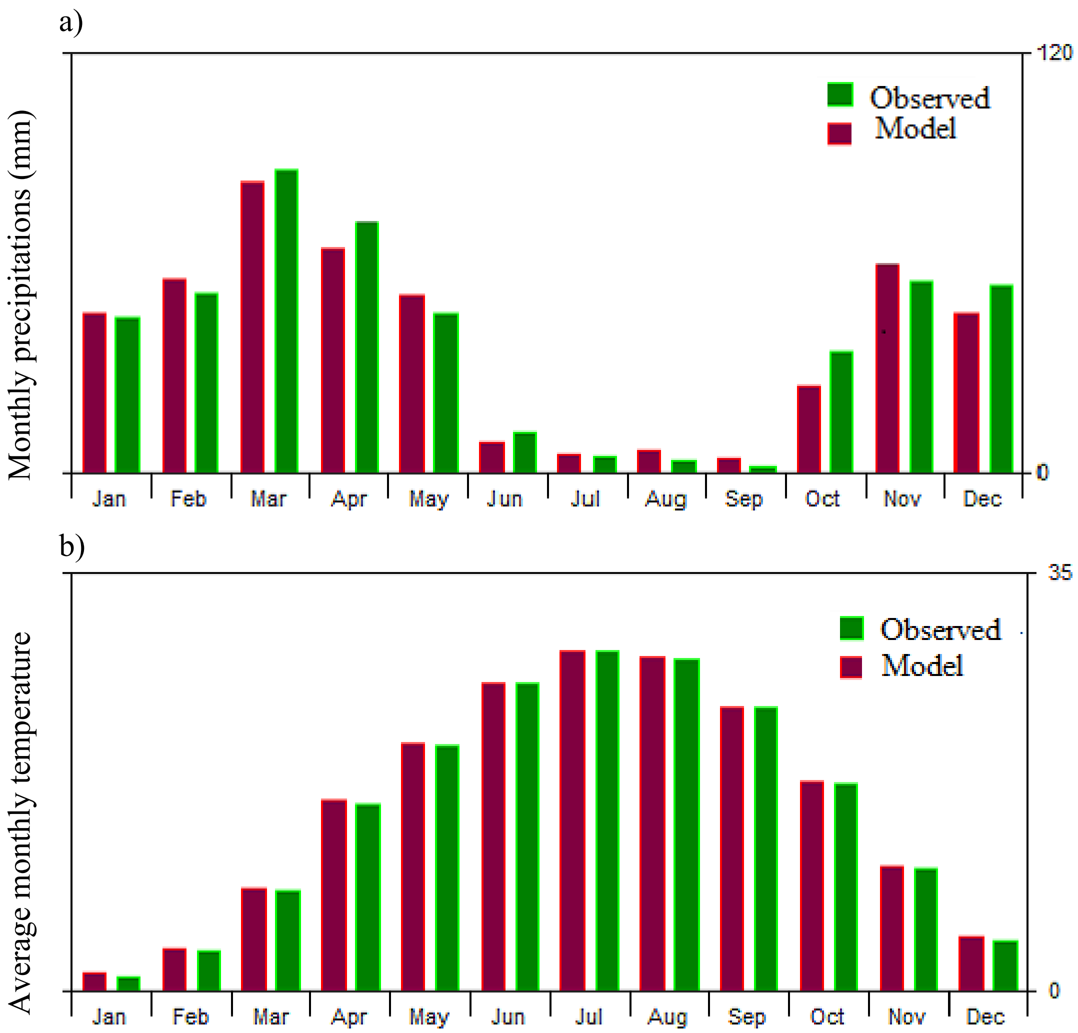
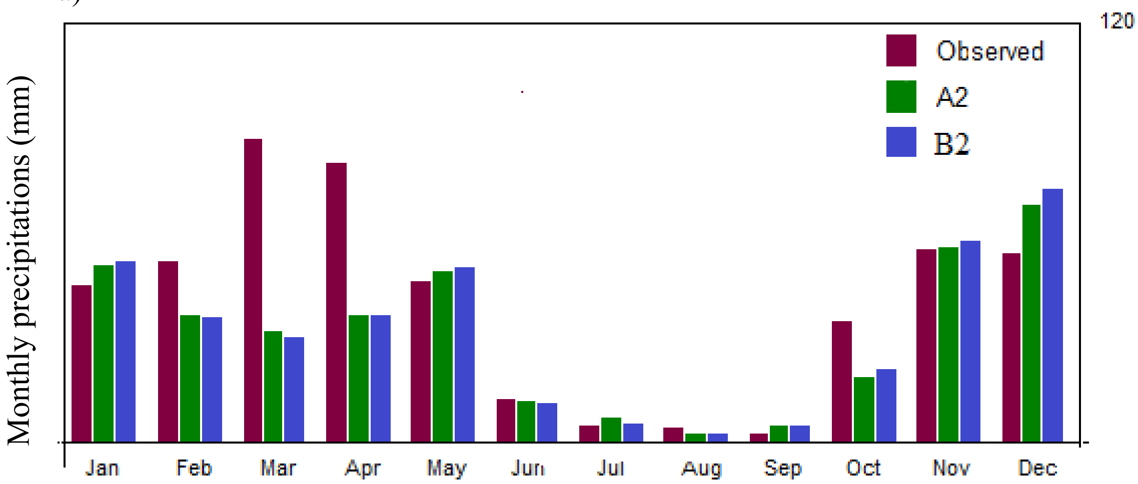


Figure 1. Validation of downscaled meteorological data. a) Monthly precipitation. b) Average monthly temperature

The average annual rainfall during the period of 1986-2001 is 680 mm and the mean annual temperature during the same period is 16.4 ^{o}C. Based on the A2 and B2 scenarios, the average annual rainfall will decrease to 576mm and 578mm respectively and the average annual temperature during the same period will increase to 17.1 and 16.9 ^{o}C respectively in period 2041-2055.

a)



b)

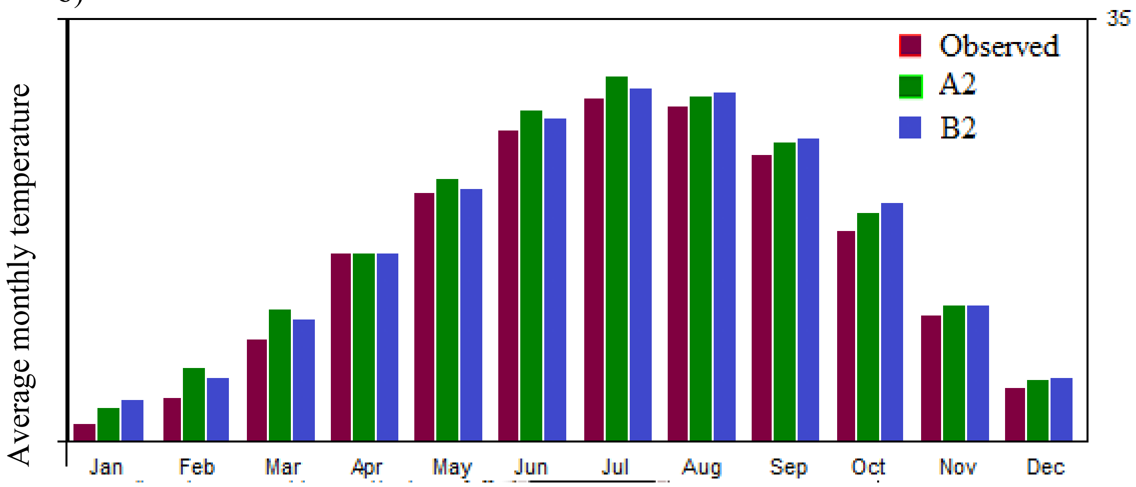


Figure 2. Comparison between1986-2000 observed data and 2041-2055 predicted data. a) Monthly precipitation. b) Average monthly temperature

3.2 *Predicting sedimentation*

Parameters required to estimate the coefficient of erosion intensity (Z) has been shown in Table (3). The coefficient of erosion intensity has been calculated and erosion class has been determined separately for each sub-watershed. Specific Erosion (W) has been calculated from observed daily temperature and precipitation data in period 1986-2001. Similarly, Specific Erosion has been calculated by using SDSM outputs for the prediction period (2041-2055).

The circumference of the Hasanjoun watershed is equal to 47.4 km, the difference between medium altitude and catchment outlet altitude is equal to 0.87 km and the watershed length is equal to 17.8 km. The Sediment delivery ratio (Ru) is estimated at 0.93 by using equation4. According to the Ministry of Agriculture of Iran's report (2001) the ratio of bed-load to total sediment is 0.15, and sediment density is1.3 ton/m^3.Table (4) shows the final results of this study.

Table 3. Coefficient erosion intensity and affecting factors

Hydrologic Unit	I	Ψ	Xa	Y	Z	Erosion intensity
H1	49	0.65	0.60	0.82	0.66	Moderate
H2	40	0.67	0.60	0.91	0.71	High
H3	45	0.66	0.60	0.86	0.69	Moderate
H4	41	0.70	0.60	1.17	0.94	High
H5	49	0.66	0.60	0.68	0.55	Moderate
H6	31	0.70	0.51	0.88	0.57	Moderate
H – int	31	0.75	0.55	0.90	0.65	Moderate
TOTAL	39	0.69	0.58	0.94	0.72	High

Table 4 The calculated erosion and sediment for Hasanjoun watershed by the EPM model

	1986-2000	2041-2055(A2)	2041-2055(B2)
average annual temperature (^{o}C)	16.4	17.1	16.9
Temperature coefficient	1.32	1.35	1.34
Annual precipitation (mm)	680	576	578
Specific Erosion (m3/Km2/yr)	1721	1487	1483
Annual erosion (ton/yr)	209154	180695	180317
Suspended sediment (ton/yr)	194513	168046	167695
Total sediment (ton/yr)	223690	193253	192850
Percent of change of total sediment	---	-13.6	-13.8

4 CONCLUSION

In this study the rate of Taleghan dam's reservoir sedimentation under climate change has been investigated. To this end, prediction of the amount of sediment that will be delivered to the reservoir from the Hasanjoun watershed was focused on.

The daily precipitation and mean daily temperature were downscaled making use of SDSM downscaling model. The SDSM downscaling model has shown a good predictive ability based on the validation of the results. These climatic data were estimated according to HadCM3 circulation model, and with A2 and B2 emission scenarios, for the period of 2041-2055. Average annual precipitation during the period of 1986-2001 is 680 mm and for the same period, the average annual temperature is 16.4. The downscaling results indicated that, Based on the A2 and B2 scenarios, the average annual rainfall will decrease to 576mm and 578mm respectively and the average annual temperature during the same period will increase to 17.1 and 16.9 ^{o}C respectively in the period 2041-2055.

The EPM model has been utilized to determine the annual sediment volume in the watershed under study for the appropriate responses to climate change. Results indicate a reduction of 13.6 and 13.8 in the annual sediment volume for the period 2041-2055 under emission scenarios A2 and B2 respectively compared to the base volume for the period 1986-2001.

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