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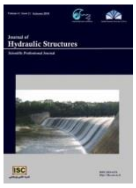

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Predicting Sediment Transport on Steep Slopes After Dam Removal: A Case Study of Zonouz Dam

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Abstract

There have been many dam removals around the world in recent decades due to safety issues, reservoir volume loss, and other factors. Sediments are deposited in dam reservoirs after years of operation, and sediment transfer downstream following dam removal requires further investigation. The aim of this research is to analyze and predict the effects of removing the dam on sediment transport, especially fine sediment transport on steep slopes. A case study of the Zonouz Dam in East Azerbaijan Province is used to demonstrate this. Sediment transport is predicted using a one-dimensional numerical model called DREAM1. Three sediment transport equations were considered for this grain size and slope to choose the most appropriate one. These equations include Brownlie, Smart and Rickenmann. Next, their results were collected for 350 laboratory experiments with conditions similar to modeling and the results were compared with each other. The calculations revealed a lower error in the Brownlie equation results. Sediment transport following the removal of the Zonouz Dam was modeled numerically for wet, dry, average, and recorded discharges. Based on the modeling results, erosion rates were high in the early years but decreased over time. Moreover, the dispersion mechanism is dominant over translation in the evolution of the pulse, resulting in sediments being transported downstream up to 11 kilometers. According to the results, approximately 82% of the sediments will be eroded after seven years under the hydrological conditions present at the Zonouz Dam.

Keywords: Dam removal, Sediment transport, DREAM, Zonouz Dam.

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1. Introduction

There are many reasons why dams are required, but they may also need to be removed for various reasons. As a result of dams, ecosystem processes such as water evaporation, aquatic animal migrations, and sediment transport are negatively affected. In addition to old dam structures and security concerns, many other factors contribute to dam removal. Another primary motivation for removing the dam is river restoration, which is the attempt to revive the river's physical and environmental characteristics. Removing the dam can improve ecological conditions, but it is essential to understand the changes in riverbeds after dam removal.

Dam removal exposes sediments deposited in reservoirs to erosion and transportation downstream. The grain size of sediment deposition affects the river's physical response. Sand is rapidly eroded from the reservoir and transported downstream, while silt and cohesive clay are eroded more slowly [1]. Since dams accumulate large amounts of sediment in their reservoirs over time, it is important to investigate how they are transported downstream.

Several models, software [2-5], and physical models [6-9] have been used to model downstream sediment transport after dam removal, including the Dam Removal Express Assessment Model (DREAM). DREAM includes three sub-models: hydrodynamic, sediment transport and morphology. This model uses quasi-normal and gradually-varied flow equations (GVF) to calculate water flow. Two sediment transport rate equations are applied in the sediment transport sub-model, depending on sediment grain size. If the sediments are coarse-grained (gravel and coarser than gravel), Parker's sediment transport equations (DREAM2) are applied. If fine-grained sediments are non-sticky, Brownlie's sediment transport rate equation (DREAM1) is employed. Also, Exner's equation models morphological changes [10].

Several studies have investigated sediment transport modeling after dam removal. Conlon [11] investigated Sohgan River bed elevation changes for four years after Merrimack Village Dam removal using DREAM1. To evaluate the model's accuracy, the numerical modeling results were compared with the field measurements. DREAM1 estimated the channel bed elevation with an accuracy of one meter and an average difference of ±0.35 meters in comparison to the average bed height in each section. Cui et al. [12] modeled sediment transport after Simkins Dam removal using DREAM1. The results obtained from modeling were compared with the measured values. Excellent agreement was found between the results and the measured values, although slight differences were still observed in some specific parts. To further improve the results, more accurate geometry was used. In a study, Stillwater Science [13] investigated the changes in the Patapsco River bed elevation after removing the Blood Dam using the DREAM1 equation. The model was developed by considering three geometric characteristics and three hydrological conditions: dry, average and wet. In the case of average and wet hydrological conditions, 26 weeks and 4 weeks were estimated for the river bed to return to its elevation before dam construction. Stillwater Science [10] modeled sediment transport following Marmot Dam removal using DREAM2. The changes in the slope of the reservoir area were fast in the early days and slowed down over time. Over four years, the majority of the sediments in the reservoir were eroded.

This study will analyze the Zonouz Dam as a case study and predict and model one-dimensional changes in the downstream river bed following dam removal.

2. Material and methods

2.1. The governing equation of DREAM

The governing equations of DREAM are used in sediment transport modeling of dam removal. This model includes three sub-models: hydrodynamic, sediment transport and morphology. The details are presented below.

2.2. The governing equation for the flow

As a result of steep slopes and sudden changes in upstream and downstream slopes, and due to subcritical and supercritical flows, the dam removal model should be able to model transitional flows.

In DREAM, the equation governing the GVF and the quasi-normal assumption are used to model water flow. In other words, based on the Froude number, it is decided which equation to be used. If the Froude number is low and the flow is subcritical, the governing equation for the GVF is applied. For high Froude numbers and supercritical flows, the quasi-normal assumption is employed. This method was evaluated by Cui and Parker [10] and showed good accuracy. This method is employed to model transitional flows. The GVF equation is only used if the flow is always subcritical or supercritical.

$$\frac{dh}{dx} = \frac{S_0 - S_f}{1 - Fr^2} \qquad Fr < F_c$$

$$S_0 = S_f \qquad Fr \geq F_c \tag{1}$$

h is the water depth, x is the distance from the downstream, S_0 is the bed slope, S_f is the friction slope, Fr is the Froude number and F_c is the critical Froude number. The critical Froude number that is smaller than and close to unity ($0.75 \leq F_c \leq 0.95$) [14].

2.3. The governing equation for sediment transport

For modeling fine and coarse sediments simultaneously, there was no effective sediment transport equation developed until recently. It was difficult to model the transport of these sediments because of this issue. Rather than a sediment transport equation that models both fine and coarse sediments simultaneously, an alternative method that models fine and coarse sediments separately can be used. [10].

Given the following assumptions, this approach is believed to be the most appropriate choice:

1) In high-flow, coarse-grained sediments are generally transported as bed loads, while fine-grained sediments are generally transported as suspended loads.
2) During intermediate-flow, fine-grained sediments are transported more than coarse-grained sediments.

Although separating the equations for coarse and fine sediments is not the most accurate solution, it provides an acceptable approximation [15].

Stillwater Science [15] developed a one-dimensional numerical model to predict fine and coarse sediment transport rates after dam removal. It evaluates and compares sediment transport modeling under various river conditions. Various parameters, including sediment grain size, determine the type of sediment transport rate equation to be employed. The sediment transport equation in DREAM can be calculated using two different methods based on sediment size. If the sediments are fine-grained (non-cohesive sand and silt), DREAM1 is applied, and if the sediment in the top layer of the reservoir is mainly coarse-grained (gravel), DREAM2 is utilized. To calculate sediment transport rates, these two models use different equations. In DREAM1, Brownlie's sediment transport rate is employed while for DREAM2, Parker's sediment transport equation is employed [15].

In this study, DREAM1 is used due to the type of sediment in the case study. As this study area has steep slopes, Smart and Rickenmann's sediment transport equations for steep slopes were also evaluated. This was done to ensure the proper performance of Brownlie's sediment transport equation.

2.3.1. Brownlie's equation

Brownlie [16] developed the sand transport rate equation in 1981. For rivers with sandy beds, this equation is extended. First, a series of parameters related to sediment grain size are considered to calculate the sediment transport rate.

$$D_g = (D_{16}\, D_{84})^{0,5} \tag{2}$$

$$\sigma_g = (D_{84}/\, D_{16})^{0,5} \tag{3}$$

D_g is geometric mean grain size of sand, σ_g is sand geometric standard deviation. Then the sediment transport rate is calculated as follows:

$$Q_s = 7155 \times 10^{-6} \times c_f \times \left(F_g - F_{go}\right)^{1,978} \times Q_w \times \frac{\gamma_w}{\gamma_s} \times S^{0,6601} \times \left(\frac{h}{d_{50}}\right)^{-0,3301} \tag{4}$$

$$F_g = \frac{Q_w}{Bh\sqrt{Rd_{50}g}} \tag{5}$$

Where, $C_f = 1$ for laboratory data, $C_f = 1.268$ for field data, F_g denotes the particle Froude number, F_{go} is the critical grain Froude number, Q_w is river discharge, S is the bed slope, h is the water depth, d_{50} is the median grain size, B is the channel width, and R is the submerged specific gravity of sediment grains.

$$F_{go} = 4,596\tau_{*o}^{0,5293} S^{-0,1405} \sigma_g^{-0,1606} \tag{6}$$

$$\tau_{*o} = 0,22Y + 0,06e^{-7,73Y} \tag{7}$$

$$Y = \left(\sqrt{R}R_g\right)^{-0,6} \tag{8}$$

$$R_g = \frac{\sqrt{gD_g^3}}{\nu} \tag{9}$$

R_g is the Grain Reynolds Number and ν is the kinematics viscosity [16].

2.3.2. Smart's equation

Smart [17] developed the sediment transport rate in a steep channel in 1984. The sediment transport rate is calculated as follows:

$$\varphi = 4 \times \left[\left(\frac{d_{90}}{d_{30}}\right)^{0,2} S^{0,6}\, C\, \theta^{0,5}\, (\theta - \theta_{cr})\right] \tag{10}$$

$$\varphi = \frac{q_s}{(s-1) g d_m^3} \tag{11}$$

φ is dimensionless sediment transport, d_{90} , d_{30} is the grain diameter for which 90% and 30% weight of a nonuniform sample is finer respectively, S is channel slope, C is flow resistance factor (= $V/(\sqrt{g, H, S})$), θ is dimensionless shear stress (Shield's parameter), θ_{cr} = critical Shield's parameter (slope adjusted), q_s is volumetric sediment discharge per unit channel width, s is ratio of sediment density to water density, and d_m is mean grain diameter [17].

2.3.3. Rickenmann's equation

Rickenmann [18] developed the sediment transport rate in a steep channel in 1991. The sediment transport rate is calculated as follows:

$$\varphi = \frac{3,1}{(s-1)^{0,5}} \times \left(\frac{d_{90}}{d_{30}}\right)^{0,2} \theta^{0,5}\, (\theta - \theta_{cr})\, F^{1,1} \tag{12}$$

$$\varphi = \frac{q_s}{(s-1) g d_m^3} \tag{13}$$

Where φ is dimensionless sediment transport, d_{90}, d_{30} is the grain diameter for which 90% and 30% weight of a nonuniform sample is finer respectively, θ is dimensionless shear stress, θ_{cr} = critical Shield's parameter, F = $V/\sqrt{(g,h)}$ is the Froude number, q_s is volumetric sediment discharge per unit channel width, s is ratio of sediment density to water density, and d_m is mean grain diameter [18].

2.4. The governing equation for the morphological changes

Exner [19] developed the Exner equation between 1920 and 1925. This equation expresses the conservation of sediment mass in flow systems such as rivers. The Exner equation describes the mass balance between bed sediments and sediments that are being transported [19].
The Exner equations for sand continuity take the following forms:

$$B\frac{\partial \eta}{\partial t} + \frac{1}{(1-\lambda_s)}\frac{\partial Q_s}{\partial x} = 0 \tag{14}$$

η is the deposition thickness, λ_s is the porosity of the sand deposit and Q_s is the volumetric transport rate of sand.
DREAM flowchart is shown in Figure 1.

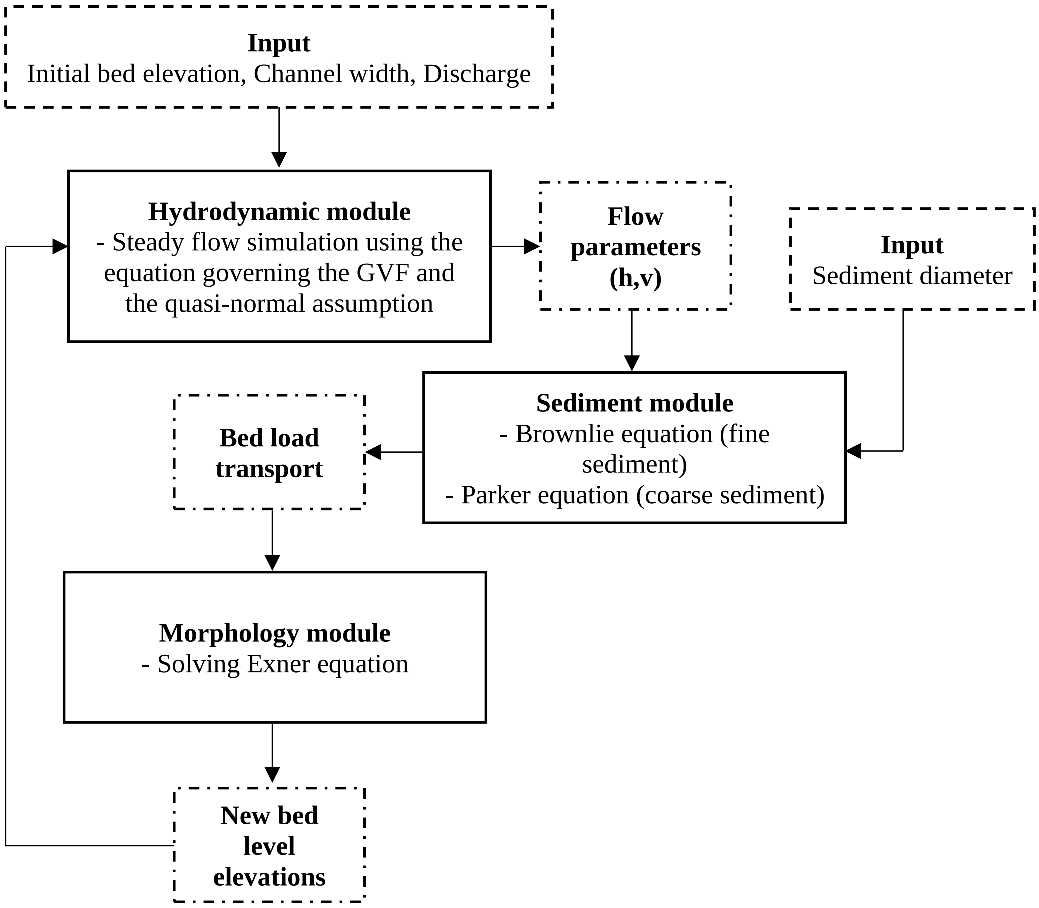

Figure 1. Flowchart of DREAM

3. Case study

Zonouz Dam is located in East Azarbaijan province, 4 kilometers east of Zonouz City and 30 kilometers northeast of Marand City. It is located on the Zonouzchay River. In addition to managing and controlling the Zonouzchay River, the dam provides water to Zonouz City and a portion of the agricultural lands. The dam is of impervious central clay core rockfill type. The dam has a height of 60 meters from its foundation and started operating in 2007. A significant decrease in the dead volume capacity of the reservoir due to sedimentation makes this dam suitable for study as a possible research case.

3.1. Zonouz Dam information

Modeling requires the following input data:
River slope, width, discharge and sediment grain size distribution upstream and downstream of the dam.

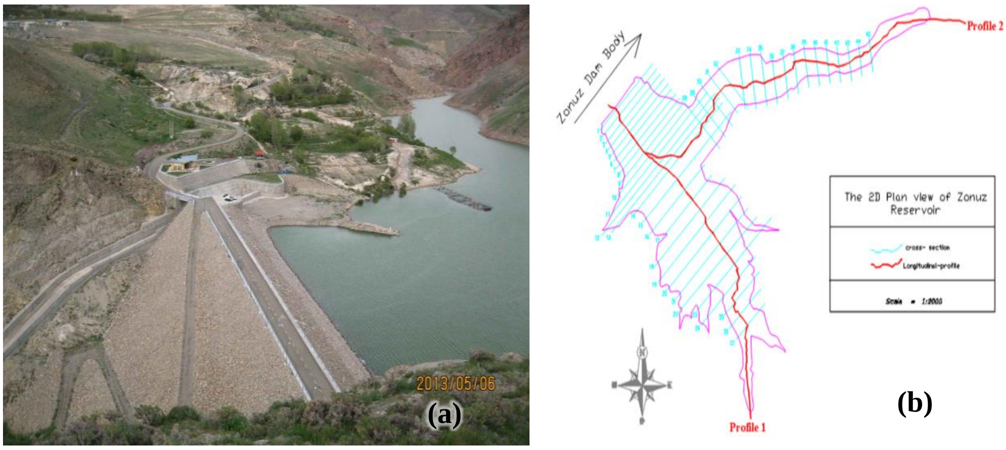

Figure 2. a) Zonouz Dam, b) Zonouz Dam reservoir in plan view

The major part of sediments in the study area were characterized as non-cohesive sands. Based on particle size analysis of bed samples the geometric mean diameters of the sediment particles were obtained as $d_g = 1$ mm, $\sigma_g = 1.82$, with a density of 2650 kg per cubic meter.

Table 1- Average slope of the Zonouzchay River

	Downstream			
Distance (Km)	0-0.4	0.4-4	4-9	9-11
Average slope	0.061	0.038	0.035	0.034

Table 2- Average width of the Zonouzchay River

	Upstream		Downstream				
Distance (Km)	Profile 1	Profile 2	0-0.5	0.5-1	1-4	4-9	9-11
Average width (m)	70	50	115	98	82	85	90

Table 3- River discharge

	Dry conditions (m^3/s)	Average conditions (m^3/s)	Wet conditions (m^3/s)
Profile 1	0.4	0.75	1.5
Profile 2	0.4	0.75	1.5
Zonouzchay River	0.8	1.5	3

In DREAM1, steady flow is assumed for calculating flow parameters. The depth at the first point is calculated using the Newton-Raphson method by applying the discharge at the upstream point due to supercritical conditions. Then, other parameters are determined. The average sediment discharge brought by the river to the dam's reservoir is used to estimate the sedimentation rate and solve Exner's equation for the input boundary condition. At the final point, the changes in the thickness of the sediments are considered zero.
The numerical model is written in MATLAB based on the equations and methods used in DREAM1.

4. Results and discussion

4.1. Verification

Due to the steep slopes in the study area, 350 laboratory data were collected under similar conditions to those used in modeling [20-24]. This was done to determine the most appropriate sediment transport rate for steep slopes. Following this, the results of the sediment equations mentioned in the previous section were compared to each other. The calculation result is presented in Table 4, which indicates the lowest error in the Brownlie sediment transport equation.

Table 4- Errors in different sediment transport equations

	Brownlie	Smart	Rickenmann
MSE	5.67E-07	1.33E-06	1.36E-06

In order to validate the accuracy of the model developed in this study, the results obtained from modeling pulse thickness changes are compared to those obtained from Cui et al. model. The numerical model was developed by Cui et al. [25] in 2003 using Fly River data. In this modeling, they investigated the movement of the sediment pulse and modeled the evolution process of the sand pulse using DREAM1. The results of this modeling after periods of 3 days, 10 days and 30 days were compared with that of the present research. This modeling was carried out along 16 kilometers of the river with the assumption of sand sediments and an initial pulse of 2 kilometers long and 1 meter high [25].

Table 5- Model parameters

Slope	Froude number	Depth (m)	Discharge (m^2/s)	D_{50} (mm)	σ_g
0.0001	0.28	5.07	10	0.2	1.5

The changes in pulse thickness at the beginning and after 3, 10 and 30 days are shown in Figure 3. The pulse thickness decreases over time. Figure 3 shows that pulse evolution occurs through two mechanisms: translation and dispersion. In low Froude numbers and fine-grained sediments, the translation mechanism is as effective as the dispersion mechanism. Comparing the simulated results with the study of Cui et al. demonstrates the success of the model.

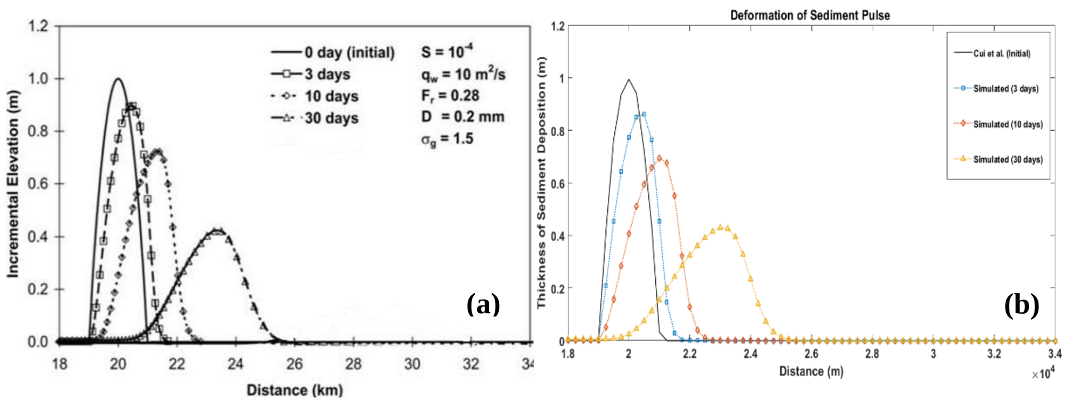

Figure 3. Simulated elimination of sediment pulse a) Cui et al., b) Simulated

4.2. Zonouz Dam

4.2.1 Short term

In order to investigate the transport of sediments in the short term, simulations were performed for periods of 24 hours, 10 days, and one month for different discharges. Table 6 shows short-term changes in sediment transport rate. Over time, the peak of sediment transport decreases. The decreasing rate of sediment transport can be attributed to the decrease in bed slope. Also, the sediment transport peak increases with the flow rate. Table 7 shows changes in sediment pulse thickness. As the discharge rose, the sediment transport rate increased and pulse evolution accelerated. The sediment transport rate in profile 3 is higher than that of the two other profiles. This is because of the higher discharge since the discharge of profile 3 is formed by the combination of profiles 1 and 2. The highest rate of sediment transport is related to locations where the bed slope is steeper.

Table 6- Sediment transport rate (m^3/s)

	24 Hr			10 Days			1 Month		
	Profile 1	Profile 2	Profile 3[3]	Profile 1	Profile 2	Profile 3	Profile 1	Profile 2	Profile 3
Wet	0.01	0.01	0.028	0.0072	0.0074	0.0234	0.0059	0.0061	0.02
Average	0.0037	0.0031	0.0085	0.0023	0.0025	0.0078	0.002	0.0021	0.0069
Dry	0.0013	0.00098	0.0027	0.00091	0.00092	0.0026	0.0007	0.00078	0.0025

Table 7- Thickness of pulse (sand deposition) (m)- Short term

	24 Hr			10 Days			1 Month		
	Profile 1	Profile 2	Profile 3	Profile 1	Profile 2	Profile 3	Profile 1	Profile 2	Profile 3
Wet	6.38	5.92	10.03	5.31	5.47	8.6	4.42	4.68	7.18
Average	6.7	6.07	10.35	5.97	5.84	9.55	5.4	5.53	8.7
Dry	6.8	6.19	10.5	6.41	5.94	10.04	6	5.85	9.58

A change in the bed level is another important result that helps in the understanding of the changes after dam removal. Figure 4 shows how bed elevation changes after one month under different hydrological conditions. It is obvious that sediments in the reservoir began to erode and accumulate downstream. Wet hydrological conditions caused faster bed level changes than the other two conditions, while dry conditions showed the smallest changes. Changes in bed elevation in the short term will result in the stability of the slope. However, in the long term, profile 1 and profile 2 will erode completely.

4.2.2 long term

In order to analyze the transport of sediments in the long term and to estimate the time required for the erosion of the deposits in the reservoir and for the dam site to reach its pre-construction state, simulations were conducted for more than one year under different hydrological conditions. Figure 5 shows bed elevation changes for three different profiles. As

[3] The junction of profiles 1 and 2 and the river

shown in Figure 5, the reservoir sediments are eroded and deposited downstream over time. Figure 5 presents the changes in bed elevation under average hydrological conditions. Modeling was also done for other hydrological conditions. The results indicate that under wet hydrological conditions bed erosion occurs much faster (3 years) while it is by far slower (28 years) under dry conditions.

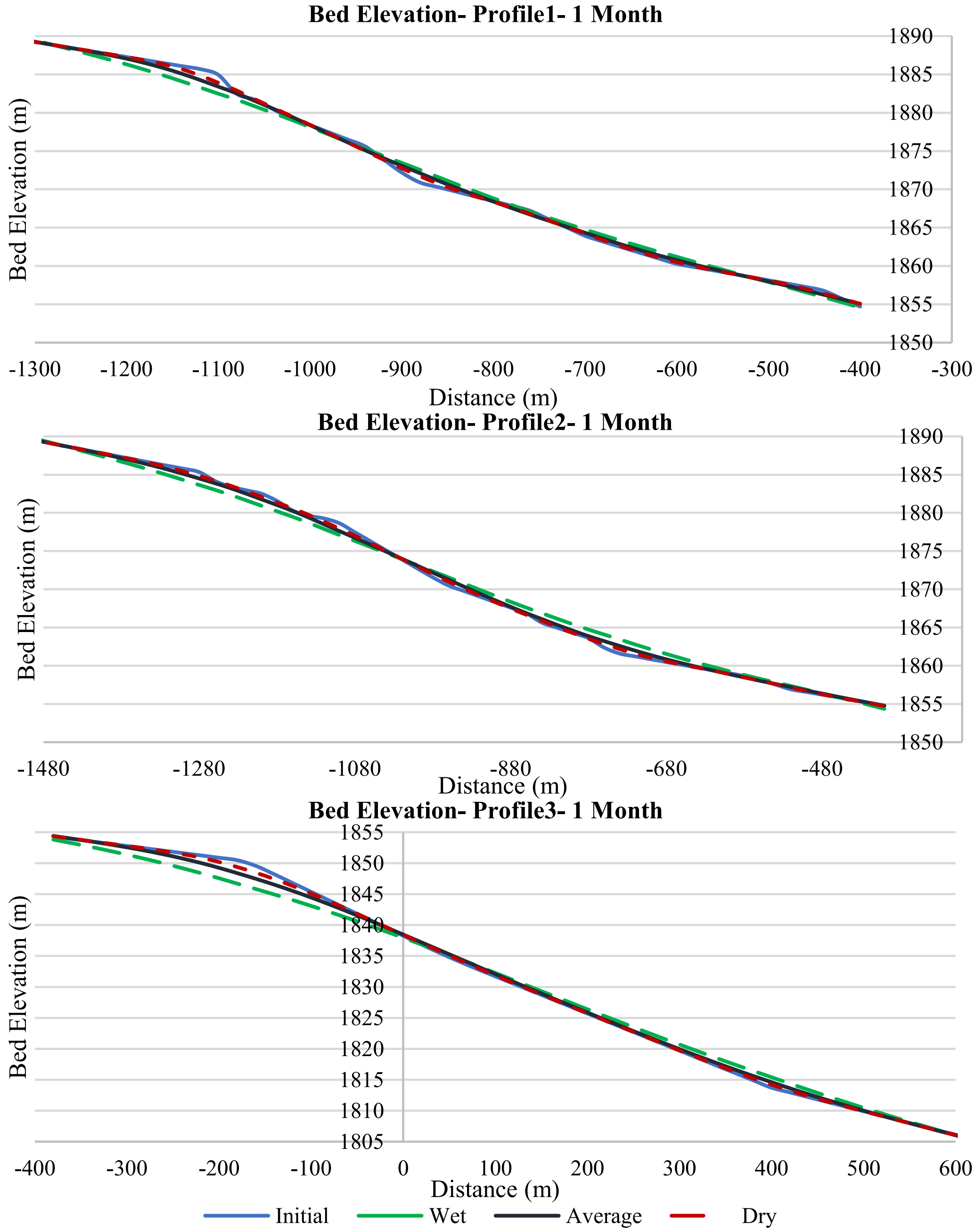

Figure 4. Bed elevation changes- Short-term

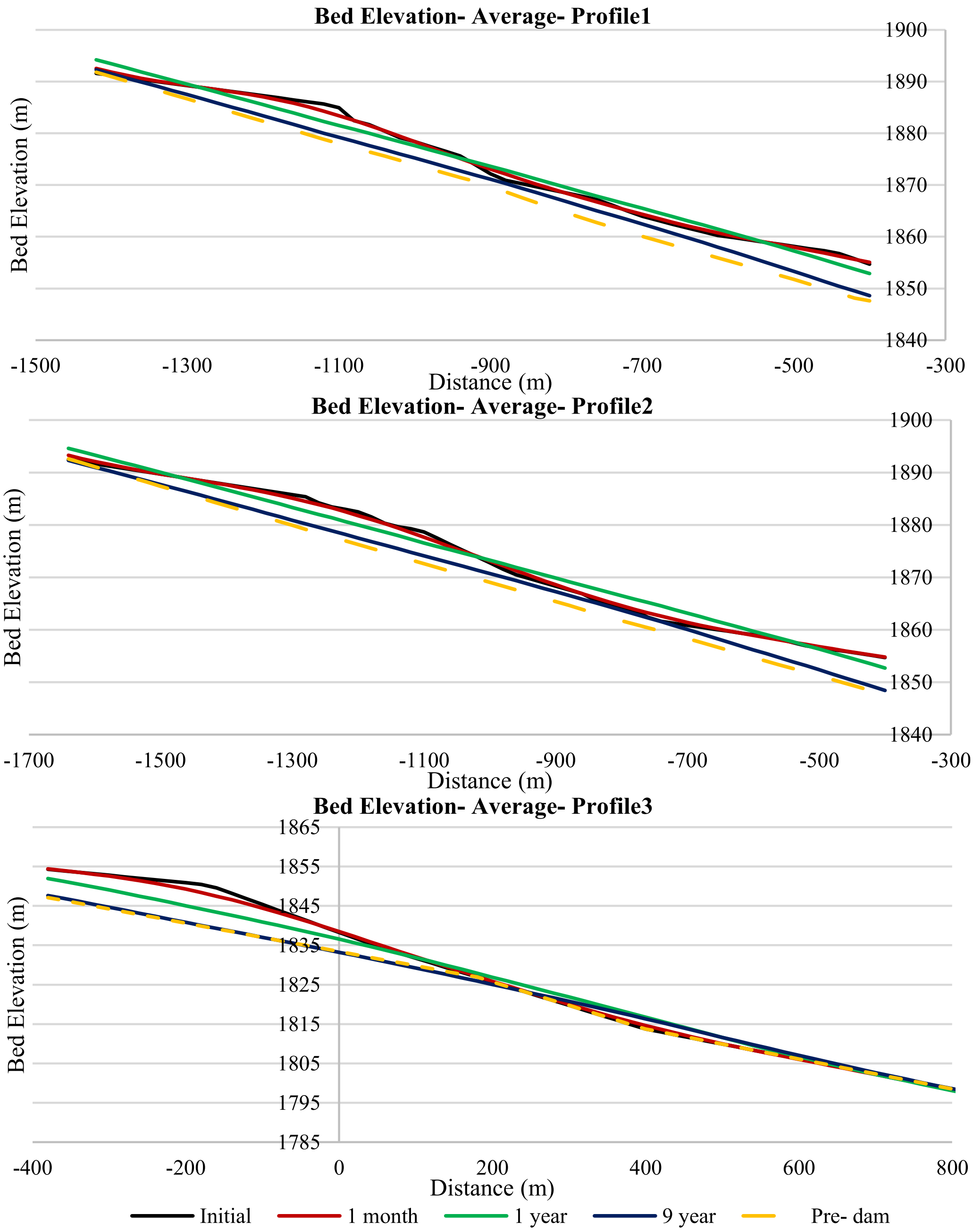

Figure 5. Bed elevation changes- Average condition- Long-term

As seen in Table 8, under all hydrological conditions, the thickness of the sediments has been more eroded in the long term than in a similar situation during the short term. Therefore, over time, a greater amount of sediment has been eroded from the reservoir but the rate of change has decreased. This means that in the first months and years after dam removal, the rate of sediment elimination was higher and it decreased over time. This phenomenon can be attributed to the decrease in the bed slope.

Table 8- Thickness of pulse (sand deposition) (m)- Long term

	1 year			**2 years**		
	Profile 1 (x=-1100)	Profile 2 (x=-1200)	Profile 3	Profile 1 (x=-1100)	Profile 2 (x=-1200)	Profile 3
Wet	3	3.28	2.77	2.06	2.3	1.36
Average	3.49	3.72	4.85	3.24	3.49	3.67
Dry	4.37	4.57	6.93	3.79	3.99	5.65
	3 years			**5 years**		
	Profile 1 (x=-1100)	Profile 2 (x=-1200)	Profile 3	Profile 1 (x=-1100)	Profile 2 (x=-1200)	Profile 3
Wet	1.01	1.25	0.34	-	-	-
Average	3.03	3.26	2.94	2.48	2.64	1.94
Dry	3.54	3.75	4.9	3.35	3.57	4.01
	9 years			**28 years**		
	Profile 1 (x=-1100)	Profile 2 (x=-1200)	Profile 3	Profile 1 (x=-1100)	Profile 2 (x=-1200)	Profile 3
Average	1.18	1.26	0.54	-	-	-
Dry	3.11	3.27	2.97	1.3	1.2	0.49

Previously, modeling results were presented for three hydrological conditions that remained constant over the years to estimate sediment erosion time. In the following, the model results are presented considering seven years of hydrological conditions at Zonouz Dam. Table 9 shows these hydrological conditions.

Table 9- Hydrological conditions at Zonouz Dam

1st year	**2nd year**	**3rd year**	**4th year**	**5th year**	**6th year**	**7th year**
Average	Wet	Average	Dry	Average	Average	Average

Figures 6 and 7 show sediment thickness changes in the third and seventh years under different hydrological conditions. In the third year, sediment erosion is mainly caused by wet hydrological conditions, while dry hydrological conditions cause small amounts of sediment erosion. Significant sedimentation has accumulated where the slope decreased or width increased.

These areas are between 1.5 to 6 and 7 to 11 kilometers and immediately downstream of the dam. Also, by comparing the average hydrological conditions and the hydrological conditions of Zonouz Dam, it is observed that erosion occurs more in the hydrological conditions of Zonouz Dam than in the average conditions. On average, hydrological conditions prevailed for seven years. However, Zonouz Dam experienced wet conditions in the second year and dry conditions in the fourth year. This illustrates that wet hydrological conditions in the early years have a significant impact on the occurrence of dry conditions in the following years.

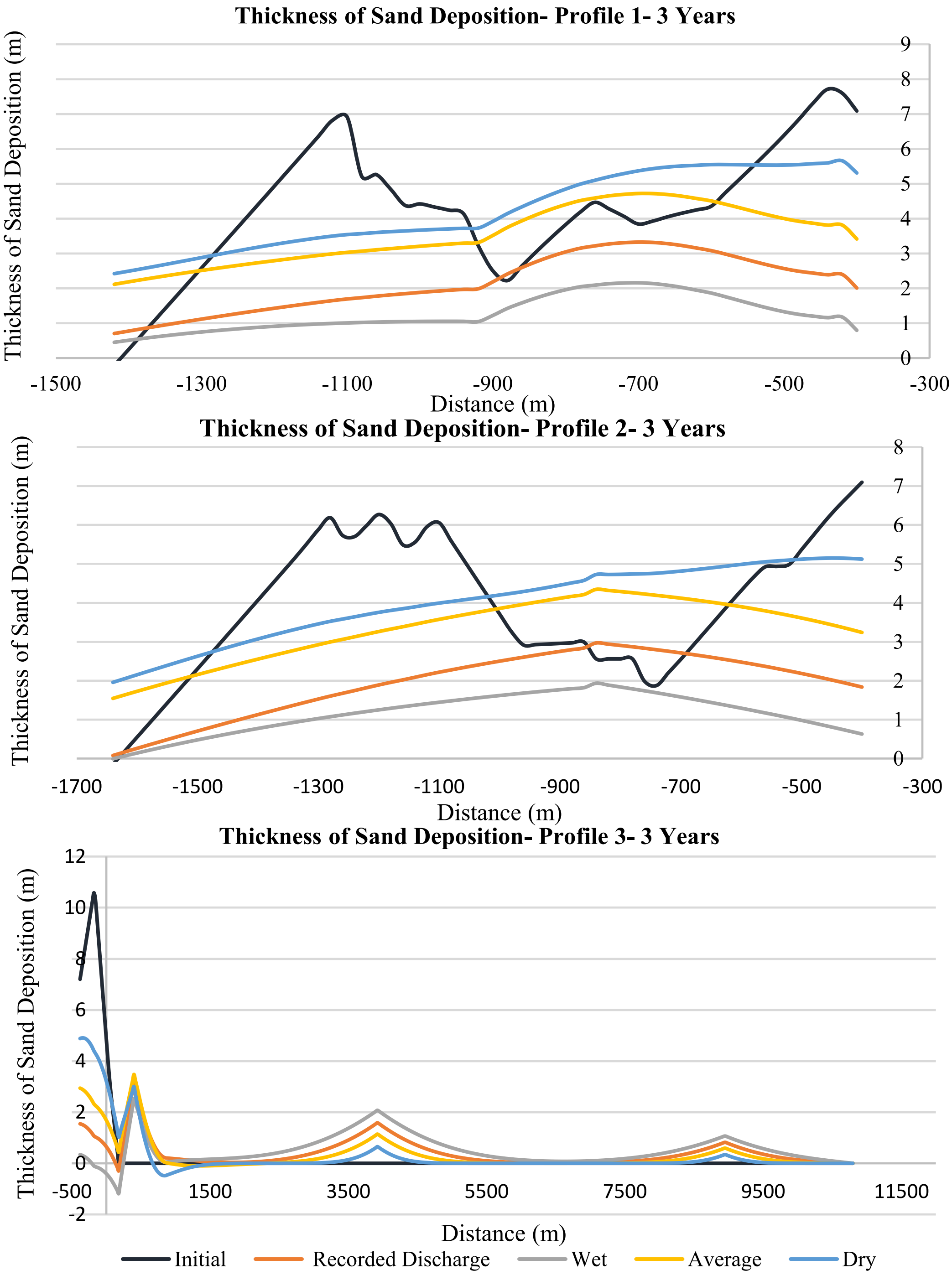

Figure 6. Thickness of sand deposition- 3rd Year

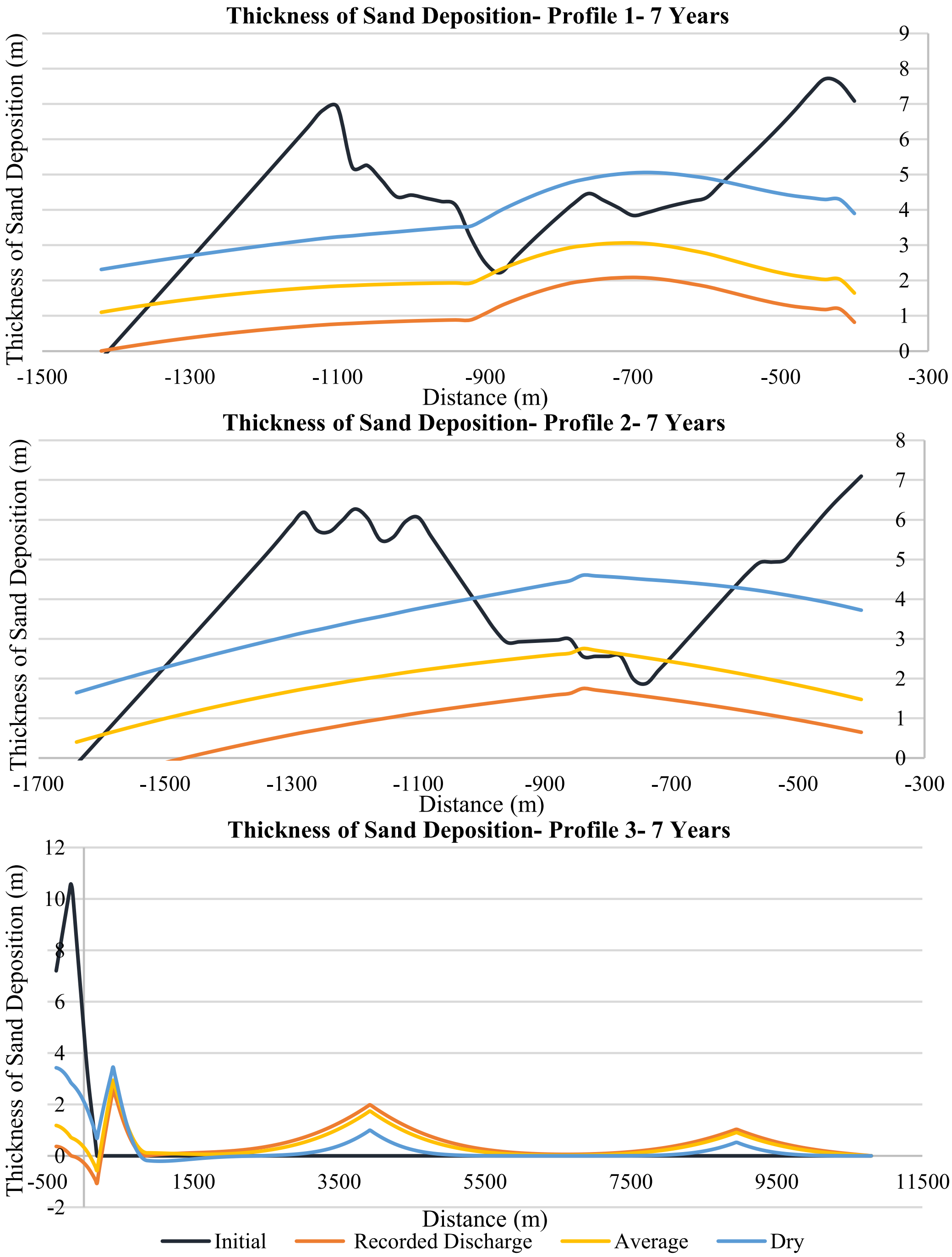

Figure 7. Thickness of sand deposition- 7th Year

Table 10 shows the percentage of sediment erosion in different years. As expected, the erosion rate is much higher at high discharge rates than at low discharge rates. In addition, erosion rates are high in the early years but decrease over time. On the other hand, by comparing the results of wet, dry, and average years with the hydrological conditions governing the dam, it is concluded that the order of wet years is very effective in controlling erosion rates. During the second year when the Zonouz Dam hydrological conditions were assumed, sediments eroded by 37%. However, in the second year when wet conditions were assumed, 23% erosion happened. This is due to the difference in discharge in the first year. In the first year, a large percentage of sediments were eroded due to wet conditions. In the second year, the reservoir slope was reduced. This led to a decrease in erosion rates in the second year compared to the dam's prevailing hydrological conditions. Table 10 presents detailed information about sediment erosion percentage in different years.

Table 10- The percentage of sediment erosion

	1 year	2 years	3 years	5 years	7 years
Dry	7	12	16	23	29
Average	18	27	35	50	65
Wet	37	60	79	-	-
Recorded discharge	18	55	62	70	82

5. Conclusions

Around the world, dams have been removed for decades because of safety concerns, reservoir volume losses, and river restorations. Dam removal exposes sediment deposited in reservoirs to erosion and transportation downstream. A river's physical response depends on the grain size of sediment deposition. The Dam Removal Express Assessment Model (DREAM) is one of the most commonly used models for modeling downstream sediment transport after dam removal. By analyzing the Zonouz Dam as a case study, this study will predict and model one-dimensional changes in the downstream riverbed following dam removal by using the governing equations of DREAM. The numerical modeling results of sediment transport indicate that the erosion rate in the first months and years is much higher than in the following years. About 79% of the reservoir sediments eroded under wet hydrological conditions after three years. The sediment waves in this reservoir also generally follow an evolution based on dispersion. Other factors that affect erosion rates are the existing hydrological conditions. For example, under average hydrological conditions, sediments erode in nine years. Under dry hydrological conditions, sediments erode in 28 years. Reservoir sediment erosion can result in sediments traveling 11 kilometers downstream in the long term. The highest deposition occurs in areas where the slope has decreased or the width has increased. In the immediate downstream of the dam, these locations are 1.5 to 6 kilometers and 7 to 11 kilometers away from the dam, respectively.

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