



# Land degradation by erosion occurred after irrigation development in the Harran plain, Southeastern Turkey

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## Abstract

A study was made to determine the erosion problem and determine the amount of suspended sediment transport in the drainage channels of the Harran Plain by conducting periodic suspended sediment sampling and discharge measurements in the field between 1997 and 2017. When irrigation in the Harran Plain started in 1990, the production of the agricultural goods quadrupled within a few years. Unfortunately, excessive amounts of irrigation water supplied to irrigate crops also led to the erosion of the soil in the fields by surface runoff. Furthermore, the mixture of clay, silt, and fine sand in the topsoil from certain areas accumulated in the tertiary and secondary drainage systems and reduced the effectiveness of the drainage system. Analysis of the suspended sediment measurements between 1997 and 2017 showed that the yearly averaged sediment transported to Syria by the main drainage canal of the Harran Plain varied between 128 ton.day<sup>-1</sup> to 1268 ton.day<sup>-1</sup>, and the average of the 21-year measurement is about 682 ton.day<sup>-1</sup>. The logarithmic plot of the suspended sediment rating curve showed that as the discharge of the Cullap Creek increases, the sediment transport rate also increases linearly. It means excess furrow irrigation could cause substantial topsoil loss. Sediment erosion resulting from rainfall events in the Harran Plain is also computed using Revised Universal Soil Loss Equation (RUSLE). The results showed that rainfall erosion from the Harran Plain is 131.5 ton.day<sup>-1</sup>. A comparison of this value with the 21-year value of average sediment erosion by irrigation shows that approximately 20% of sediment erosion from the Harran Plain was caused by rainfall events, and the remaining 80% was caused by excess irrigation water in the area. A 2D numerical model was constructed with MIKE 21 software applying Van Rijn Method to calculate suspended sediment load due to irrigation, and it allowed to calculate the load with a 6.47% error. Grouping the irrigated and non-irrigated periods and applying independent *t* test, a statistical approach constituted and resulted in 79.2% of suspended sediment load is caused by irrigation. The numerical model and statistical analysis supported the findings of field data and RUSLE Model results. The study showed that the main reason of the topsoil loss in the Harran Plain is the excess furrow irrigation.

**Keywords** Erosion · Suspended sediment · Drainage · Furrow irrigation · RUSLE · MIKE 21 · Harran plain

## Introduction

Irrigation is a widely adopted method for increasing agricultural crop production worldwide to supply the increasing needs of the growing world population. Even though

countries are shifting investments from classical irrigation techniques to modern irrigation techniques, surface irrigation methods by controlled flooding is still a widely used system for crop production, because it does not require skilled labor and requires less operational cost.

Among the controlled surface irrigation methods, furrow irrigation is the main application method of the surface irrigation systems, which contributed to approximately 90% of the world's crop (Mailapalli et al. 2013). In contrast to those advantages of furrow irrigation schemes, sediment transport and corresponding soil deterioration problems due to surface runoff have affected most of the plains irrigated with this method. It was pointed out by Berg and Carter (1980), Kemper et al. (1985), Trout (1996), Mailapalli et al. (2013) and

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FAO (2013) that poor design and management, non-uniform application of water and over-irrigation are responsible factors leading to inefficient irrigation, surface ponding and runoff and causing waste of irrigation water, surface and water pollution and groundwater salinity, and also substantial soil loss from highly erodible soils in the agricultural areas. It was also pointed out by Mailapalli et al. (2013) that soil erosion problems in various agricultural areas in the U.S. occurred during the irrigation periods. Several studies have been conducted to determine the amount of sediment transported from the erodible irrigation areas. Irrigation-induced furrow erosion problems are studied using hydraulic simulation modeling and semi-empirical methods by Strelkoff and Bjorneberg (1999), Mailapalli et al. (2009) and Meral et al. (2016). Strelkoff and Bjorneberg (1999) used surface irrigation simulation model SRFR based on sediment transport formulas of Laursen (1958), Yalin (1963) and Yang (1973) to predict the erosion and transport from agricultural fields. Comparison of SRFR model results with the field measurements showed that all three formulas significantly over-predict the transport.

Mailapelli et al. (2013) used a steady-state sediment transport model by integrating a physically-based furrow irrigation model that employed three infiltration equations: 2D-Fok (Fok and Chiang 1984), 1D-Green Ampt (Green and Ampt 1911), and Kostiaqpv–Lewis (Walker and Skogerboe 1987). The results of the irrigation model were evaluated for estimating sediment load using Yalin's and Modified Yalin's equations. Mailapelli et al. (2013) conducted a sensitivity analysis and found that the soil erodibility coefficient is the most influential parameter in predicting sediment transport in free drained furrows; however, an irrigation model could not simulate sediment load accurately.

Harran Plain, one of the major agricultural crop production areas of the Southeastern Anatolian Project known as the GAP Project, has been irrigated since 1990 by surface furrow irrigation scheme. It is pointed out by Chao et al. (2018) that this region have been subject to severe drought after 2003, and, as a result of the drought in the region, development of irrigation systems in the plain has accelerated. After the development of the irrigation scheme in the plain, problems of soil deterioration caused by soil erosion and insufficient drainage system existed in the field (Darama and Kas 1997). Several studies conducted by Hatipoğlu et al. (2003), Hatipoğlu and Darama (2004), Darama et al. (2007) and more recently Bilgili et al. (2018) to point out the problems of soil deterioration by erosion and salinity in the Harran Plain. Darama et al. (2007) studied soil erosion due to irrigation development in the Harran plain based on field measurements. Bilgili et al. (2018) studied post-irrigation problems in the Harran Plain and concluded that uncontrolled and excessive flood irrigations caused the level of groundwater to rise over critical levels and led to an

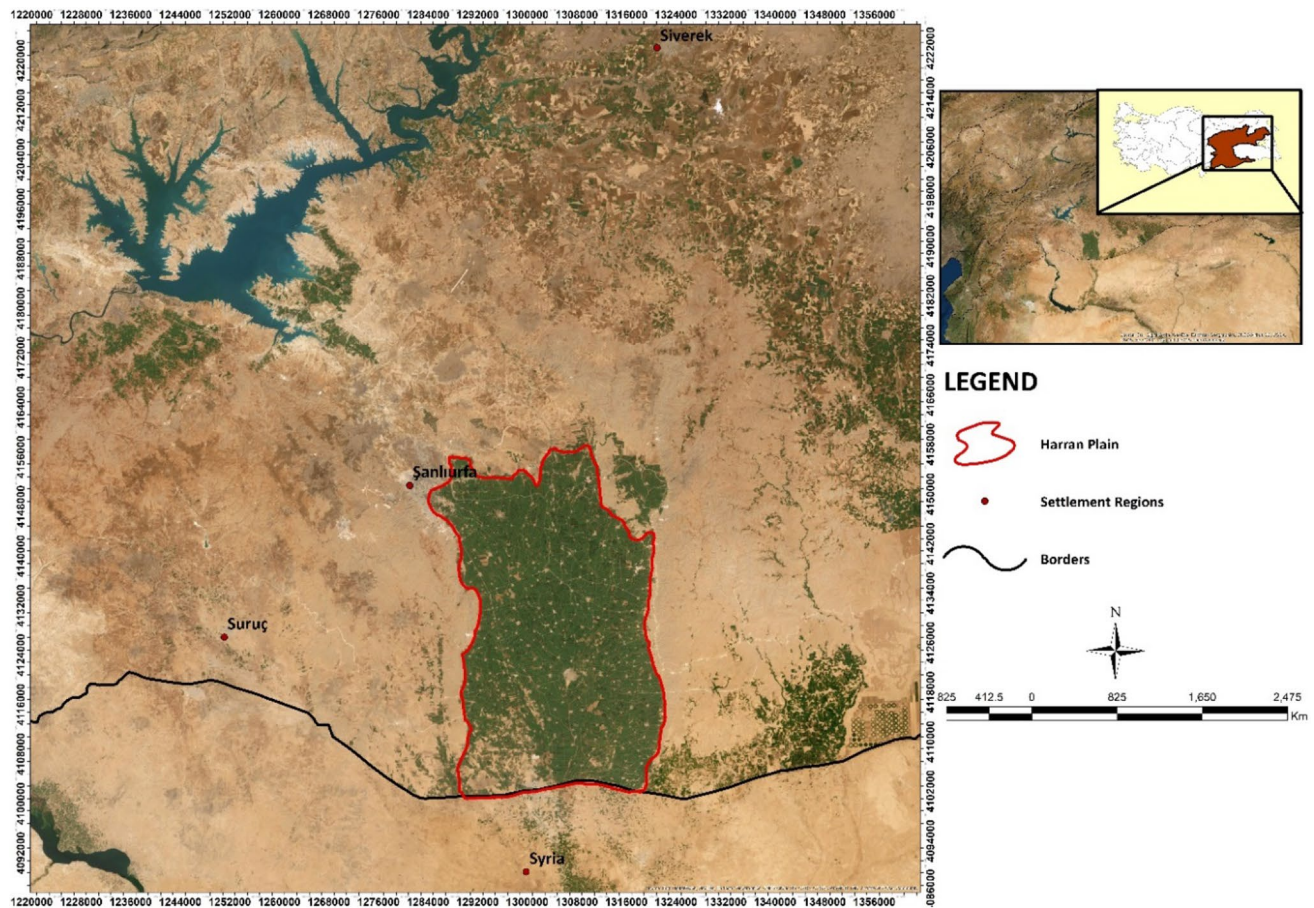
increase in salinity. Furthermore, Bilgili et al. (2018) stated that uncontrolled and excessive irrigation combined with intensive soil tillage led to the erosion occurrence with run-offs, sediment losses, and soil degradation with salinity and high groundwater levels in the area. Meral et al. (2016) studied the determination of non-erosive rate of flow to prevent erosion in furrow irrigation using semi-empirical methods, and they found that field measurement is crucial to quantify the sediment load. Studies of Mailapelli et al. (2013) and Meral et al. (2016) showed that field measurements are the most accurate way of determining erosion from the irrigated lands due to surface irrigation.

Therefore, this study focuses on long-term field measurements of irrigation erosion from the Harran plain. The aim of the study is to determine the amount of sediment erosion from the Harran Plain caused by irrigation and transported by the Cullap creek using 21 years of field measurements and set up a model to calculate the amount of sediment transported by the Cullap creek, which is the main drainage canal of the Harran plain. Although the study area is categorized as an arid region, the average precipitation is observed as  $400 \text{ mm.yr}^{-1}$ , which means irrigation is not the only phenomenon for erosion. To obtain the erosion due to rainfall, Revised Universal Soil Loss Equation (RUSLE) was used. Also, a 2D numerical model was implemented using MIKE 21 software for modeling of the suspended sediment transport at one of the sampling stations (Turluk Station) to calculate the erosion amount due to the furrow irrigation. Sediment rating curves were drawn, and their effectiveness was discussed. Grouping the available data as irrigated and non-irrigated periods and applying the Levene  $F$  test, the effect of the precipitation and furrow irrigation on the amount of suspended sediment was determined.

## Materials and methods

### Study area

The study area is located in Southeastern Anatolia, and the south boundary of the area is bounded by Syria, as shown in Fig. 1. The Harran plain has a very flat topography that gently slopes to Syria. Sieve analysis of the samples obtained from the field to determine soil structure showed that soil in the area consists of fine sand, silt, clay, and is categorized loam to sandy clay loam in the piper diagram (DSI 2013). The area has arid climate nature and is located at  $38^\circ$  latitude north. The average temperature in winter is around  $10^\circ \text{C}$ , while in summer, it is  $35^\circ \text{C}$ . The average precipitation is about  $400 \text{ mm.yr}^{-1}$ , and most of it occurs during winter between mid-November to April. The period from May to November is dry (DSI 2013; Usul 2013). Due to the very low and seasonally variable precipitation in the southeastern



**Fig. 1** Location of the study area in the GAP region of Turkey

part of Turkey, agricultural activities were severely limited, and agricultural crop production was very low until 1990. Especially the Harran and the Mardin plains located between the Euphrates and the Tigris rivers contain highly valuable agricultural soils. These plains were known as the upper Mesopotamia, which was the cradle of the ancient Mesopotamian Civilization. Since 1990, the agricultural activities on these plains have significantly intensified under the umbrella of the Southeastern Anatolian Project known as the GAP project (DSI 2013). After the completion of the construction of the Atatürk Dam and the Şanlıurfa Tunnels, water from the Atatürk Dam reservoir was diverted to the Harran Plains, through the Şanlıurfa Tunnel System discharging  $124 \text{ m}^3 \cdot \text{s}^{-1}$  that irrigate 150,000 hectares of land (Hatipoğlu et al. 2003; Darama et al. 2007) by gravity.

The flow of water first started to irrigate the Harran Plain in 1990 using a classical open channel irrigation scheme that was constructed by means of six contracts (Fig. 2). Table 1 shows that agricultural areas increased in the Harran Plain after the completion of the construction of the irrigation system and put into operation, according to the investment budget and to the irrigation scheme (Hatipoğlu et al. 2003;

and Hatipoğlu and Darama, 2004). The first irrigation scheme, shown Şanlıurfa-1 in Fig. 2, was realized in 1990 when the irrigation systems of the other areas were constructed and put into operation until 2009. Irrigation water was applied to the field by controlled flooding furrow irrigation techniques. It was determined that social and economic benefits from irrigation increased very fast and led to a vast increase in food production in the region, which tripled the output of several crops in the irrigated area of 150,000 hectares in the plain (Altınbilek 1997; Hatipoğlu et al. 2003 and Hatipoğlu and Darama 2004). In contrast to these benefits of excess irrigation, soil erosion problems emerged in the Harran Plain. This problem started with excessive amounts of water withdrawn to irrigate the crop, which eroded the topsoil of the irrigated areas, and a portion of this eroded soil was deposited in the drainage system. The remaining amount is transported by the main canal extending the Syrian border. As seen from Table 1, the size of the irrigated land increased by five times from 1990 to 2009, during which soil erosion problems in the project site was also increased severely, and thus suspended sediment measurements in the main drainage canal were conducted accordingly.



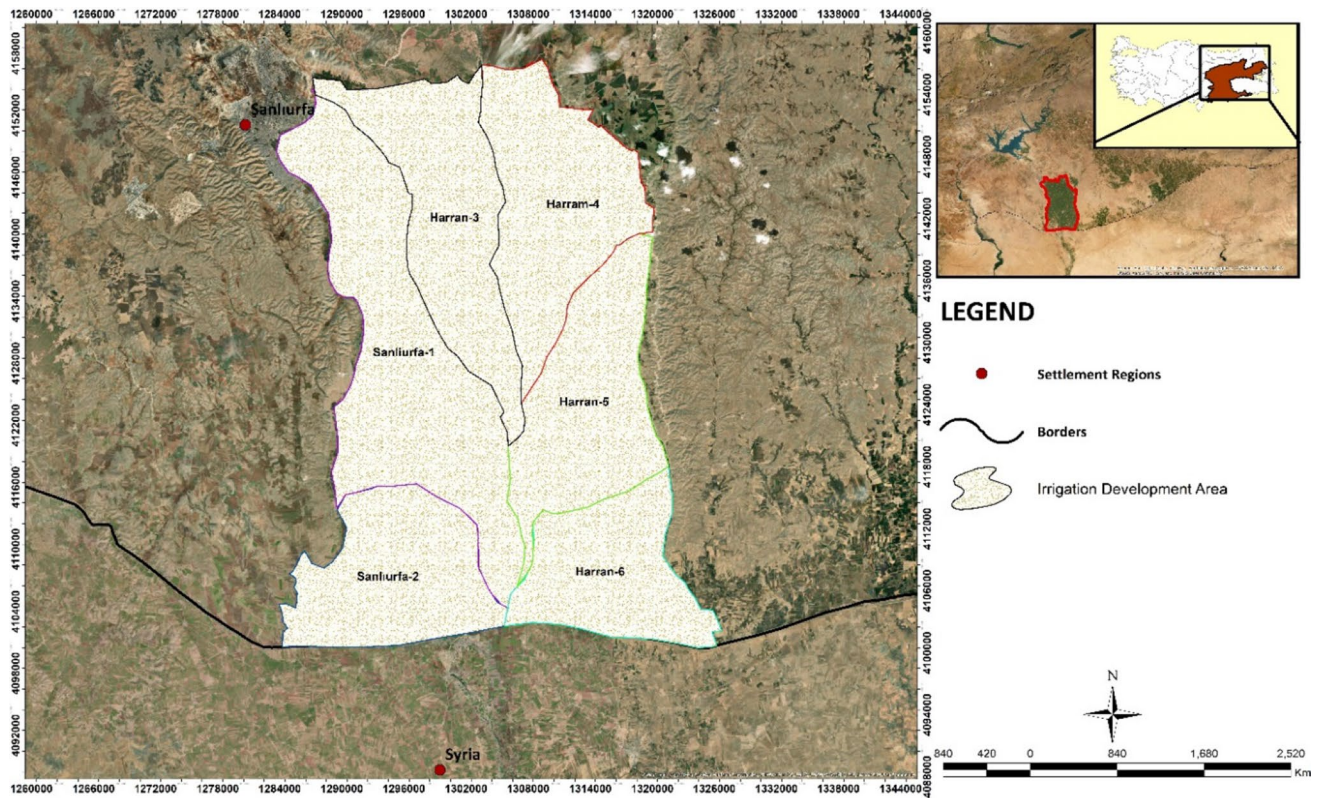


Fig. 2 Irrigation development schemes of the Harran Plain

**Table 1** Irrigated areas in the Harran Plains between 1990 and 2009

Year	Irrigated area (ha)
1990	29,950
1991	31,050
1996	40,000
2000	111,600
2001	116,000
2002	119,000
2003	121,400
2004	123,340
2005	125,000
2006	130,000
2007	145,700
2008	147,581
2009	149,000

**Methodology**

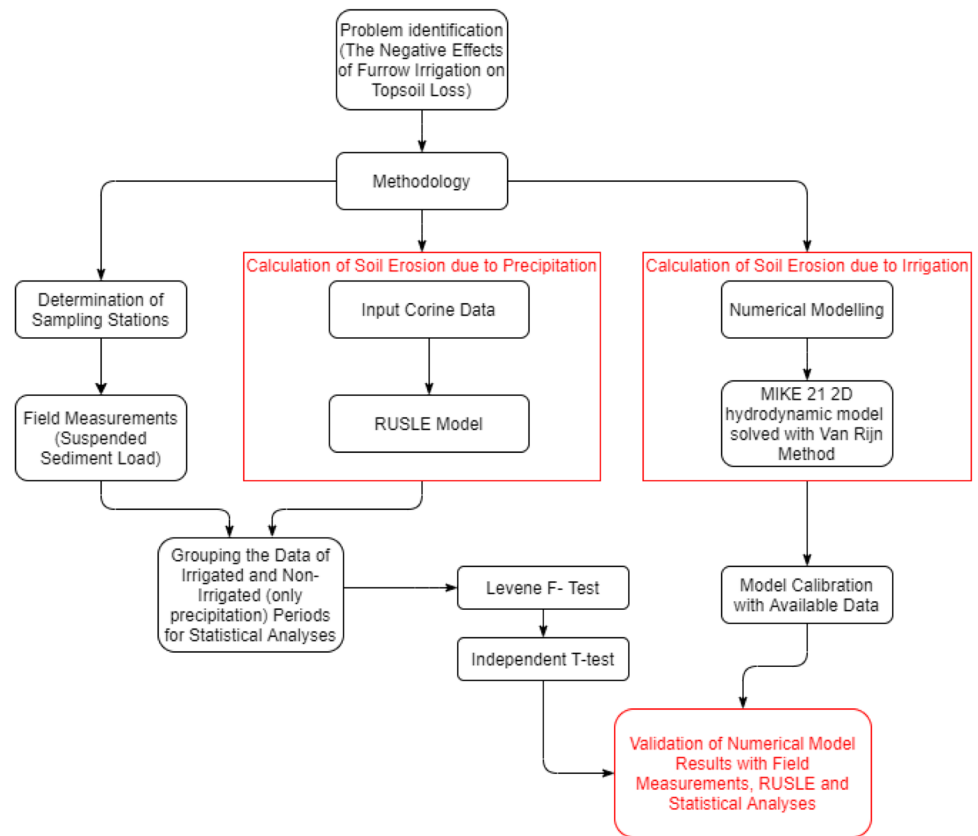
In this research, four methods were applied to calculate the suspended sediment load and specify the reason of the topsoil loss. The field measurements were analyzed to calculate the total amount of suspended sediment. The suspended sediment load due to precipitation was calculated by RUSLE, and the suspended sediment load due to furrow irrigation

was indicated by the numerical MIKE 21 model. The suspended sediment originating from either irrigation or precipitation was statistically determined by grouping the field data as irrigation and precipitation periods (non-irrigated). Figure 3 shows the workflow of this study. At the end of the study, the numerical solution results were validated with field measurements, RUSLE, and statistical analyses. The reliability of the results was discussed.

**Suspended sediment measurement**

To investigate erosion and drainage problems in the field caused by excessive surface irrigation by means of furrows, a study was conducted between 1997 and 2017. During this time span, suspended sediment sampling was performed once a day during the irrigation period and a week after the irrigation period. Sediment sampling was performed at the stations, where the soil erosion and sediment deposition problems were very severe (Darama and Kas 1997). It was determined from field studies that water withdrawn from the secondary and tertiary canals (prefabricated concrete flumes) conveyed irrigation water to each parcel in the plain, and this excessive amount of irrigation water caused surface ponding and surface runoff, and thus produced erosion problems in the field. A portion of this eroded soil was

Fig. 3 Workflow of the study

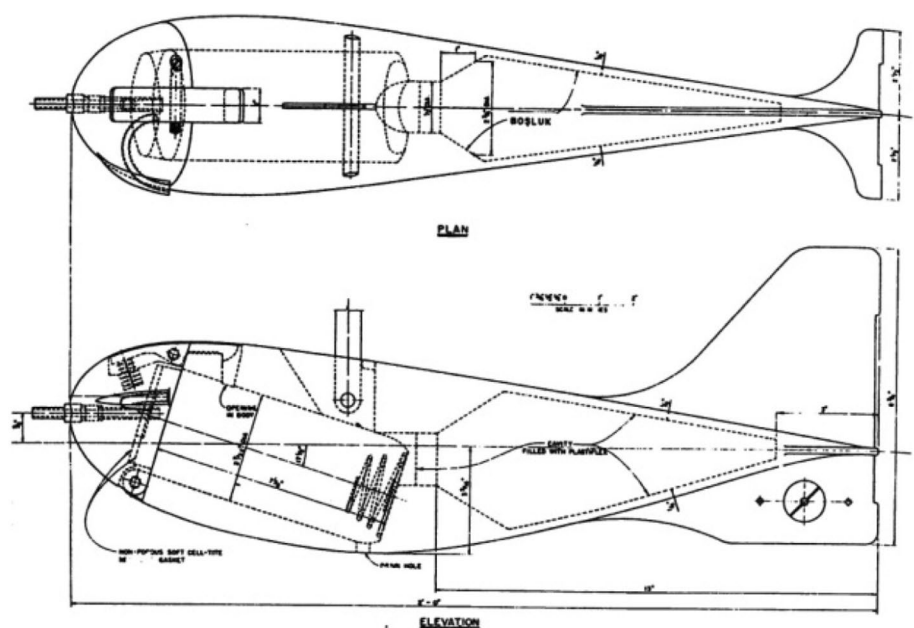


deposited in the tertiary and secondary drainage canals, and the remaining portion was transported to the main drainage canal named Cullap Creek.

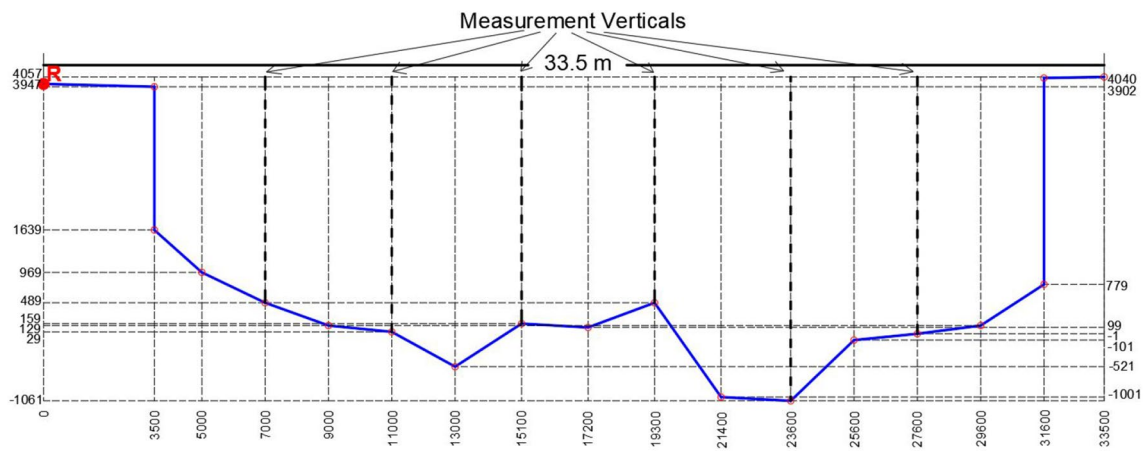
Discharge and suspended sediment measurements were conducted at the project site between 1997 and 2017.

Figure 4 depth-integrated suspended sediment sampler was used to collect suspended sediments in the Cullap Creek at the cross section of the Arican Bridge (Fig. 5). The flood-plain and main channel widths at the measuring cross section are 33.5 m and 6 m, respectively, as shown in Fig. 5.

Fig. 4 US DH-49 depth-integrated sampler used in suspended sediment sampling





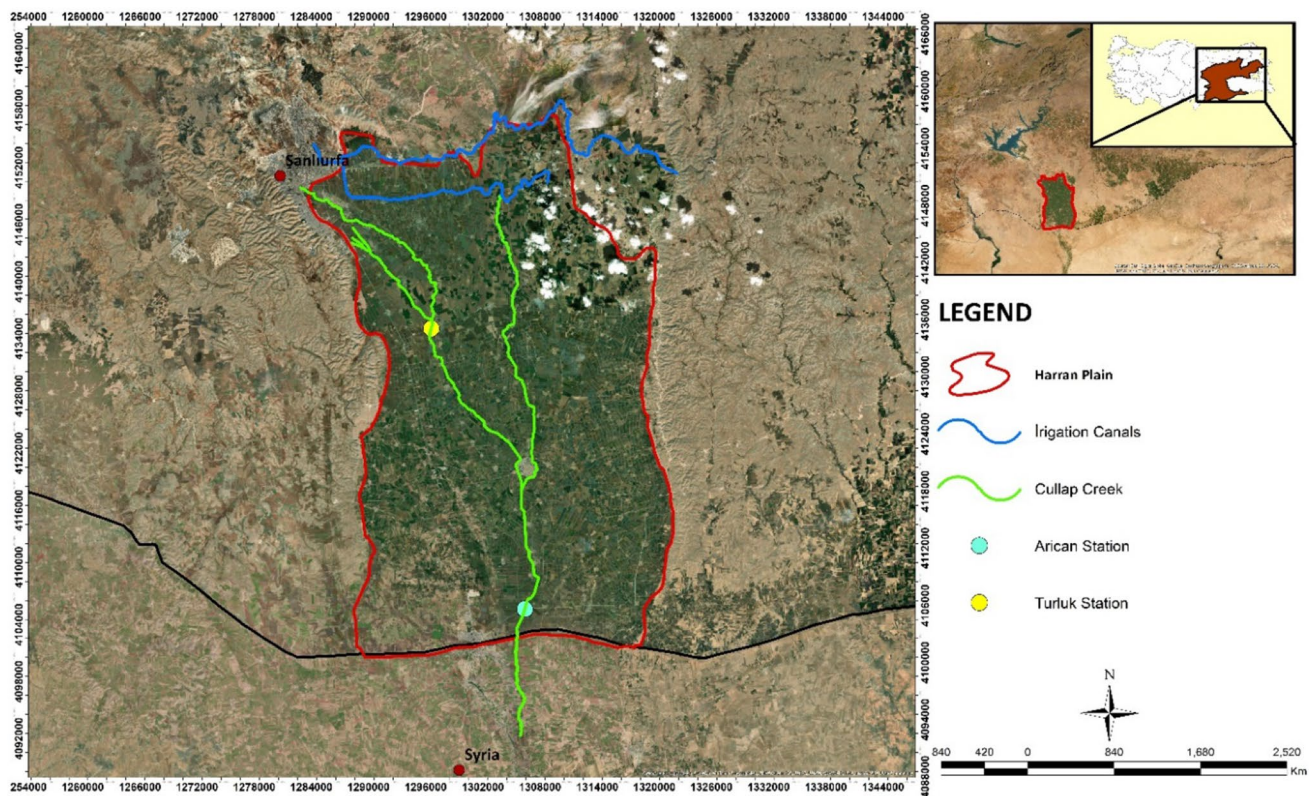


**Fig. 5** Suspended sediment sampling x-section of the Cullap Creek Arican bridge station

The measuring cross section is located at the downstream end of the Cullap Creek before the canal enters the northern plains of the Syrian territory (Fig. 6). The maximum discharge at the measuring cross section can reach  $40 \text{ m}^3 \cdot \text{s}^{-1}$  with depths of 1–1.5 m.

The Quality Control Laboratory of the 15th Regional Directorate of State Hydraulic Works (DSI) located in the city of Şanlıurfa conducted the sampling studies in the field. Sediment

sampling was done at six vertical depths equally spaced in the cross section, as shown in Fig. 5. During the sampling, to obtain the best measuring condition which avoided accumulation of too much mixture in the bottle, the vertical velocity of the sampler was adjusted such that 80% of the volume of the bottle in the sampler was filled with the mixture. The volume and weight of the collected samples were determined. The samples were then filtered, and the filtered sediments



**Fig. 6** Main and secondary drainage canals of the Harran plain and sampling stations

were dried in an oven. The concentration of suspension was expressed in terms of weight of dry sediment per unit volume of suspension ( $\text{g.L}^{-1}$  or  $\text{kg.m}^{-3}$ ), or in percent by weight, which is equal to the weight of dry sediment divided by the weight of the suspension and multiplied by 100. The relation between these two expressions is given below (Demiröz 1994).

$$C_1 = \frac{1000}{\frac{1}{\gamma_s} + \frac{100}{\gamma_0 C_2} - \frac{1}{\gamma_0}} \quad (1)$$

$$C_2 = \frac{1000}{1 + \frac{1000\gamma_0}{C_1} - \frac{\gamma_0}{\gamma_s}} \quad (2)$$

where  $\gamma_s$  is the unit weight of sediment in  $\text{g.cm}^{-3}$ , and  $\gamma_0$  is the unit weight of water equal to  $\text{g.cm}^{-3}$ .  $C_1$  (in terms of weight of sediment per unit volume of suspension) can be expressed as

$$C_1 = \frac{W_s}{V} \quad (3)$$

and  $C_2$  is the percent concentration of suspension by weight is given by

$$C_2 = 100 \times \frac{W_s}{W} (\%) \quad (4)$$

In Eqs. 3 and 4,  $W_s$  is the dry weight of sediment in grams,  $W$  is the weight of the sample (sediment and water) in grams,  $V$  is the volume of the sample in liters. If the variation of sediment concentration for any set of measurement points within the cross section is less than 20% of their arithmetic mean, the arithmetic mean value is adopted as the average. Otherwise, the arithmetic mean of each vertical is computed and multiplied by the corresponding discharge of the segment. The sum of these products, when divided by the total cross-sectional discharge, gives the average value of concentration:

$$\bar{C} = \frac{\sum C_i Q_i}{\sum Q_i} \quad (5)$$

In general, the graphical integration method is used to evaluate the suspended sediment load from the field data. For this purpose, the distribution of water flow velocity and concentration along the verticals has to be determined by the field measurements. In the case of depth integration measurements in the field, suspended sediment load can be computed for a given cross-sectional concentration and velocity (Figs. 7 and 8). Unit suspended sediment load along verticals shown schematically in Fig. 7 can be obtained by

$$q_i = \bar{C}_i \bar{U}_i \quad (6)$$

where  $\bar{C}_i$  and  $\bar{U}_i$  are mean concentration and velocity at the vertical. The total suspended sediment load can be found

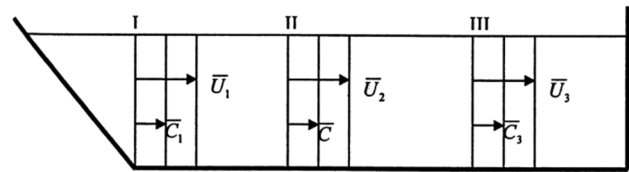


Fig. 7 Mean values of flow velocity and concentration in the case of depth-integrating method

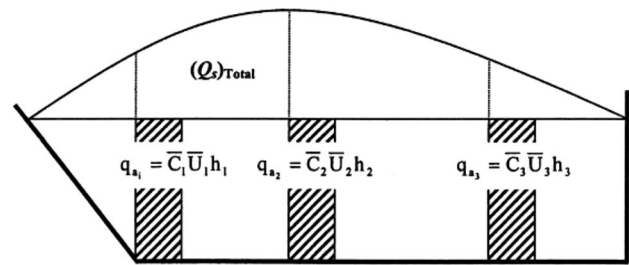


Fig. 8 Graphical integration for depth-integrating sampling

by graphical integration along the canal width, as shown in Fig. 7 (Demiröz 1994).

The samples collected at the Arican Bridge (Fig. 5) were analyzed to determine the amount of solid particles. This analysis showed that when the discharge was  $1\text{--}5 \text{ m}^3.\text{s}^{-1}$ , samples approximately contain 50 to 60% silt and clay and 50 to 40% fine sand. When the discharge is greater than  $5 \text{ m}^3.\text{s}^{-1}$ , a major portion of the suspended sediment consists of 60–70% fine sand and 40–30% silt and clay. Such evaluation shows that the textures of soil samples are clay loam and/or sandy clay loam whose color is brownish and considered as good agricultural soils. The results of the analysis for the samples collected between May 1997 and September 2017 are presented in Table 2. In this table, the reason for low values of 2003 and 2006 compared to the other years is because, in those 2 years, severe drought occurred in the region and limited amount of water provided during the irrigation period. In addition, the number of measurement months were lower for the referred years, which resulted in the amount of transported sediment due to irrigation were lower.

### Calculation of sediment amount by RUSLE

Soil losses by erosion are a significant event for Turkey as well as most countries of the world. There are several methods to calculate soil loss due to erosion caused by rainfall. The most common method used among those is Revised Universal Soil Loss Equation, known as the RUSLE, which is an updated version of the Universal Soil Loss Equation (USLE) model (Wischmeier and Smith 1978). The RUSLE

**Table 2** Computed sediment discharge at the Arican station on the Cullap Creek

Year	Discharge (m <sup>3</sup> .s <sup>-1</sup> )	Sediment transport rate (ton.day <sup>-1</sup> )	Number of months of measurement
1997	13.3	655	9
1998	17.6	740	9
1999	18.1	750	9
2000	20.5	792	9
2001	13.1	338	12
2002	18.5	754	12
2003	9.3	128 (*)	6
2004	13.5	660	10
2005	20.6	698	12
2006	14.0	177 (*)	5
2007	10.3	567	10
2008	17.2	730	10
2009	13.0	631	10
2010	12.5	522	9
2011	13.6	558	9
2012	13.3	646	9
2013	39.7	1261	12
2014	28.8	803	12
2015	28.5	802	12
2016	39.7	1268	10
2017	37.9	838	9

has been widely used to estimate the average annual soil loss per unit land area that is associated with rill and sheet erosion, and it is well suited for predicting water-induced erosion in temperate climates (Renard et al. 1997). This

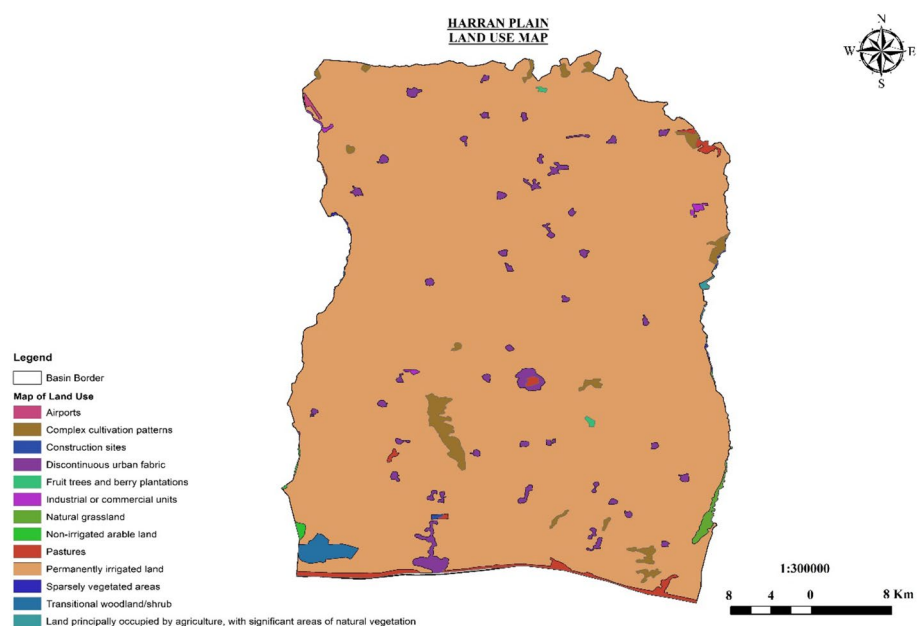
method has also been used in Turkey for many water projects to determine the amount and rate of erosion in the drainage basins by rainfall. The RUSLE is defined by the following equation (Renard et al. 1997):

$$A = R \times K \times LS \times C \times P \quad (7)$$

where A is annual soil loss (ton.ha<sup>-1</sup>.yr<sup>-1</sup>), R is the rainfall-runoff erosivity factor (MJ.mm<sup>-1</sup>.ha<sup>-1</sup>.h<sup>-1</sup>.yr<sup>-1</sup>), K is the soil erosion sensitivity factor. This factor is obtained from Soil Erosion Sensitivity Maps of Turkey developed by the General Directorate of Erosion and Desertification Prevention and based on soil information databank containing 23,000 profile covering 0–30 cm depths. LS is the gradient factor obtained from the 1/25,000 scale digital elevation model of the study area. C is the vegetal cover, and land use factor obtained using forest cover maps and CORINE 2012 data (Fig. 9). With respect to the soil and water conservation activity factor, P, it is assumed the value to be the unity for the Harran Plain. The annual average rainfall in the Harran Plain is about 400 mm.yr<sup>-1</sup> (Usul 2013). Using 329 min rainfall value obtained from meteorological gauging stations' data in the area, the General Directorate of Erosion and Desertification Prevention developed soil erosion severity areas of the Harran Plain by rainfall as shown in Table 3.

#### Numerical modeling to calculate sediment transport amount by MIKE 21

2D hydraulic modeling process was conducted using MIKE 21 Flow Model software, which is widely accepted and used for modeling of hydraulic engineering problems. Modules of MIKE 21 FM, such as hydrodynamic (HD) and sand

**Fig. 9** Land use map of the Harran Plain



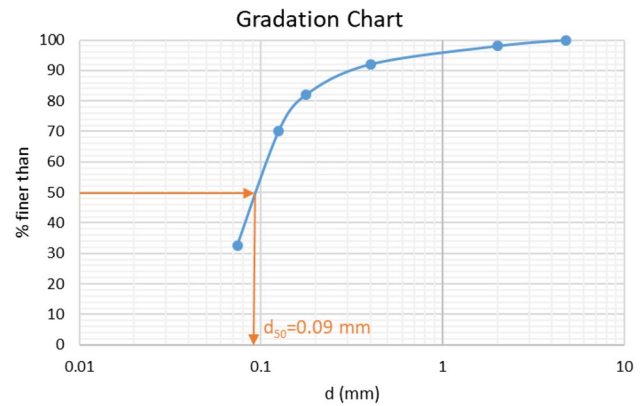
**Table 3** Harran Plain erosion severity by rainfall

Harran	Very light	Light	Medium	Severe	Very severe	Total
Degree	1	5	10	20	20+	
Area (ha)	136,511.32	3,785.93	73.51	7.12	0.21	140,378.10
Area (%)	97.25	2.7	0.05	0.01	0	100

transport (ST), are enabled for modeling. With the help of the option of MIKE to run coupled Sand Transport Model with the Hydrodynamic Model, it is possible to investigate sediment transport effects on the hydrodynamic model and the inundation area. The sediment transport module calculates bed level, bed level changes, sediment loads, suspended sediment concentration, etc. for all meshes within the computational domain. Therefore, it is possible to determine morphological changes, sediment transport, and hydrodynamics of the whole study area or of specified locations. Depending on the constraints and definition of the problem, the Van Rijn method, which is recommended for suspended load calculations by the user manual of DHI's MIKE 21 FM, was used. (DHI 2016).

For hydrodynamic modeling, the digital elevation model (DEM), roughness, boundary conditions, and sediment properties, such as grain diameter, porosity and the relative density of sediment, should be specified. Morphological data is obtained using the digital elevation model (DEM) of the specified area. Bed resistance data is taken as  $n = 0.03125$  with respect to observations made by DSI as constant in time and domain. Also, the grain size is defined as constant in the domain and in time. Throughout the modeling process, the grain size is obtained by constructing a sediment gradation chart from the suspended sediment distribution (Fig. 10). In the DSI report, the clay + silt ratio of the suspended sediment sample is given as 32.6%, while the remaining part is classified as sand. Since the fine content (clay + silt) is very high, most of the sand is assumed as fine sand, and the midpoints are selected from ASTM sieve sizes and filled on the basis of this assumption. The real gradation distribution could change throughout the plain, so the drawn chart using suspended sediment load is adequate to indicate the approximate grain size of the flushed material due to the furrow irrigation. Sediment grain size ( $d_{50}$ ) of 0.09 mm is obtained from the gradation chart. Boundary conditions can be defined as sediment inflow or outflow if it is known that additional sediment load input or output occurs. In this study, boundary conditions are defined as in equilibrium. The porosity of sediment is taken as 0.4 and the relative density of sediment is taken as 2.65.

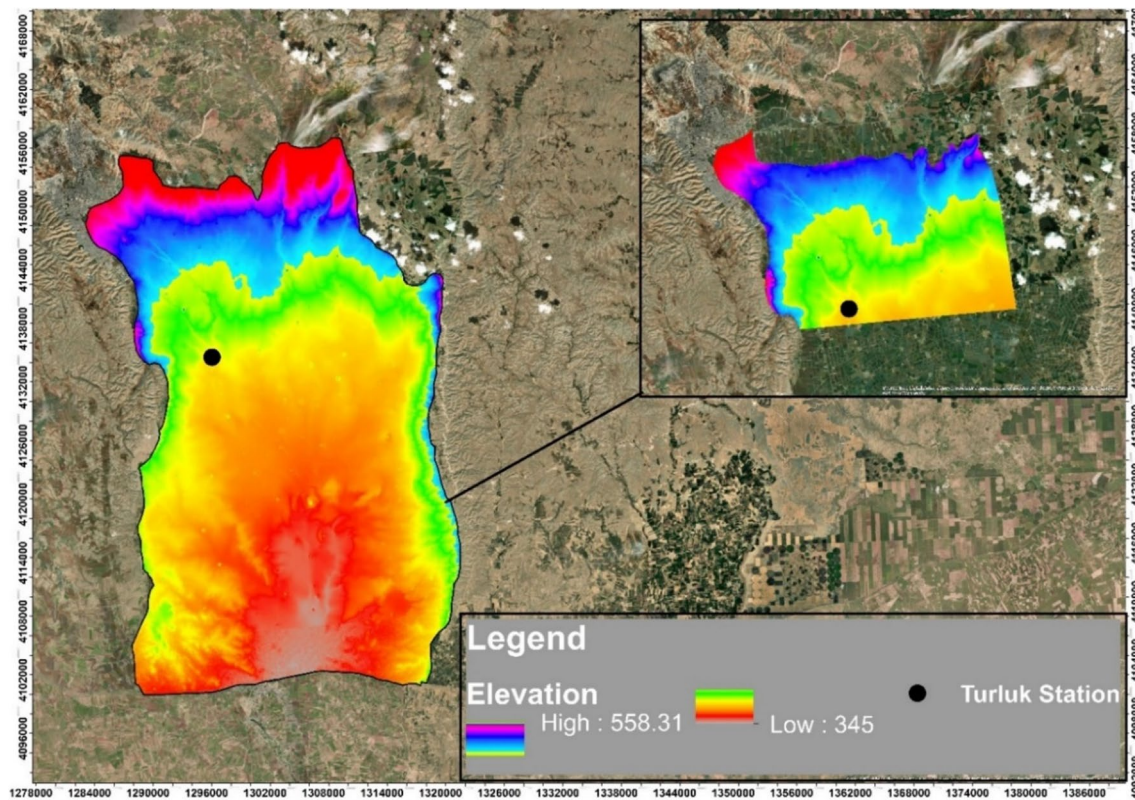
**Two-dimensional hydrodynamic model** The hydrodynamic module of MIKE 21 FM solves two-dimensional shallow water equations that are depth-integrated Reynolds averaged Navier–Stokes equations. The explicit scheme is used for

**Fig. 10** Gradation chart obtained from suspended sediment load

time integration (DHI 2016). Using flexible meshes (non-uniform unstructured mesh) to represent bathymetry of the study area is a very detailed and precise way of defining morphology. Since using flexible meshes give an advantage of changing mesh sizes, it is possible to use smaller meshes for the area, where the user needs detailed information and larger meshes for other parts of the study area. This flexibility brings faster computation and detailed results for the interested parts. Morphological data was implemented using the digital elevation model (DEM) (Fig. 11).

Meshes could be constructed as triangular and quadrangular. In this study, only triangular meshes were implemented to represent the computational domain. Meshes having a maximum area of 20 m<sup>2</sup> implemented for river bed and for the area closer to the river. Other parts of the study area are defined with meshes having a maximum area of 300 m<sup>2</sup>. The meshing of the computational domain can be seen in Fig. 12. Bed resistance can be defined as varying in domain and time. In this study, it is defined as constant in time and varying in domain according to the observations made by DSI. Boundary conditions can be defined for inflow and outflow as the boundary of computation meshes.

In addition to the inputs stated above, some specifications can also be defined for the MIKE 21 hydrodynamic model. Such specifications include, salinity and temperature, eddy viscosity formulation, Coriolis force, wind forcing, ice coverage, tidal potential, precipitation and evaporation, infiltration, wave radiation, structures. Due to lack of data, those specifications were not considered in this study. After computing the hydrodynamic model, water depth, surface



**Fig. 11** Digital elevation model (DEM) of whole basin and DEM of modelled area

elevation, and mean flow velocity were obtained. In addition, detailed information about the sediment transport amount can be taken as a result of the model.

2D numerical model was constructed using the upper area of the basin, which includes Turluk Station (Fig. 11). The main idea behind the approach is to shorten computational time, because Harran Plain is about 150 km<sup>2</sup>, and the average width of the Cullap Creek and irrigation canals were about 35–40 m. Therefore, to obtain an accurate solution, at least two mesh should be implemented within the width of the channel, and implementing two meshes for the channel width results in enormous computational time.

The upper area of the irrigation channel was extracted from the DEM, because in real case situation, irrigation discharge is released from Cullap Creek, and excessive discharge from irrigation channels are released like a flood from the right overbank of the canals. In the numerical model, real case physics was achieved by providing discharge from Cullap Creek and releasing an excessive amount of water from the right overbank of the irrigation canals.

Turluk Station has a sampling period of 4 years, but numerical modeling of 4 years is not a suitable approach due to the computational time concerns. Therefore, irrigation discharge was provided constantly for a period of 1 day and 3 days. Measurements such as discharge and suspended

sediment load were taken from the exact location of Turluk Station. In addition, the Courant–Friedrichs–Lewy or CFL condition, which should be smaller than 1 for the convergence of finite difference schemes, was checked throughout the computations to provide an accurate solution.

Average values of discharge and suspended sediment load of the field data (Turluk Station) were compared with the numerical data to validate the numerical model. Results obtained by the numerical model with the Van Rijn Method are shown in Table 5 in the Results and Discussion part.

### Statistical approach

The data of the periodic measurement of sediment sampling and discharge measurements at the Arican station and the Turluk Regulator of the Cullap Creek show that the suspended sediment concentration is proportional to the discharge. This situation can also be seen in Fig. 13, showing the Cullap Creek Arican station sediment rating curve developed using nonlinear regression on 98 discharge and sediment measurements between 2013 and 2017. The coefficient of determination  $R^2 = 0.70$  is found for this data set. Nonlinear regression analysis was also applied for the data of the yearly average sediment discharge with corresponding discharge data given in Table 2 (Fig. 14), and the coefficient



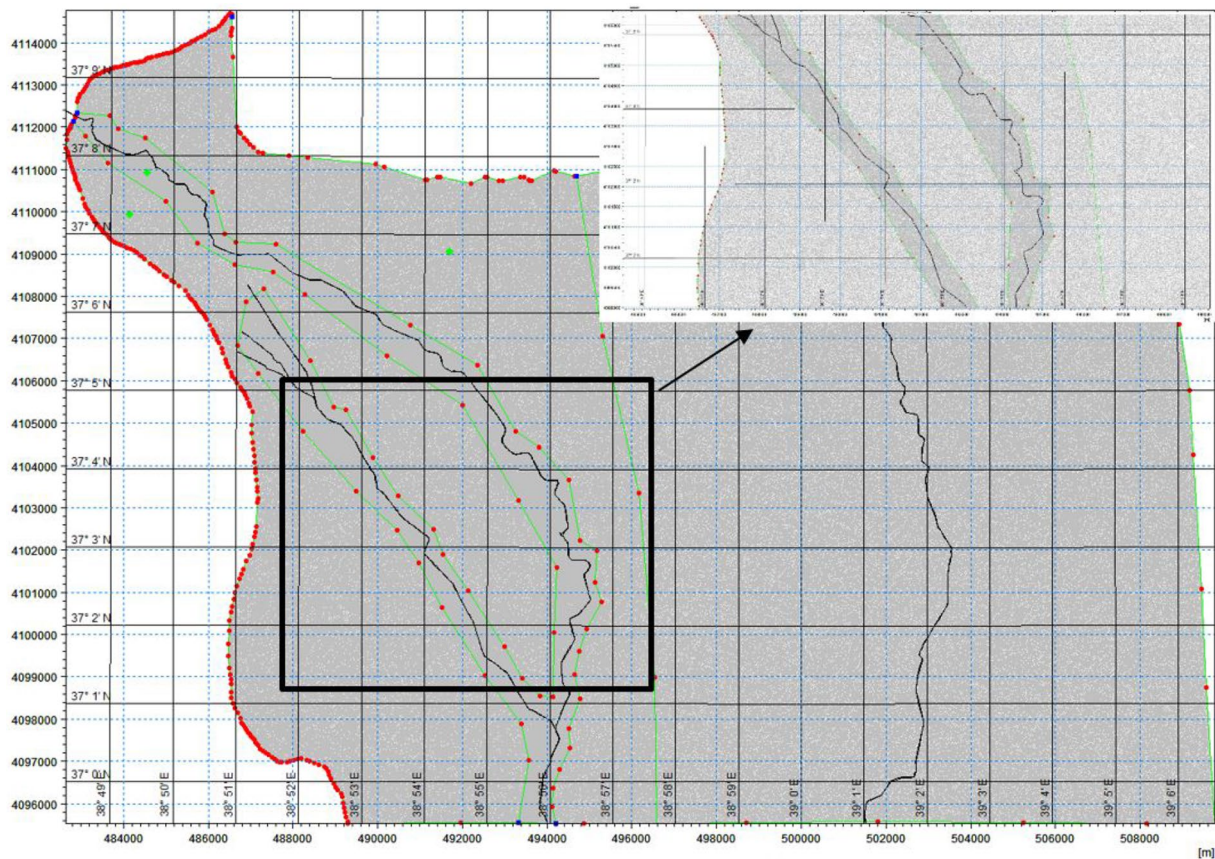
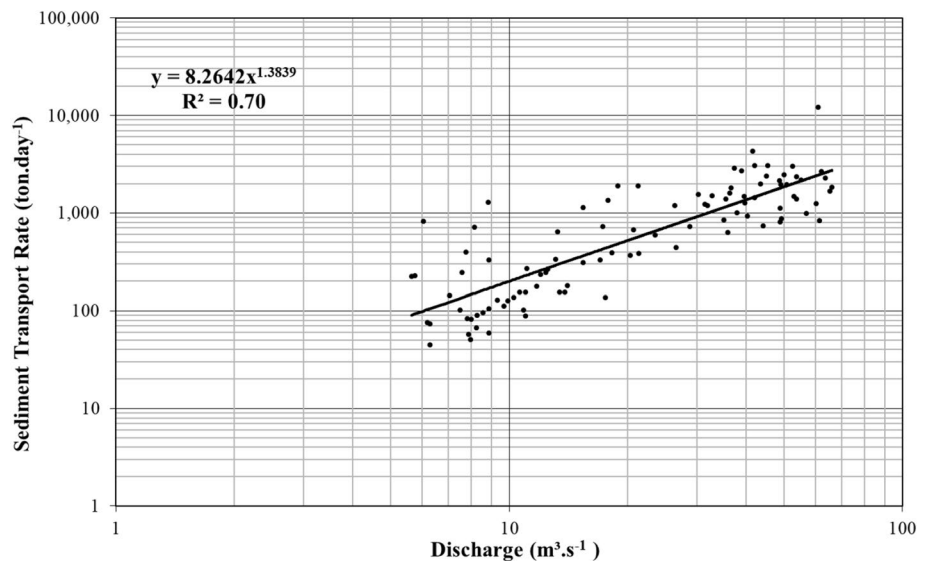


Fig. 12 Non-uniform unstructured meshing of the computational domain

of determination  $R^2=0.63$  is found for this case. The coefficients of determination of the data of 2013 and 2017 (98 values) and the data of average yearly values (21 values) are very close. Thus it can be said that the method of analysis

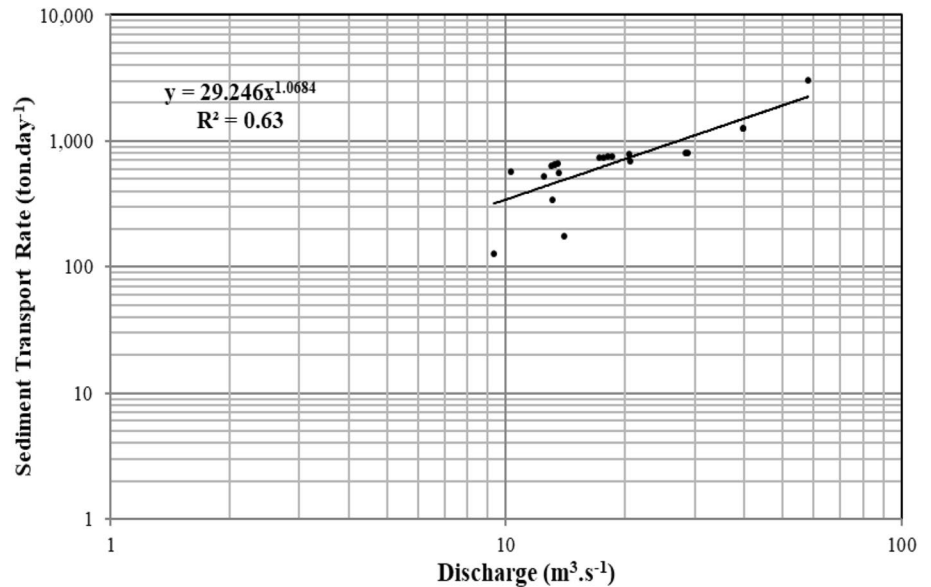
of samples is coherent. A similar trend for the data obtained between 2013 and 2017 (51 measurements) from the Turluk regulator located on the tributary of the Cullap Creek was determined (Fig. 15). The coefficient of determination

Fig. 13 D21A146 Cullap Creek–Arcan sediment rating curve





**Fig. 14** Cullap Creek Arican station-21 years of yearly average sediment transport rate



$R^2 = 0.88$  is found for this data set. These figures clearly document that excess irrigation water withdrawn from the irrigation canals caused erosion from the field and transported sediment to the main drainage system corresponding the Cullap Creek.

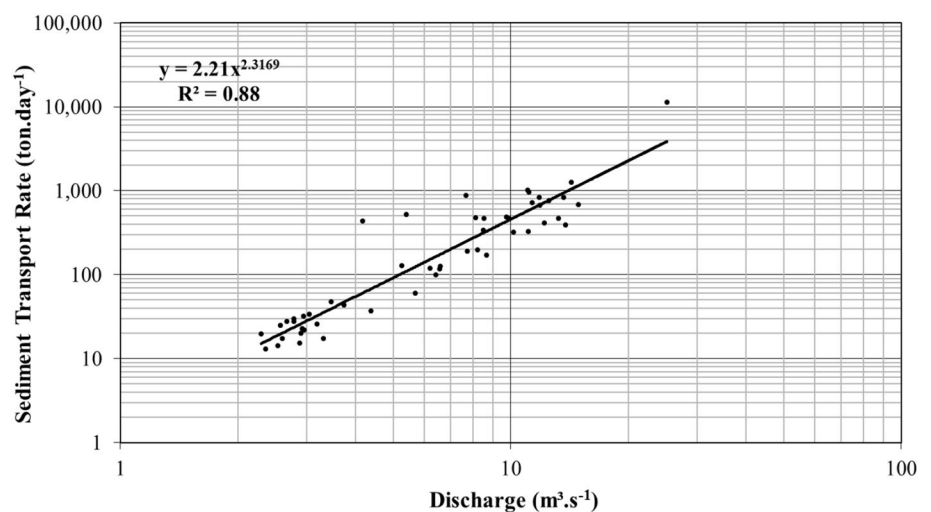
The data from the Turluk Station of DSI was analyzed by conducting homogeneity of variance tests. (Levene  $F$  test). Before applying Levene  $F$  test, data from Turluk Station was classified by precipitation and irrigation periods considering meteorological records. According to 100 years of meteorological observations (Turkish State Meteorological Service 2020), precipitation within the Harran Plain is nearly negligible for the months of June, July, August, and September. In addition, these specified months are excessive irrigation periods for the plain, according to DSI. Therefore, before applying statistical analysis, Turluk Station data was

classified for irrigation and precipitation period, and Levene  $F$  test was applied. These statistical analyses were conducted with the intend of validation of the results of the RUSLE and numerical model by comparing the suspended sediment loads in the irrigation dominant period and precipitation dominant period.

## Results and discussion

Soil erosion and its results are a serious matter in the agricultural lands of Turkey. While fertile agricultural soils are being lost due to erosion, dams are being filled by the sediment transported by rivers. Mathematical models developed to quantify the soil erosion by surface irrigation techniques generally overestimate the amount of sediment transported.

**Fig. 15** D21A019 Cullap Creek, Turluk Regulator sediment rating curve



Mailapelli et al. (2013) and Meral et al. (2016) suggested that field measurements to quantify the erosion caused by surface irrigation are the most accurate method. Thus, systematic data collection, compatible with international standards on sediment transport characteristics, was initiated between 1997 and 2017 to determine the amount of suspended sediment transport in the drainage canal of the Harran Plain named the Cullap Creek.

Analysis of suspended sediment sampling at the Arican station on the Cullap Creek of the Harran Plain also showed that measurements between 1997 and 2017 the yearly averaged sediment transported to Syria by the Cullap Creek varied between 128 ton.day<sup>-1</sup> to 1268 ton.day<sup>-1</sup>, and the average of 21-year measurement is about 682 ton.day<sup>-1</sup>. The sediment rating curve based on 98 measurements from the Cullap Creek Arican Station and Turluk Station showed that as the discharge increases, the sediment transport rate also increases linearly.

The amount of sediment erosion from the Harran Plain by rainfall was also calculated using RUSLE. GIS and remote sensing data for the variables used in RUSLE are presented between Fig. 16 and Fig. 20. Rainfall erosivity factor, *R*, varies between 240.45 and 511.04 MJ.mm<sup>-1</sup>.ha<sup>-1</sup>.h<sup>-1</sup>.yr<sup>-1</sup> throughout the Harran Plain, and the distribution can be seen in Fig. 16. The results showed that, although the region is subjected to severe drought from time to time, the rainfall erosion energy is substantially great. Especially, the northern part of the Harran Plain, including the Turluk Station, has considerable rainfall erosion energy.

It was stated that the type of agricultural products, soil type, and the variation of climatic conditions are responsible for the soil erodibility of the region (Bou-imajjane et al. 2020). Figure 17 represents the soil erosion sensitivity factor of the Harran Plain. The soil erosion sensitivity factor, *K*, ranges from 0.01432 to 0.02304 ton.ha.h.ha<sup>-1</sup>.MJ<sup>-1</sup>.yr<sup>-1</sup>.

The gradient factor, *LS*, also named as the topographic factor, is generally one of the most dominant parameters affecting soil erosion. Since the elevation differences are not so much for the Harran Plain, *LS* is not the main driving force to determine the soil erosion amount. Figure 18 represents the gradient factor of the Harran Plain, and it varies between 0 to 10.986.

The agricultural land use of the Harran Plain is presented in Fig. 19. The value 1 corresponds to the cultivated and irrigated area in this figure, while the value 0 corresponds to non-agricultural lands. The detailed information of the land use can be obtained from Fig. 9. It is obvious that a large portion of the land is used for agricultural production, and it is exposed to furrow irrigation.

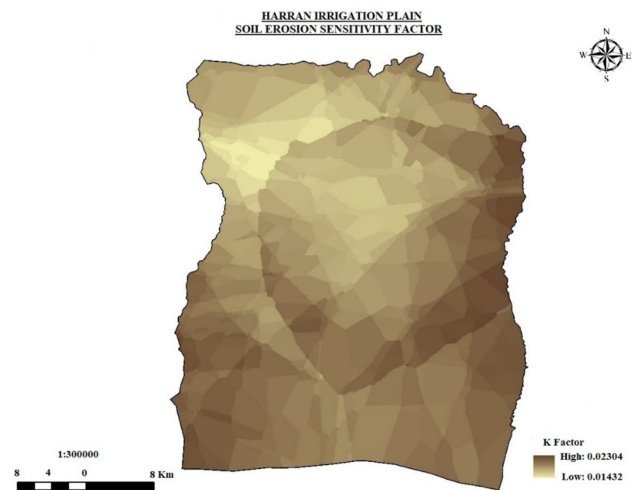


Fig. 17 Soil erosion sensitivity factor (*K*)

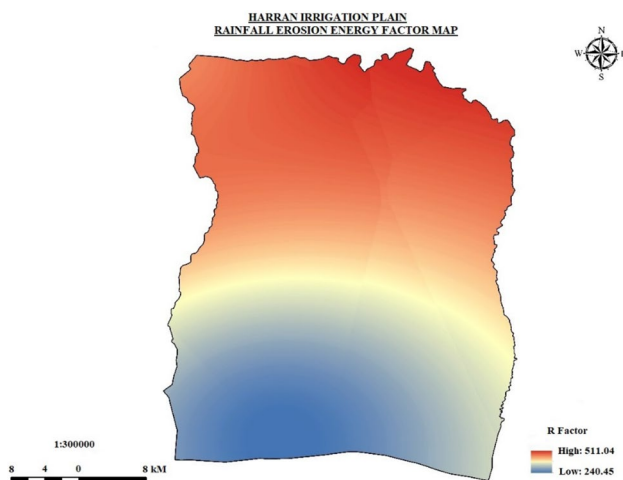


Fig. 16 Rainfall erosivity factor (*R*)

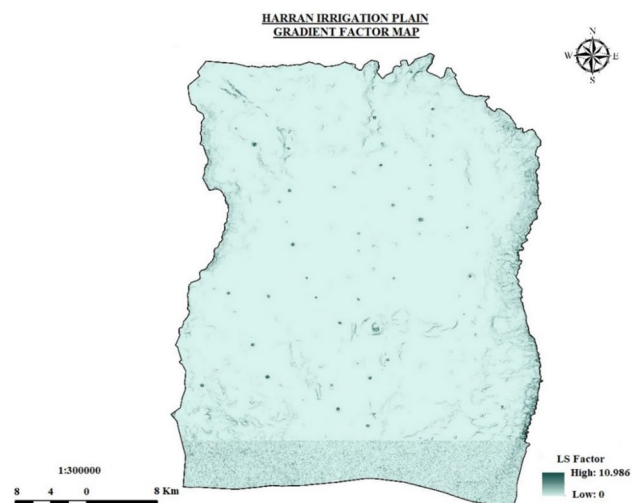


Fig. 18 Gradient factor (*LS*)

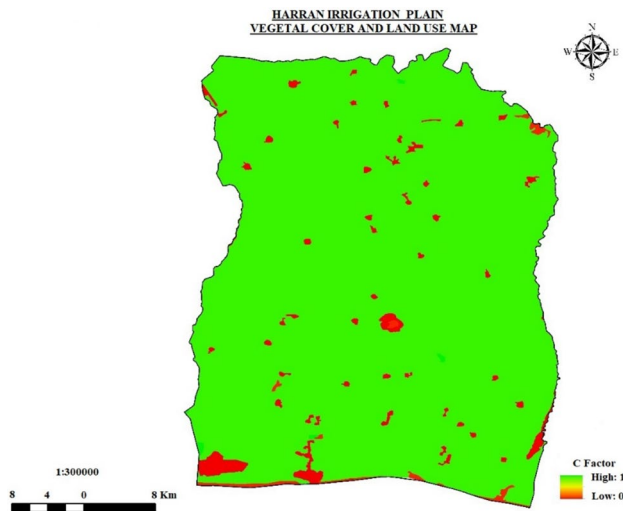


Fig. 19 Vegetal cover and land use map (C)

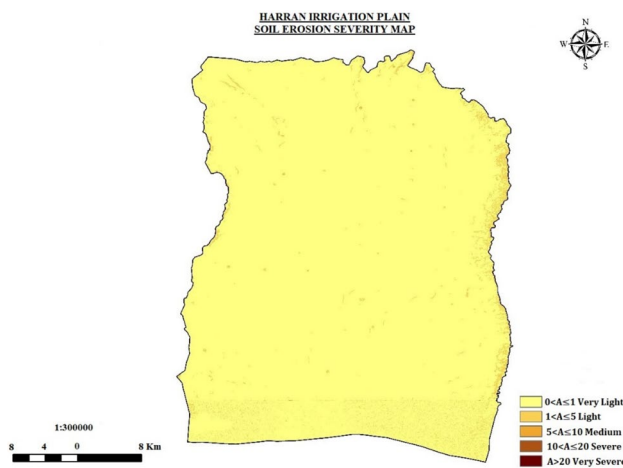


Fig. 20 Soil erosion severity map

The soil erosion severity of the Harran Plain is also shown in Fig. 20. If Fig. 20 is examined, most of the land has a very light erodibility risk. The numerical representation of the erosion severity of the land can be seen in Table 3.

As seen from Table 3, 97.25% of the study area is very light, 2.7% is mild, 0.05% is medium, 0.01% is severe, and 0.001% is very severe erosion is found.

Although the total irrigated area is 149,000 ha, DSI used the area of the plain as 140,378.1 ha for the calculations of the RUSLE. In the Harran irrigation basin, 146,622.9 tons of soil erosion, which is the total amount of the sediment relocated within the basin per year, is expected due to the precipitation (Table 4). This means that 1.05 ton.yr<sup>-1</sup>.ha<sup>-1</sup> (146,622.9/140,378.1) soil in the unit area is moved by rainfall.

140,378.1 ha area of the Harran basin was divided into 34 micro basins (Fig. 21), and the sediment delivery rate (SDR) of those micro basins was calculated using the USDA-SCS formula. Vanoni (1975) proposed a simplified version of the sediment delivery ratio formula given below:

$$SDR_w = k(a_w)^{-c} \tag{8}$$

where *k* and *c* are both dimensionless empirical coefficients, and *a<sub>w</sub>* is the watershed area in m<sup>2</sup>.

DSI estimated the empirical coefficients via field tests, and the sediment delivery rates of the micro basins were calculated by the following equation (DSI 2019):

$$SDR = 0.51(A)^{-0.11} \tag{9}$$

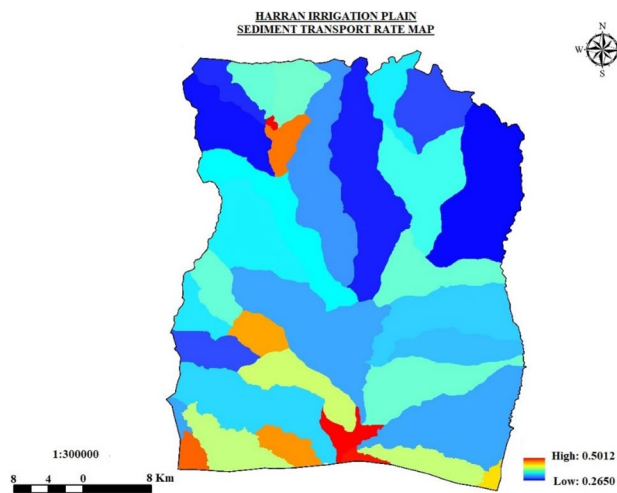
Ferro and Porto (2000) proposed a sediment delivery distributed model (SEDD), and its simple version given in the followed equation:

$$Y_i = SDR_i A_i S U_i \tag{10}$$

Table 4 Soil loss from the Harran Plain by RUSLE

Harran	Degree of erosion	Number of pixels (10 m × 10 m)	Area (m <sup>2</sup> )	Area (ha)	Max. soil loss ton year <sup>-1</sup> )
1	1	13,651,232.0	1,365,113,200.0	136,511.3	136,511.3
2	2	305,297.0	30,529,700.0	3,053.0	6105.9
3	4	66,469.0	6,646,900.0	664.7	2658.8
4	8	13,101.0	1,310,100.0	131.0	1048.1
5	16	1744.0	174,400.0	17.4	279.0
6	30	66.0	6600.0	0.7	19.8
Total			1,403,780,900.0	140,378.1	146,622.9





**Fig. 21** Sediment transport rate of 34 micro basins

where  $A_i$  is the soil loss ( $\text{ton}\cdot\text{ha}^{-1}$ ) from the  $i$ th morphological unit,  $SU_i$  is the area of the morphological unit, and  $A_i$  is the calculated soil loss of  $i$ th morphological unit by RUSLE.

The total amount of sediment transported by the drainage system of the Harran plain was calculated by multiplying the SDR of those micro basins with their areas using Eq. 10. The total amount of sediment transported by the Cullap Creek was calculated by adding the results of those micro basins sediment yield, which is equal to  $44,893 \text{ ton yr}^{-1}$ . This implies  $0.32 \text{ ton}\cdot\text{yr}^{-1}\cdot\text{ha}^{-1}$  ( $44,893/140,378$ ) soil is transported by the Cullap Creek from the unit area. By multiplying the amount of sediment transported from the unit area,  $0.32 \text{ ton}\cdot\text{yr}^{-1} \text{ ha}^{-1}$ , with the size of the Harran Plain and dividing the result by the number of days in 1 year, yields the amount of daily sediment erosion by rainfall is equal to  $(0.32 \cdot 150,000)/365 = 131.5 \text{ ton}\cdot\text{day}^{-1}$ . Comparing this result with the average sediment erosion by irrigation yields  $131.5/682 = 19.3\%$ , which means approximately 20% of the total erosion caused by rainfall events in the Harran Plain.

MIKE 21 HD with Sand Transport module is a useful tool for calculating suspended sediment load and discharge. For accurate numerical modeling, sensitive DEM, and implementation of appropriate meshing within the computational domain required. Van Rijn Method calculates suspended sediment load accurately for the study area.

MIKE model was calibrated with the available data. Since the roughness of the area was not determined by DSI, the roughness was not considered as a calibration parameter. Another parameter that can be used for calibration is the depth of water of the station at a specified time. However, the DSI station did not provide any water depth data. Therefore, the only available data from the station is sediment amount and discharge. The calibration of the numerical

model was implemented by only considering discharge data. Throughout the modelling process, irrigation discharge was known, and measured discharge at the specified station sought throughout the modelling process. After having conducted several meshing attempts, optimum mesh size was determined, and at the end of the model run, discharge at the station for numerical model and DSI data was compared. Lastly, the model having the minimum difference between calculated and measured discharge was considered as a validated model.

Results obtained by the numerical model with the Van Rijn Method are shown in Table 5. These results show that average discharge within the measurement station is compatible with the numerical model. Error in discharge measurement was found as 1.63%, which is acceptable for the numerical model. On the other hand, error in suspended sediment load was found as 6.47%, which is acceptable and compatible with field data.

The average discharge and suspended sediment load were taken for the Turluk Station, since the numerical solution was implemented in that region. However, with the RUSLE, the topsoil loss due to precipitation was calculated for the whole plain. That is already presented; approximately 20% of the total erosion is due to precipitation. Thus, the total suspended sediment load on Turluk Station was proportioned to obtain the amount of the sediment load due to irrigation and precipitation. 20% of the average suspended sediment load at the Turluk station ( $525.39 \cdot 0.2 = 105 \text{ ton day}^{-1}$ ) was accepted as the result of the precipitation, while the remaining part ( $525 - 105 = 420 \text{ ton day}^{-1}$ ) is the result of furrow irrigation. The numerical model results showed that the suspended load due to irrigation is  $447.18 \text{ ton day}^{-1}$ . Thus, the RUSLE correctly predicts suspended sediment load due to precipitation and irrigation, and the numerical model was validated with the RUSLE and field data.

If the averaged values are considered from Table 5, the average discharge at Turluk Station is  $7.4 \text{ m}^3\text{s}^{-1}$ , and the suspended sediment load is  $525.39 \text{ ton day}^{-1}$ . When the equation of the sediment rating curve is used (Fig. 15), the suspended sediment load will be calculated as  $228.2 \text{ t}\cdot\text{day}^{-1}$  ( $y = 2.21 \cdot 7.4^{2.3169} = 228.2 \text{ ton day}^{-1}$ ) instead of  $525.39 \text{ ton day}^{-1}$  for a discharge of  $7.4 \text{ m}^3\text{s}^{-1}$ . Warrick (2015) stated that the time-dependent rates of discharge and sediment load should accompany with sediment rating curves for the trend analysis. Instead of using sediment rating curves, numerical models or RUSLE can be used for arid or semi-arid regions to obtain more reliable results. In addition, it is observed that a steady-state solution was obtained by implementing the MIKE 21 model, since very compatible results were obtained from the numerical model and the average field measurements of the suspended load.

According to Levene  $F$  test results, which was determined to be significant ( $p = 0.021$ ), it was proved that the

**Table 5** Comparison of field data and numerical results (Van Rijn Method for suspended sediment calculation)

Field data	RUSLE		Model		Error		
	Average Discharge at Turluk Station ( $m^3 \cdot s^{-1}$ )	Suspended Sediment Load due to Discharge ( $ton \cdot day^{-1}$ )	Suspended Sediment Load due to Precipitation ( $ton \cdot day^{-1}$ )	Discharge at Turluk Station ( $m^3 \cdot s^{-1}$ )	Suspended Sediment Load ( $ton \cdot day^{-1}$ )	Discharge (%)	Suspended Sediment Load (%)
7.4	525.39	420	105	7.28	447.18	1.63	6.47

**Table 6** Irrigation and precipitation period mean values as a result of statistical analysis

Season	N	Mean
Irrigation	20	550.14
Precipitation	31	144.48

data is eligible for independent *t* test. Therefore, Turluk Station data were analyzed by applying an independent *t* test through SPSS software. According to results, suspended sediment load due to irrigation ( $M = 550.14$ ) and precipitation ( $M = 144.48$ ) significantly different from each other [ $t(31) = 4.908, p < 0.05$ ] (Tables 6 and 7).

Comparison of the means of irrigation and precipitation shown in Table 6 and 21-year average field measurements showed that  $([550.14 / (550.14 + 144.48)] * 100)$  79.2% of suspended sediment load caused by irrigation. This figure is compatible with RUSLE calculations and MIKE 21 hydrodynamic model.

### Conclusions

Harran Plain has been subject to severe drought for the past decade caused by the effect of climate change in southern Turkey and in Mesopotamia. Due to severe drought in the region since 2003, the application of excessive irrigation water by farmers to irrigate the crops also caused severe erosion and salinity in the irrigated areas. This excessive amount of irrigation water by surface flooding also drained the topsoil of the agricultural areas, and thus, malfunctioned the drainage facilities in the field by depositing the portion of the topsoil in the drainage system while transporting the remaining part to the main channel that extends to the Syrian border. Intense field studies were conducted to investigate the erosion problem, and suspended sediment measurements were performed at the main drainage canal of the Harran Plain. Analysis of those suspended sediment measurements between 1997 and 2017 showed that the yearly averaged sediment transported to Syria by the main drainage canal of the Harran Plain varied between  $128 \text{ ton day}^{-1}$  to  $1268 \text{ ton day}^{-1}$ , and the average of 21-year measurement is about  $682 \text{ ton day}^{-1}$ . Sediment erosion as a result of rainfall occurring to the Harran Plain is computed by applying the RUSLE, and the result obtained from the RUSLE is  $131.5 \text{ ton} \cdot \text{day}^{-1}$ . Comparison of this value with the 21-year value of average sediment erosion by irrigation yields that approximately 20% of sediment erosion from the Harran Plain caused by rainfall events, and the remaining 80% resulted from the excess irrigation water in the area. These results are also verified by statistical analysis and MIKE 21 Hydrodynamic model results. The application of the RUSLE is only valid for the arid and semi-arid regions. The results are supported by numerical solutions and statistical approaches. If the

**Table 7** Independent *t* test results

	Levene's test for equality of variances		<i>t</i> test for equality of means				
	<i>F</i>	Sig.	<i>t</i>	<i>df</i>	Sig. (2-tailed)	95% confidence interval of the difference	
						Lower	Upper
Equal variances assumed	5.70	0.02	5.30	49.00	0.00	251.77	559.55
Equal variances not assumed			4.91	30.85	0.00	237.04	574.28

field data is valid, and the irrigation period and precipitation regime are known, the dependency of the suspended sediment amount among precipitation and irrigation could be determined statistically. MIKE 21, with its essential tools, could be a good way to solve such surface irrigation problems to predict land degradation and sediment transport in the absence of long-term field data. However, it is not easy to measure some soil properties like  $d_{50}$  without field data, because the flushing particle size may not be envisaged. Due to the lack of the time-dependent rates of discharge and sediment load, sediment rating curves may not give reliable results all the time. Instead, for semi-arid and arid regions, RUSLE can be used to determine the sediment load amount due to precipitation, and numerical solutions can be applied to calculate the sediment load due to irrigation. Van Rijn Method gives accurate results when calculating the suspended sediment amount.

Furthermore, especially for the irrigation of such regions with erodible material, different type of irrigation methods should be applied instead of furrow irrigation to avoid land degradation.

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