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Legacy of Dam and Sediment Flushing Operation: Geomorphological Changes of Sefidrud Delta during 7 Decades, South of the Caspian Sea

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Abstract

Human-induced changes profoundly affect deltaic systems. This paper examines the evolution of the Sefidrud Delta, impacted by the Manjil Dam and sediment flushing operation (SFO), through a hybrid approach that observes the hydrological and morphological linkages of the fluvial system and the delta over seven decades. All changes in the delta were detected by analyzing numerous aerial photographs and satellite images. The construction of the Manjil Dam altered the delta's morphotype from a river-dominated bird's foot to a wave-dominated arcuate shape. Coastal lagoons were formed by the progradation of mouth bars, influenced by wave actions. An increase of 343% in the mean annual sediment load, due to the SFO, significantly accelerated these changes and reinitiated delta development. The Boujagh point bar expanded by 1.7 km^2 between 1981 and 1990, ultimately causing the Sefidrud channel to migrate by 45˚, along with a 2540-meter displacement of the river mouth. Sediment discharge increased by the flushing operation choked coastal lagoons. The sinusoidal trend in sediment load during the SFO transformed the delta into a fluvial and wave-dominated pointy cuspate shape. The sediment starvation induced by a sharp decrease in sediment load after 1998 resulted in 1.166 km^2 of erosion. The effects of the dam construction and SFO on the Sefidrud deltaic system represent the Anthropocene in the southern Caspian Sea. We conclude that, the critical sediment demand to maintain delta is about 14 Mt/yr, while due to limiting the output of the Manjil Dam and construction of dam on the sefidrud main tributaries, only about 3.16 Mt/yr has been delivered since 1999. The continuation of current conditions will lead to severe erosion and the eventual disappearance of the delta. Repeating the SFO will result in further changes to the delta and cause environmental damage.

Keywords

Sefidrud Delta, Manjil Dam, Sediment Flushing Operation, Hydrological-Morphological Linkage, Sediment Load, Coastal Lagoons

1. Introduction

Deltaic plains have always exhibited complex interactions with climatic, sedimentary, and tectonic processes because they are formed during the transition between fluvial and maritime environments (Orton & Reeding, 1993; Overeem, 2005). Also, deltas are highly susceptible to changes due to natural and human activities (Syvitski & Saito, 2007). Since ancient times, deltas have been of great interest to humans due to their fertile lands, and their accessibility for transportation and trade (Stanley & Warne, 1997; Fan et al., 2017). Therefore, deltas hold significant social, ecological, and economic importance (Bergillos & Sanchez, 2017). Due to intense human interventions, the morphology of deltas worldwide has changed significantly from their natural state (Fan et al., 2019). One of the most important human activities in recent centuries that have modified deltaic environments is damming, which has reduced the sediment load of large rivers over the past century (Yang et al., 2006a; Hood, 2010; Kondolf et al., 2014a; Wang et al., 2011; Fan, 2018). By reducing the sediment load of rivers, damming causes instability in deltaic systems and promotes the erosion of coastal deltas (Yang et al., 2003, 2006b; Giosan et al., 2014). On the other hand, dams are key structures that affect sediment transport and increase sediment deposition in their reservoirs by reducing water flow velocity (Syvitski et al., 2005). Sedimentation in dam reservoirs decreases their capacity and causes various economic problems (White, 2001). Therefore, various methods are used to reduce reservoir sedimentation (Kondolf et al., 2014b). Sediment flushing operation (SFO) is the most common method regularly implemented to remove and reduce sediments stored in dam reservoirs (Brown, 1944; Shen, 2010; Kondolf et al., 2014b; Randle et al., 2015; Panthi et al., 2022), particularly the finest particles that accumulate near the dam (Dahal et al., 2021). In SFO, deposited material in the reservoir is eroded by increasing water velocity and lowering the reservoir pool elevation through the release of water from the reservoir (Brandt, 2000; Kondolf et al., 2014b; Lai et al., 2024).

The Sefidrud Delta in the southern Caspian Sea has been chosen as the study area for the following reasons: i) Reports and evidence indicate changes in the Sefidrud Delta and its shoreline over the past few decades, with the last major evolution occurring around AD 1600 (Lahijani et al., 2009); ii) The Manjil Dam was constructed on the Sefidrud River in 1962; and iii) Sediment flushing operations were conducted in the Manjil Dam reservoir between 1980-1981 and 1997-

1998. While most recent studies have focused on shoreline changes in the Sefidrud Delta, much remains to be investigated regarding the morpho-sedimentary dynamics of the Sefidrud Delta. By dividing the Sefidrud Delta shoreline into different sections, Kazanci and Gulbabazadeh (2013) concluded that there is an imbalance between sediment discharge and deltaic progradation in the Sefidrud River. Haghani et al. (2016) identified rapid Caspian Sea-level rise between 1977 and 1995, along with sediments from the Manjil Dam flushing operation (1981-1998), as two main factors affecting the lagoons in the Sefidrud deltaic area. By analyzing 14 sections of the Sefidrud Delta shoreline using the Digital Shoreline Analysis System (DSAS), Toorani et al. (2021) concluded that the mismatch between Caspian Sea level fluctuations and changes in the Sefidrud Delta shoreline suggests other influencing factors. Other studies have mentioned various reasons for the evolution of the Sefidrud Delta or shoreline changes, including sediment accumulation in the Sefidrud channel, the direction of Caspian Sea waves, or the neotectonic movements of Caspian Sea faults following the 1990 Manjil Earthquake (Kousari, 1986, 1992; Krasnozhan et al., 1999; Khoshraftar, 2005; Sarvar, 2008). The implications of river damming on deltaic system evolution have also been widely studied (Ly, 1980; Stanley & Warne, 1997, 1998; Brandt, 2000; Le et al., 2007; Wang et al., 2007, 2011, 2017; Blum & Roberts, 2012; Bergillos et al., 2015; Bergillos & Sanchez, 2017; Li et al., 2017; Zaimes et al., 2019; Bussi et al., 2021; Li et al., 2021). These studies emphasize that river damming has significant morphological and ecological impacts (Best, 2019; Dunn et al., 2019), one of which is a decrease in sediment load that leads to sediment starvation and erosion in deltas (Meybeck et al., 2003; Wang et al., 2011; Chen et al., 2022). A global review by Syvitski et al. (2005, 2007, 2009) stated that over half of the world's large rivers are affected by dams, leading to coastal erosion and delta shrinkage. However, compared to the effects of river damming on deltas, few studies have examined the short and long-term implications of sediment flushing operations on the morphological evolution of deltas. SFOs have generally been investigated in terms of their impact on water quality (Kemp et al., 2011; Espa et al., 2016; Hauer et al., 2018), damage to aquatic life (Grimardias et al., 2017; Panthi et al., 2022), sediment dynamics, and river characteristics (Lepage et al., 2020). Pourafrasyabi & Ramezanpour (2014) stated that the turbidity of the Sefidrud River is primarily due to the SFO of the Manjil Dam. The sediments released from the dam concentrate and remain at the riverbed for several years, delaying the recovery of the river. Flooding events resuspend this sediment in the water column, increasing turbidity and affecting aquatic life (Pourafrasyabi & Ramezanpour, 2014). Therefore, the SFO may have created a sedimentary legacy for the Sefidrud Delta. To analyze the impact of damming and SFO on deltaic systems, two primary data sets are needed for the hybrid approach of this study:

1) Long-term hydrometric data from the basin, including water discharge and sediment load. More complete and long-term data increases the ability to analyze the sedimentary characteristics of the deltaic basin and other coupled factors.

2) Identification of all morphological changes in the delta over time.

Remote sensing, with its ability to detect detailed changes through time (change detection), plays a crucial role in this analysis (Ghanavati et al., 2008; Munasinghe et al., 2020). Satellite remote sensing has proven to be an effective technology for monitoring morphological changes due to its ability to provide spatially continuous observations (Cracknell, 1999; Munasinghe et al., 2020). To investigate changes in the Sefidrud Delta caused by the dam and SFO, this study analyzed aerial photographs and satellite images (Landsat) from 1956 to the present, alongside water discharge and sediment load data, to examine the morphological evolution and its relationship with anthropogenic factors. This investigation is complex and significant in four ways:

i) Investigating deltaic systems is critical as these areas provide valuable insights into the interaction between fluvio-deltaic and marine sedimentation processes (Trincardi et al., 2005; Bergillos & Sanchez, 2017).

ii) Evaluating the role of dams in sedimentation and delta development is challenging (Hauer et al., 2018).

iii) Investigating the short- and long-term environmental effects of SFO is difficult (Lepage et al., 2020).

iv) The extent to which sediment from upstream sources contributes to different delta components remains unclear (Quang et al., 2023).

This study aims to address all of these aspects by applying a hybrid approach to examine the hydrological-morphological linkages in the Sefidrud Delta.

2. Study Area

2.1. General Geographical Characteristics

The Caspian Sea, with a surface area of 371,000 km^2, is the largest enclosed water body in the world. The Volga River in the northern basin supplies about 60% of the Caspian Sea's freshwater, while the Sefidrud River in the southern basin provides about 40% of its sediments (Lahijani et al., 2008). The Sefidrud River, Iran's second-longest river at 820 km, originates in the Zagros Mountains and drains into the southern Caspian Sea, where it forms a large delta (Lahijani et al., 2008) (**Figure 1**). The Sefidrud River is the fifth-largest river in the Caspian Sea basin in terms of water discharge (Kazanci & Gulbabazadeh, 2013). The area of the Sefidrud Delta ranges from 2400 to 3600 km^2, according to various studies (Gulbabazadeh, 1997; Kazanci & Gulbabazadeh, 2013).

The Sefidrud Delta is the largest delta on the southern Caspian Sea shoreline, with a complex evolutionary history and an annual sedimentation rate of 47 million m^3 (Eyvazi et al., 2005; Fathi et al., 2013). Based on development stages, the delta is divided into three parts, from the oldest to the most recent (Khabbaz-Nia & Sadeghi, 2004; Nazari et al., 2004; Kazanci & Gulbabazadeh, 2013) (**Figure 1(D)**). In the modern part of the delta, only the northernmost lobe remains active. Therefore, this research focuses on this part (**Figure 1(C)**). Kazanci & Gulbabazadeh (2013) suggested that the Sefidrud Delta complex formed D1, D2, and D3 lobes from the Late Pleistocene to the Holocene, in order from the oldest to the

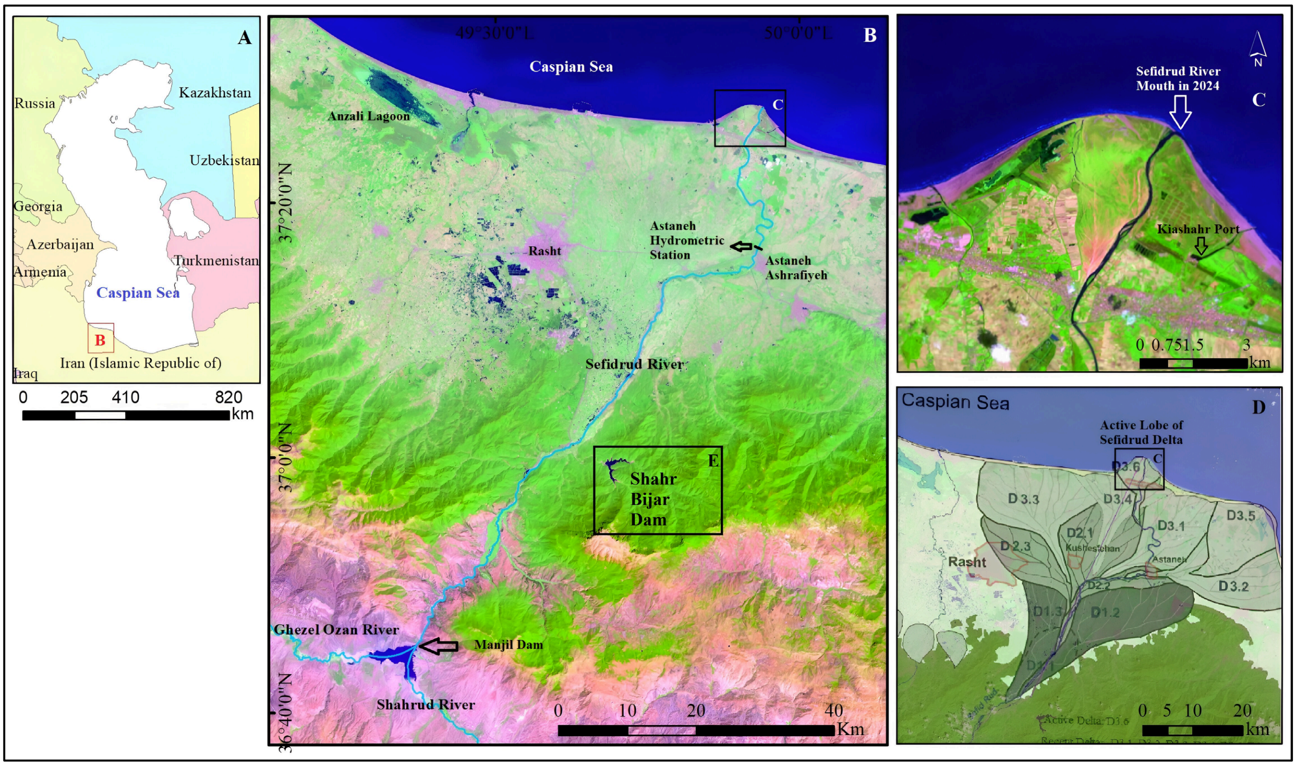


Figure 1. Study area in SW Asia. (A) Southern Caspian Sea and site of the Sefidrud Delta; (B) Sefidrud River, from the Manjil Dam to the delta, and location of the Astaneh hydrometric station; (C) Area of interest, only the active lobe of the Sefidrud Delta, the delta shoreline, and the Sefidrud river mouth in 2024; (D) Different parts of the Sefidrud Delta according to their development stages. The northern lobe is the only active modern lobe of the Sefidrud Delta and the area of interest for this study (development stages map of the delta from Kazanci & Gulbabazadeh, 2013); (E) Loacation of the Shahr Bijar Dam.

most modern lobes (**Figure 1(D)**). The lithology of the active modern part of the delta predominantly consists of moderately to fine-grained sand, silt, and clay (Kazanci & Gulbabazadeh, 2013). Investigating the active lobe of the Sefidrud modern delta is essential because data on this area are inconsistent across recent studies (Kousari, 1986, 1992; Khabbaz-Nia & Sadeghi, 2004; Lahijani et al., 2008). Consequently, the Sefidrud modern delta must be described, with particular emphasis on delta progradation (Kazanci & Gulbabazadeh, 2013). The geology of the Sefidrud Delta is highly complex, featuring rock sequences from the Paleo-Neo and Para-Tethys periods (Kazanci & Gulbabazadeh, 2013). Additionally, the area is seismically active (Berberian & King, 1981; Djamour et al., 2010). Despite this seismic activity, no structural deformation or surface rupture has been detected within the Late Quaternary delta deposits (Kazanci & Gulbabazadeh, 2013). Based on existing evidence, the most significant impact of tectonic activities appears to be the westward migration of the downstream Sefidrud River channel from Amirabad to its current location approximately 500 years ago (Khoshraftar, 2005; Lahijani et al., 2009). Yamani & Kamrani-Dalir (2011) in their examination of rivers in the Sefidrud Delta area, concluded that tectonic activities did not significantly affect the morphology of rivers in the downstream portions of the delta. The Sefidrud Delta complex extends to a depth of 700 meters, forming a rectangular sediment prism (Kazanci & Gulbabazadeh, 2013). This prism exhibits typical deltaic morphology (Coleman & Wright, 1976; Broussard, 1976).

2.2. Manjil Dam and Sediment Flushing Operation

Construction of the Manjil Dam began in 1956 and was completed in 1962. Located at the junction of the Ghezel Ozan and Shahrud rivers, the dam was designed for hydroelectric power generation and water supply for agricultural lands (**Figure 1(B)**). The dam lies approximately 100 km upstream of the active lobe of the Sefidrud modern delta. In the absence of sediment flushing operations, the sediment load of the Sefidrud River has significantly decreased over the past four decades, contributing to rapid siltation and a reduced reservoir capacity (Arcangeli & Ciabbari, 1994; Hassanzadeh, 1995). Around 48 Mt (Million tons) of sediment enter the Manjil Dam reservoir annually, while only 14 Mt/yr (Million tons per year) are released under normal conditions (Morris & Fan, 1998; Khosronejhad, 2009). Approximately 87% of the sediments entering the Manjil Dam reservoir are transported by the Qezel Ozan River (10 Mt/year), while only 13% originate from the Shahrud River (1.8 Mt/year) (Ramezani & Ghomeshi, 2011). Due to its passage through erodible silicate formations, the Qezel Ozan River carries a substantial sediment load composed of clay (48%), silt (40%), and sand (12%) (Ramezani & Ghomeshi, 2011). These fine particles, if released from the reservoir, can be transported downstream by the Sefidrud River flow, increasing its turbidity and contributing to delta evolution. By 1978, approximately 40% of the reservoir was filled with sediment, leading to the initiation of sediment flushing operations in 1980. These operations, carried out in the autumn and winter months from 23 October 1980 to 20 January 1998, were suspended in 1998 due to prolonged droughts in Iran (Yamani et al., 2013). Water discharge and sediment load data for the Sefidrud River were recorded from the 1956-1957 and 1961-1962 hydrological years, respectively, at the Astaneh hydrometric station by the Water Research Institute, the Ministry of Energy of Iran. In this study, data from the Astana hydrometric station, located at the delta's inlet, were analyzed to distinguish the effects of dam flushing operations on the sedimentary budget of the delta and associated morphological changes (Sorour, 2009). It is evident that the contribution of Sefidrud River tributaries in terms of water and sediment discharge is limited and not comparable to the sediment transport capacity of the Sefidrud River itself (Kazanci & Gulbabazadeh, 2013). Although small dams on tributaries may have influenced the sediment transport regime, the Sefidrud River and its sediment discharge have remained the primary agents driving delta progradation (Kazanci & Gulbabazadeh, 2013).

3. Materials and Methods

To detect changes in the Sefidrud Delta, aerial photographs from 1956 and 1971 were obtained from the Iran National Cartographic Center (https://www.ncc.gov.ir), and all available multi-temporal remote sensing data from Landsat MSS, TM, ETM+, and OLI satellite images (1972-2024) were acquired from the EROS Center (https://earthexplorer.usgs.gov/) (Table 1). After radiometric and atmospheric correction of satellite images using ENVI 5.6 software, three different techniques were applied:

Table 1. Aerial photographs and Landsat satellite images were used in this study.

No.	Type	Date of acquisition	Path/Row	No.	Type	Date of acquisition	Path/Row
1	Aerial photo 1:55,000	1956	—	**21**	Landsat TM	18/07/1992	166/035
2	Aerial photo 1:20,000	1971	—	**22**	Landsat TM	12/12/1993	166/034
3	Landsat MSS	17/11/1972	178/034	**23**	Landsat TM	15/12/1994	166/034
4	Landsat MSS	09/07/1973	178/034	**24**	Landsat TM	24/05/1995	166/034
5	Landsat MSS	20/06/1975	178/034	**25**	Landsat TM	13/07/1996	166/034
6	Landsat MSS	21/04/1976	178/034	**26**	Landsat TM	18/11/1996	166/034
7	Landsat MSS	13/06/1978	178/034	**27**	Landsat TM	21/11/1997	166/034
8	Landsat MSS	11/12/1980	179/034	**28**	Landsat TM	04/08/1998	166/034
9	Landsat MSS	29/05/1981	179/034	**29**	Landsat TM	8/11/1998	166/034
10	Landsat MSS	17/07/1982	179/034	**30**	Landsat ETM	03/11/1999	166/034
11	Landsat TM	05/02/1985	166/034	**31**	Landsat ETM	20/08/2001	166/034
12	Landsat TM	20/09/1986	166/034	**32**	Landsat ETM	30/01/2003	166/034
13	Landsat TM	05/07/1987	166/034	**33**	Landsat ETM	15/08/2005	166/034
14	Landsat TM	13/06/1988	166/034	**34**	Landsat TM	08/10/2006	166/034
15	Landsat TM	02/07/1989	166/034	**35**	Landsat TM	22/11/2009	166/034
16	Landsat TM	24/04/1990	166/034	**36**	Landsat ETM	14/08/2014	166/034
17	Landsat TM	11/06/1990	166/034	**37**	Landsat ETM	05/08/2016	166/034
18	Landsat TM	13/12/1990	165/034	**38**	Landsat OLI	23/07/2017	166/034
19	Landsat TM	29/12/1990	165/034	**39**	Landsat OLI	19/08/2021	166/034
20	Landsat TM	14/06/1991	166/034	**40**	Landsat OLI	27/08/2024	166/034

1) Normalized Difference Water Index (NDWI): Used to detect changes in the Sefidrud Delta shoreline. The NDWI is commonly used to monitor changes related to water content in water bodies (McFeeters, 1996). In this study, NDWI was applied to various satellite images as shown in Equation (1) to Equation (3) (Yulianto et al., 2019).

$$\mathrm{NDWImss} = (\rho_1 - \rho_4)/(\rho_1 + \rho_4) \quad (1)$$

$$\mathrm{NDWI}_{\mathrm{TM\&ETM+}} = (\rho_2 - \rho_4)/(\rho_2 + \rho_4) \quad (2)$$

$$\mathrm{NDWI}_{\mathrm{OLI}} = (\rho_3 - \rho_5)/(\rho_3 + \rho_5) \quad (3)$$

2) Tasseled Cap Wetness (TCW): Used to distinguish water and land areas within the delta, which is an effective spectral analysis method for this purpose (Ouma & Tateishi, 2007; Mukhopadhyay et al., 2018). The TCW is presented in

Equation (4).

$$\begin{aligned}\text{TCW} = {} & (0.1509 \times \text{Blue}) + (0.1793 \times \text{Green}) + (0.3279 \times \text{Red}) \\ & + (0.3406 \times \text{NIR}) - (0.7112 \times \text{MIR}) - (0.4572 \times \text{SWIR})\end{aligned} \tag{4}$$

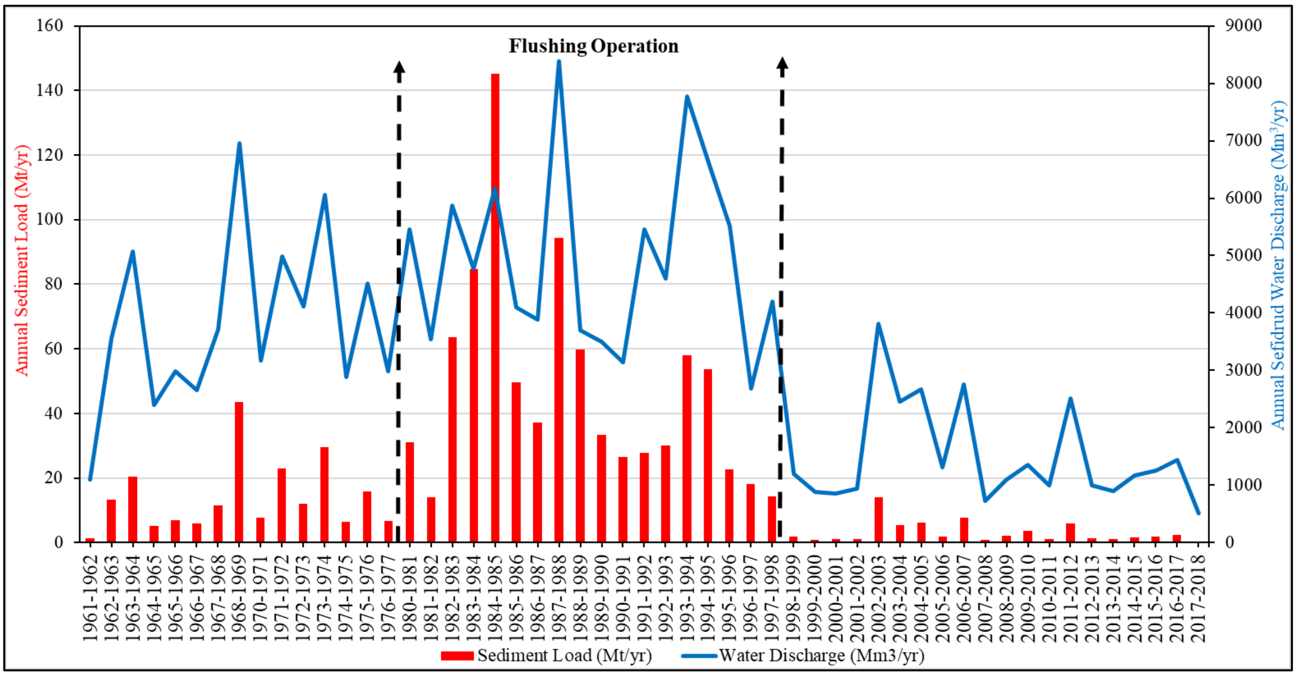


Figure 2. Variation in sediment load and water discharge at the Astaneh Hydrological Station from 1961-1962 to 2017-2018, Water Research Institute, Ministry of Energy of Iran. Water discharge data were recorded starting from 1957, but sediment load data were available from the 1961-1962 hydrological year. No data were recorded for the 1969-1970, 1977-1978, 1978-1979, and 1979-1980 hydrological years. Data after 2018 are unavailable.

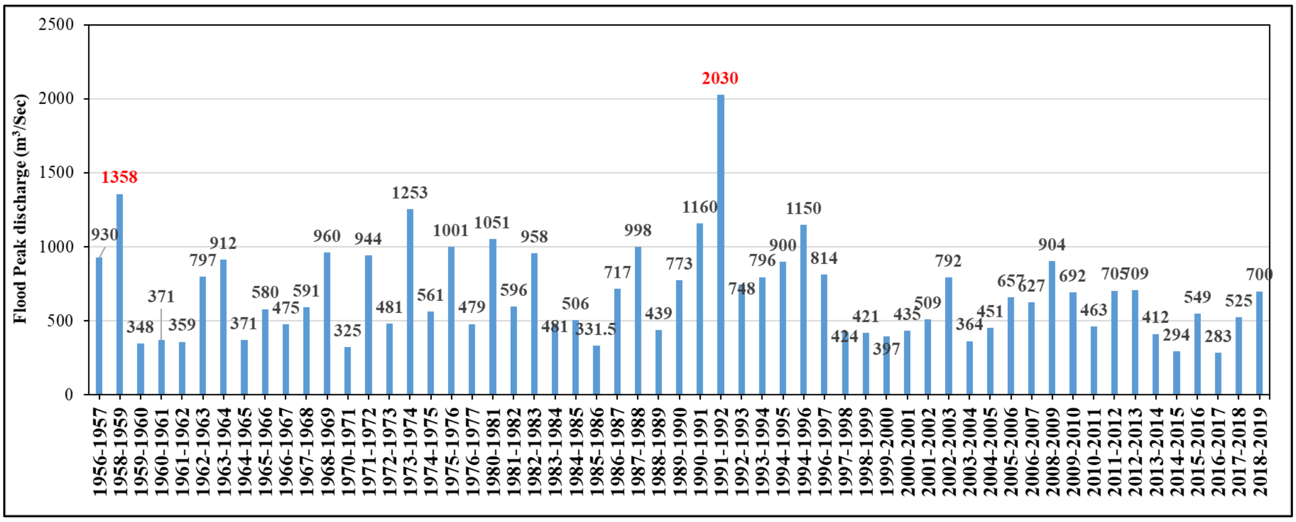


Figure 3. Maximum flood peak discharge of the Sefidrud River from the 1956-1957 to the 2018-2019 hydrological year.

3) Principal Component Analysis (PCA): Used to illustrate the evolution of the delta and for change detection during the study period. PCA is one of the most

widely used and effective methods for detecting changes (Cakir et al., 2006). The daily water discharge and sediment load observed between the 1961-1962 and 2017-2018 hydrological years at the Astaneh hydrological station were obtained from the Water Research Institute, Ministry of Energy of Iran (**Figure 2**). The Manjil Dam plays a crucial role in preventing floods by storing water and reducing the sediment load from the Ghezel Ozan and Shahrud rivers (Kazanci & Gulbabazadeh, 2013; Haghani et al., 2016). The maximum flood peak discharge is shown, with only one flood discharge recorded exceeding those observed before the construction of the Manjil Dam (**Figure 3**, **Table 2**).

Table 2. Highlighted hydrological data of the Sefidrud from 1962 to 2018.

Time Period	Mean Sediment Load (Mt/y)	Mean Water Discharge (Mm^3/yr)	Mean Precipitation (mm/yr)	Max flood peak Discharge (m^3/sec)	Number of Flood peaks more than 1000 (m^3/sec)	Max Annual Sediment Load (Mt/yr)	Max Annual Water Discharge (Mm^3/yr)
First time interval **(1962-1980)**	13.975	3809.13	1103.61	1253 (year 1973-1974)	6	43.55 (year 1968-1969)	6962.2 (year 1968-1969)
Second time interval, **(1980-1998)**	48.04	4964.78	1229.14	2030 (year 1991-1992)	12	145.1 (year 1984-1985)	8389 (year 1987-1988)
Third time interval **(1998-2018)**	3.16	1493.46	1227.9	904 (year 2008-2009)	0	14.09 (year 2002-2003)	3811.8 (year 2002-2003)

4. Results

The development and evolution of deltas are governed by a delicate equilibrium between fluvial sediment supply and various external factors (Somoza & Santalla, 2014). Disruptions to this equilibrium can result in delta retreat and, ultimately, its disappearance (Somoza & Santalla, 2014). This study examines the variations in water discharge and sediment load concerning the morphological changes of the Sefidrud Delta over three-time intervals between 1962 and 2024.

4.1. First Time Interval (1962-1980): Pre-SFO

4.1.1. Hydrometric Characteristics (1962-1980)

The average annual sediment load during this period was approximately 13.975 Mt/yr, which is nearly identical to the 14 Mt/yr reported in earlier studies (Morris & Fan, 1998; Khosronejhad, 2009) (**Table 2**). Sediment peaks were recorded during the 1968-1969 and 1973-1974 hydrological years due to the filling of the dam reservoir after floods and the release of water through emergency valves, highlighting the rapid siltation of the Manjil Dam reservoir (Arcangeli & Ciabbari, 1994; Hassanzadeh, 1995) (**Figure 2**). During this period, there was a direct relationship between sediment load and water discharge in the Sefidrud River, indicating a balance between upstream sediment sources and the river's ability to transport them. Higher flow rates typically increase sediment transport (Matos et al., 2024).

4.1.2. Morphological Changes in the Sefidrud Delta from 1962 to 1980

In 1956, when construction of the Manjil Dam began, the Sefidrud Delta was a river-dominated delta with a bird's foot morphology, characterized by mouth bar complexes (Figure 4, 1956). The formation of river mouth bars is a key process in delta development, as mouth bar growth is one of the initial stages of deltaic landform formation, leading to the development of delta plains and distributary networks (Xiong et al., 2024; Tamura et al., 2012). Over time, the altered hydrological regime, influenced by the dam, changed the delta's morphology to a wave-dominated arcuate shape (Figure 4, 1980).

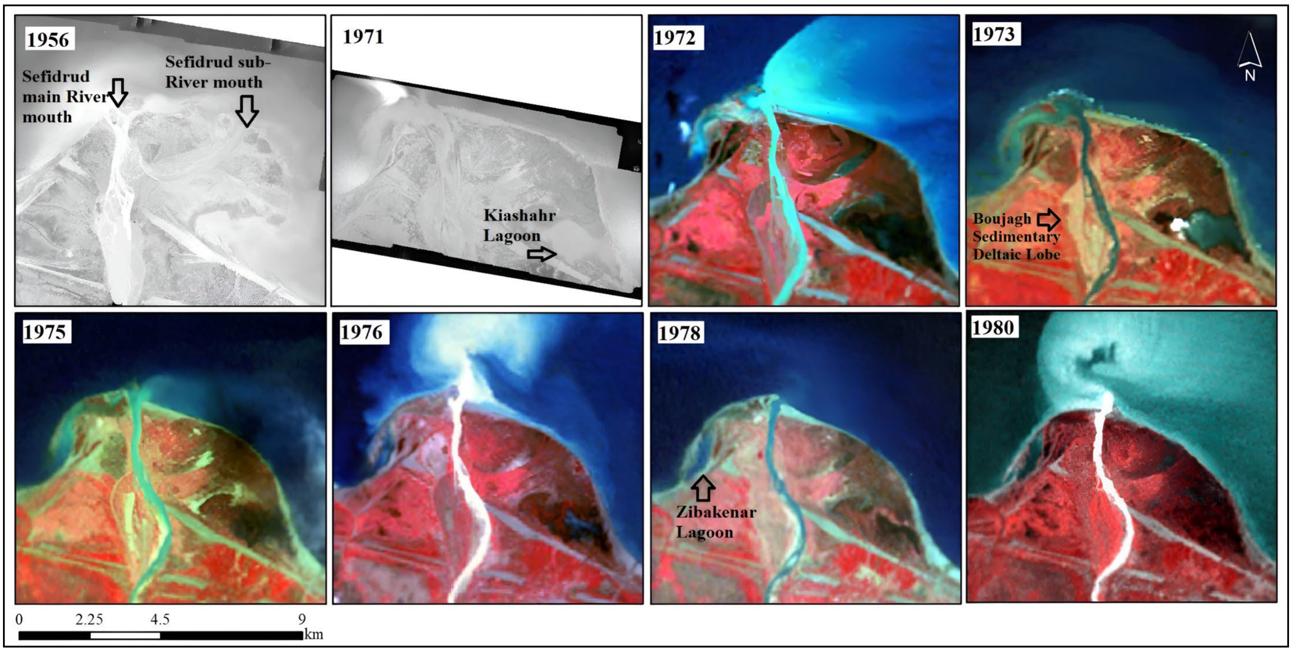


Figure 4. Morphological changes of the Sefidrud Delta from 1956 to 1980. In 1956, aerial photographs show the delta as river-dominated with a bird's foot morphology and mouth bar complexes. By 1971, the influence of the Manjil Dam had transformed the delta into a wave-dominated arcuate shape. Coastal lagoons, such as Kiashahr, were formed as the eastern mouth bars prograded into sandbars (1971). The western mouth bars also evolved into sandbars, forming the Zibakenar lagoon (from 1972 to 1978). Sediment deposition in the Boujagh area led to the formation of an active point bar and caused the Sefidrud channel to shift eastward by 380 meters between 1971 and 1980.

After the construction of the Manjil Dam, the eastern mouth bars, influenced by wave action, evolved into long sandbars, forming a new shoreline and the Kiashahr coastal lagoon (Figure 4, 1971 and 1972). A similar process occurred with the western mouth bars, which began forming new sandbars in 1971, ultimately creating the Zibakenar coastal lagoon (Figure 4, 1978 and 1980). Additionally, sediment deposition along the old sidebar in the Boujagh area resulted in the formation of an active point bar.

Between 1971 and 1980, the development of the Boujagh point bar caused the Sefidrud channel to shift approximately 380 meters eastward. This shift in the river channel highlights the effect of the dam on altering the flow regime of the Sefidrud River. The deceleration of the flow reduces the river's capacity to transport sediment, leading to the formation of point bars (Dietrich, 1987). The evolution of the Sefidrud Delta during this period demonstrates a relative equilibrium between river-dominated and wave-dominated morphology.

4.2. Second Time Interval (1980-1998): During SFO

4.2.1. Hydrometric Characteristics (1980-1998)

During this period, SFO greatly increased the sediment load, with the average annual sediment load reaching approximately 48 Mt/yr (**Figure 2**, **Table 2**). The relationship between water discharge and sediment load, which was direct in the previous period, shifted to a more dynamic connection due to the significant influence of the SFO. As a result, the highest water discharges were not necessarily associated with the highest sediment loads (**Figure 2**).

The effect of the flushing operation on sediment load increased and decreased over time. In the 1984-1985 and 1987-1988 hydrological years, 145.1 and 94.4 million tons of sediment were transported to the Sefidrud Delta, respectively—1.14 times the total sediment load of the previous period (before the sediment flushing operation) (**Figure 2**). These findings prove that the flushing operation was highly effective in the Sefidrud Reservoir (Emamgholizadeh et al., 2005).

4.2.2. Morphological Changes in the Sefidrud Delta (1980-1998)

The large volume of sediments released during the SFO contributed to continued delta growth, leading to the formation of mouth bars. As a result, the delta's morphology shifted to a pointy cuspate shape (**Figure 5**, between 1981 and 1990). During this period, the Caspian Sea level rose by an average of 13.09 cm per year, peaking in 1996 (Toorani et al., 2021). The morphology of the delta transitioned to a fluvial and wave-dominated cuspate shape between 1987 and 1995, influenced by this rise in the Caspian Sea level. Coastal lagoons also transformed into open lagoons during this time (Haghani et al., 2016). Despite rising sea levels, the influx of sediment from the flushing operation spurred the delta's growth, accelerating morphological changes.

The large volume of sediments resulted in the formation of mouth bars and the expansion of the delta in the northern part between 1981 and 1990, leading to the development of a more pointy cuspate shape. However, after 1997, the reduction in the sediment supply from the SFO caused the delta to return to a wave-dominated arcuate shape, similar to the first time interval. The area of Boujagh point bar sediment deposition expanded by approximately 62% during the 10 years of flushing operation (**Figure 5**, between 1981 and 1990), resulting in a 780-meter eastward shift of the Sefidrud channel. By the end of 1990, the Sefidrud River, influenced by the Boujagh point bar, expanded a new channel along the old upstream channel (**Figure 5**, 29/12/1990).

The rapid progradation of active point bars caused by faster flow outside the channel resulted in bank erosion and, eventually, river channel migration (Amissah et al., 2019). In 1994, the old river mouth of the Sefidrud was completely blocked by sedimentation, and a new river mouth and channel were fully expanded (**Fig-**

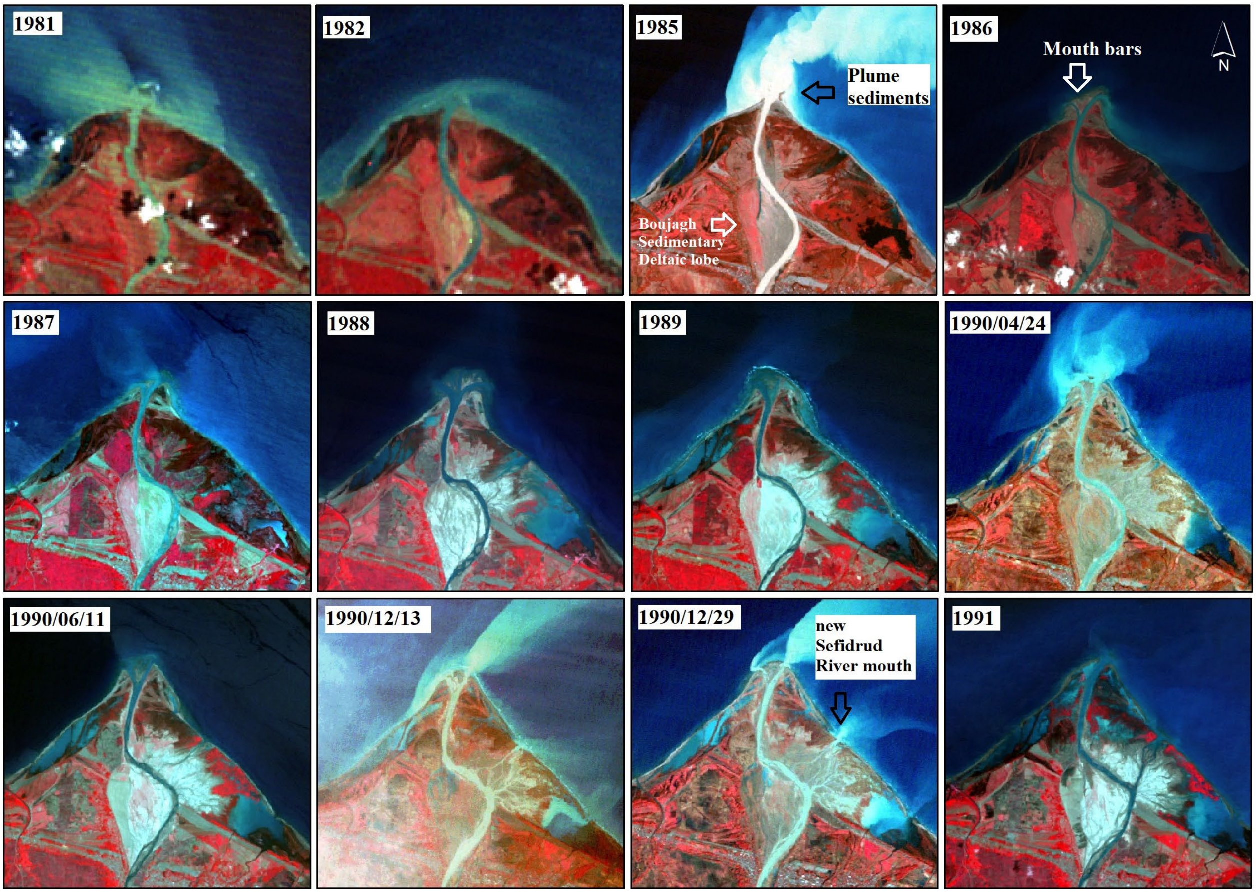
ure 5, 1994). This change led to the displacement of the river mouth by 2540 meters eastward. Since 1992, mouth bar complexes in the new river mouth have begun to form. The rapid progradation of these complexes, influenced by wave action, resulted in the development of new shorelines and forming the Northern Kiashahr Lagoon between 1992 and 1998 (**Figure 5**, between 1992 and 8/11/1998). The formation of the Northern Kiashahr Lagoon has not been mentioned in previous studies. This indicates that the mechanism of coastal lagoon formation in the Sefidrud Delta was the result of a dynamic equilibrium between fluvial sediment deposition and wave erosion, creating a cyclical process:

i) Formation of mouth bar complexes in the presence of sufficient fluvial sediment supply.

ii) Transformation of mouth bars into long sandbars by wave action.

iii) Creation of new shorelines and coastal lagoons.

The large volume of sediments provided by the flushing operation led to the shrinkage of the Zibakenar and Kiashahr lagoons, which were short-lived and would fill more quickly if the Sefidrud River were to divert into them (Haghani et al., 2016) (**Figure 6**). The area of these lagoons reduced by 10% and 83%, respectively (**Table 3**). According to the diverging model, coastal lagoon evolution is driven by sediment infill, making lagoons natural sediment sinks (Oertel et al., 1992; Nichols & Boon, 1994). As a result, Sefidrud's coastal lagoons filled rapidly



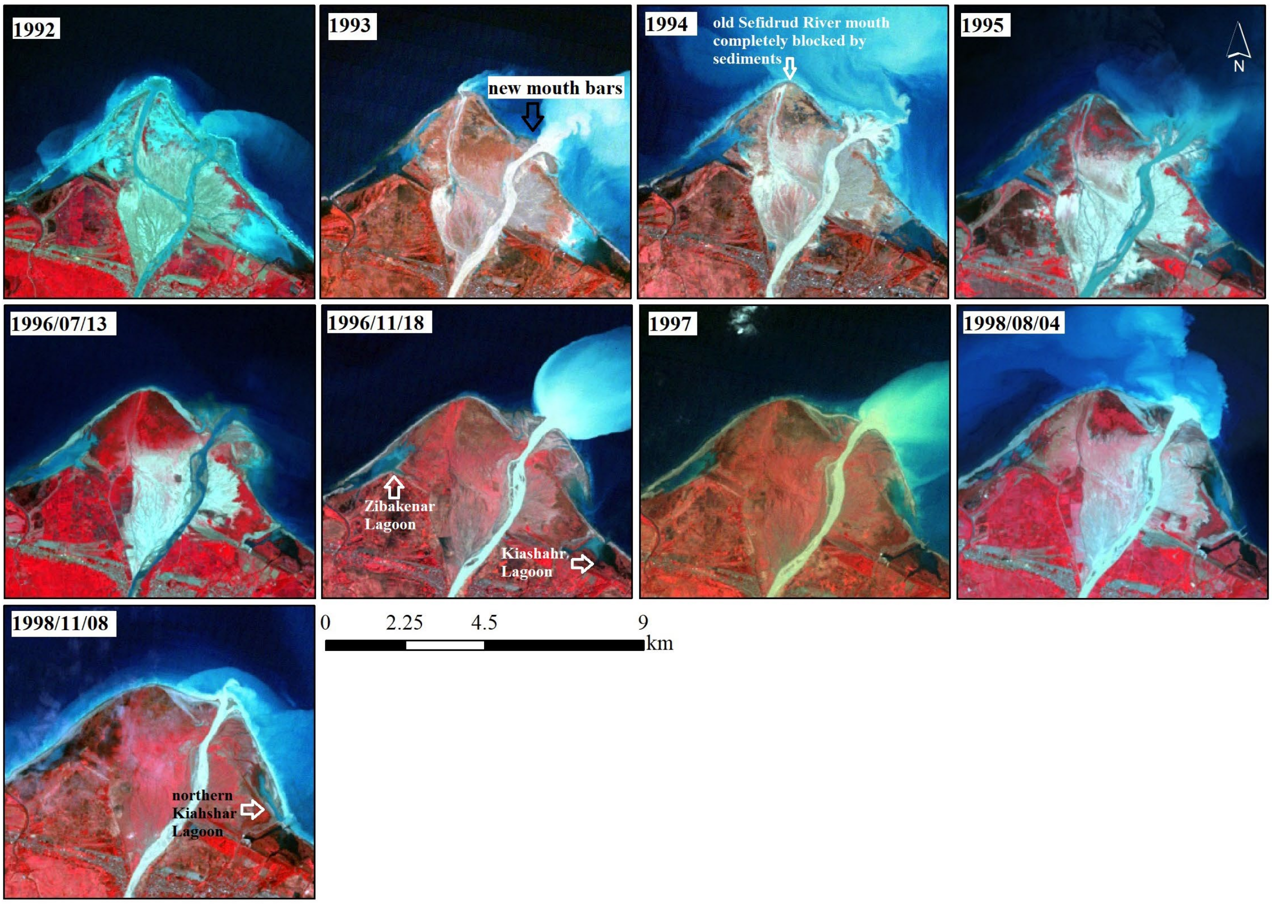


Figure 5. Morphological changes of the Sefidrud Delta during sediment flushing operation (between 1980-1981 and 1997-1998). Mouth bars formed between 1981 and 1990, transitioning the delta's morphology from arcuate to pointy cuspate. Between 1987 and 1995, the delta became fluvial and wave-dominated pointy cuspate shape due to the coupled large amount of flushing sediments and rise in the CSL. Coastal lagoons evolved into open lagoons. By 29/12/1990, the new river mouth and Sefidrud channel began to expand, with mouth bars rapidly forming by 1992. The formation of Northern Kiashahr Lagoon occurred between 1996 and 1998.

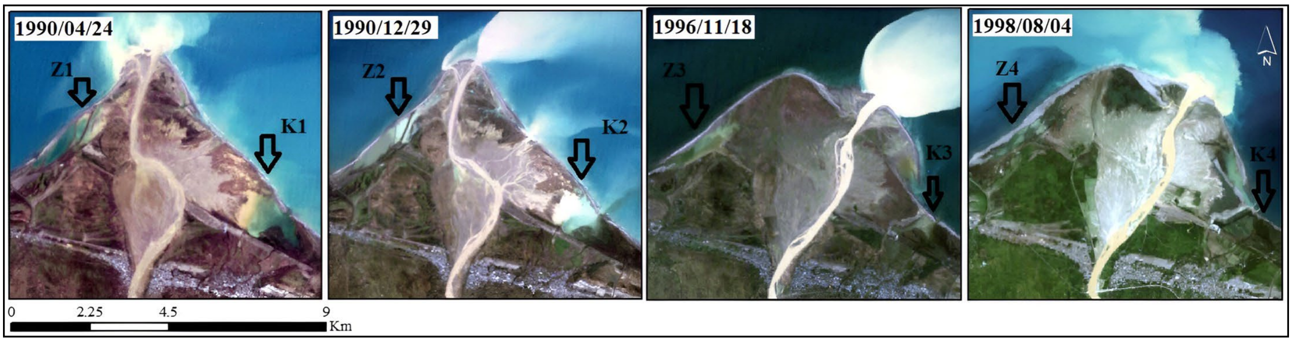


Figure 6. The effects of sediment flushing on coastal lagoons during SFO. The plume sediments in Z1/K1 (24/04/1990) and Z2/K2 (29/12/1990) show sediments entering the lagoons through the fluvial stream network. In Z3/K3 (18/11/1996) and Z4/K4 (04/08/1998), the area of the lagoons reduced drastically.

due to the large sedimentation rate during the SFO between 1990 and 1998. Kiashahr Lagoon filled faster than Zibakenar Lagoon, as Sefidrud directly diverted into it (Figure 6 and Figure 7).

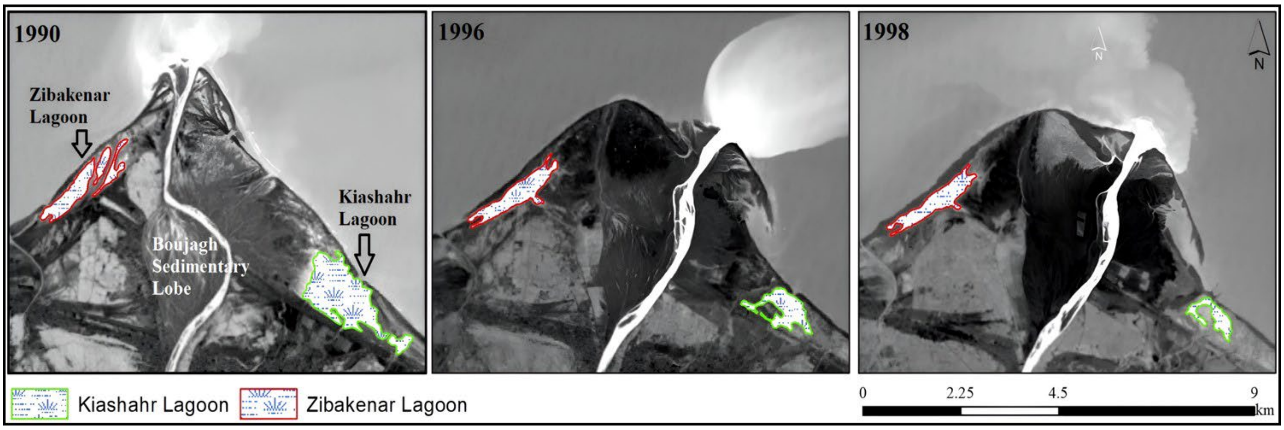


Figure 7. The Reduction of coastal lagoon areas during the flushing operation between 1990 and 1998, as shown in TCW images and Table 3.

Table 3. Reduction of coastal lagoon areas during the flushing operation according to Figure 7.

Lagoon's name	1990	1996	1998	Area reduction percent
Zibakenar Lagoon's area (km^2)	0.771	0.768	0.694	10%
Kiashahr Lagoon's area (km^2)	1.835	0.607	0.318	0.83

4.2.3. Progradation of Boujagh Point Bar

Point bars influence hydraulics, morphodynamics, and channel geometry in alluvial rivers (Reyes et al., 2018). Previous studies have shown that point bars are generally twice as effective at trapping sediment compared to floodplains. The rapid development of the Boujagh point bar was significantly influenced by the sediment supplied through the flushing operation. By 1990, the area of the Boujagh point bar had expanded to 4.45 km^2, compared to 2.75 km^2 at the end of the previous period (**Figure 8**). The cumulative annual sediment load between 1980-1981 and 1989-1990 was approximately 579.9 Mt, which led to the expansion of the Boujagh sedimentary lobe by 1.7 km^2. This expansion resulted in the migration of the Sefidrud River channel (**Figure 5**, 1992-1993 and 1994).

To quantify the role of the flushing operation in the Sefidrud Delta, we can consider these values:

- Active-modern delta lobe area: 54.06 km^2 (Kazanci & Gulbabazadeh, 2013).
- Boujagh point bar area in 1990: 4.45 km^2.
- Development of Boujagh point bar during flushing operation: 1.7 km^2.
- Volume of the Sefidrud active-modern delta lobe: 6.4×10^8 m^3 (Kazanci & Gulbabazadeh, 2013).
- Volume of sediment from flushing operation: 3.263×10^8 m^3 (assuming a specific gravity of 2.65 based on components of Boujagh point bar, which include sand, silt, and clay, according to Van Asselen et al., 2018).
- Formation time of the active-modern delta lobe: 450 years (Kazanci & Gulbabazadeh, 2013).

- Formation time of the Boujagh point bar: 10 years.

These results highlight the rapid impacts of the flushing operation on delta morphology. Eighteen years of flushing operation delivered sediments equivalent to approximately 51% of the total volume of the active-modern delta. The deposition of sediments in the Boujagh point bar during the 10 years of flushing operation expanded the area by 3.14% of the total delta area, ultimately leading to the migration of the Sefidrud River (**Figure 8**).

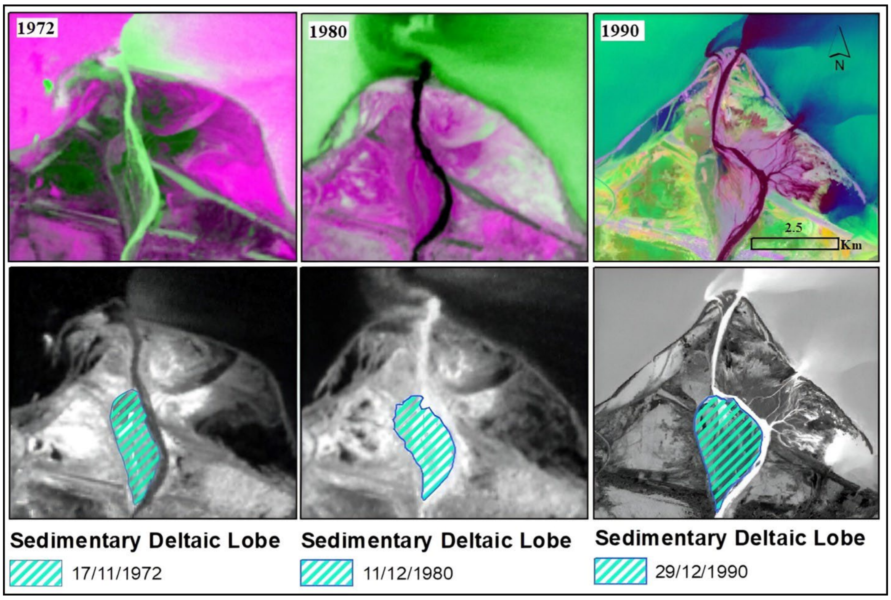


Figure 8. Progradation of the Boujagh point bar in PCA and NDWI images from 1972 to 1990. Color differences in the Boujagh point bar on PCA images indicate the areas that expanded during the sediment flushing operation.

4.3. Third Time Interval (1998-2024): Post-SFO

4.3.1. Hydrometric Characteristics (1998-2024)

Since 1998, due to prolonging drought condition in Iran SFO have been suspended SFO (Yamani et al., 2013). With the decision of the Ministry of Energy of Iran to supply the required water reserves, the water output of the Manjil Dam reduced significantly resulted in drastic decrease in both of the Sefidrud Delta's water discharge and sediment load from upstream. The mean annual sediment load during this period decreased by 93.4% compared to the previous period and by 77.3% compared to the first interval.

The mean annual water discharge during this time interval also decreased by 70% and 61%, respectively, compared to the two previous periods (**Table 2**). Caldwell et al. (2019), studying 5399 coastal rivers, stated that water discharge and sediment load are the most crucial factors in delta formation. Additionally, delta formation results from constructive upstream forces dominating destructive downstream marine forces (Boyd et al., 1992; Anthony, 2015). During this period, there were no favorable hydrological conditions for the continued development of the Sefidrud Delta. Similar to the first interval, the fluctuation between sediment load and water discharge of the Sefidrud River showed a direct relationship (**Figure 2**). However, the highest recorded flood peak water discharge was 904 m^3/sec (**Table 2**), below the threshold value of 1000 m^3/sec required for delta formation (Xu et al., 2021). This indicates a lack of adequate hydrological conditions for maintaining or developing the Sefidrud Delta during this time.

4.3.2. Morphological Changes in the Sefidrud Delta (1998-2024)

Not only did delta formation halt during this period, but the drastic reduction in sediment load also caused sediment starvation and erosion in various parts of the delta (**Figure 9**). This process was further aggravated by the declining Caspian Sea level (Toorani et al., 2021). The area of the delta decreased by 1.166 km^2 during this period. Since then, due to the lack of water discharge and sediment load from upstream, the delta's morphology shifted to a more wave-dominated arcuate shape (**Figure 10** and **Figure 11**). The Caspian Sea level (CSL) decline during this period (Toorani et al., 2021) likely reduced the rate of erosion in the delta. The Kiashahr Lagoon mostly dried up, and both the Zibakenar and Northern Kiashahr Lagoons transformed into swampy wetlands (**Figure 10**, 2014).

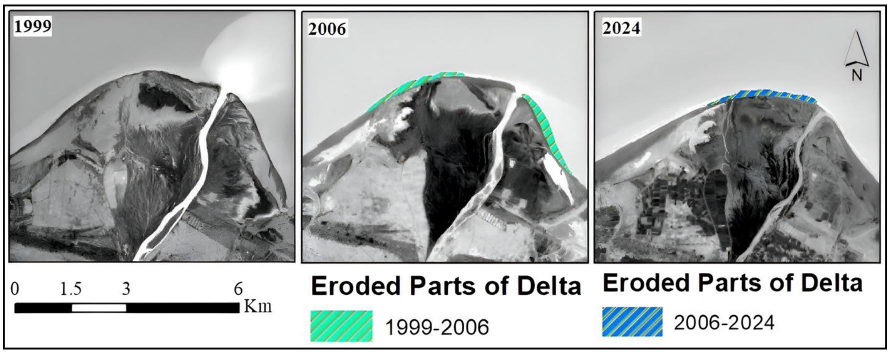


Figure 9. Eroded parts of the Sefidrud Delta due to the drastic reduction in sediment load during the third time interval (1999-2024).

The shrinkage and drying of the Sefidrud coastal lagoons indicate the combined effects of reduced water discharge from the Sefidrud River and the lowering of the Caspian Sea level. The coastal lagoons, which were impacted by the morphological changes of the delta, transitioned into closed lagoons in the infilling phase, with depths ranging from 0 to 76 cm (Haghani et al., 2016). Along the wave-dominated coastline, the longshore sediment transport caused by wave action resulted in the formation and growth of a sandspit, which may progressively choke the lagoons by reducing their equilibrium volume (Duck & da Silva, 2012). The shoreline progradation on both the eastern and western flanks of the Sefidrud Delta, influenced by the drop in CSL between 1990 and 2024, was 430 meters and 380 meters, respectively (**Figure 11**). Even though many deltas around the world are eroding due to sea level rise (Ericson et al., 2006; Nienhuis & Van de Wal, 2021; Nienhuis et al., 2023; Haq & Milliman, 2023), the Sefidrud Delta has been experiencing degradation even with the decline in Caspian Sea level. The severe

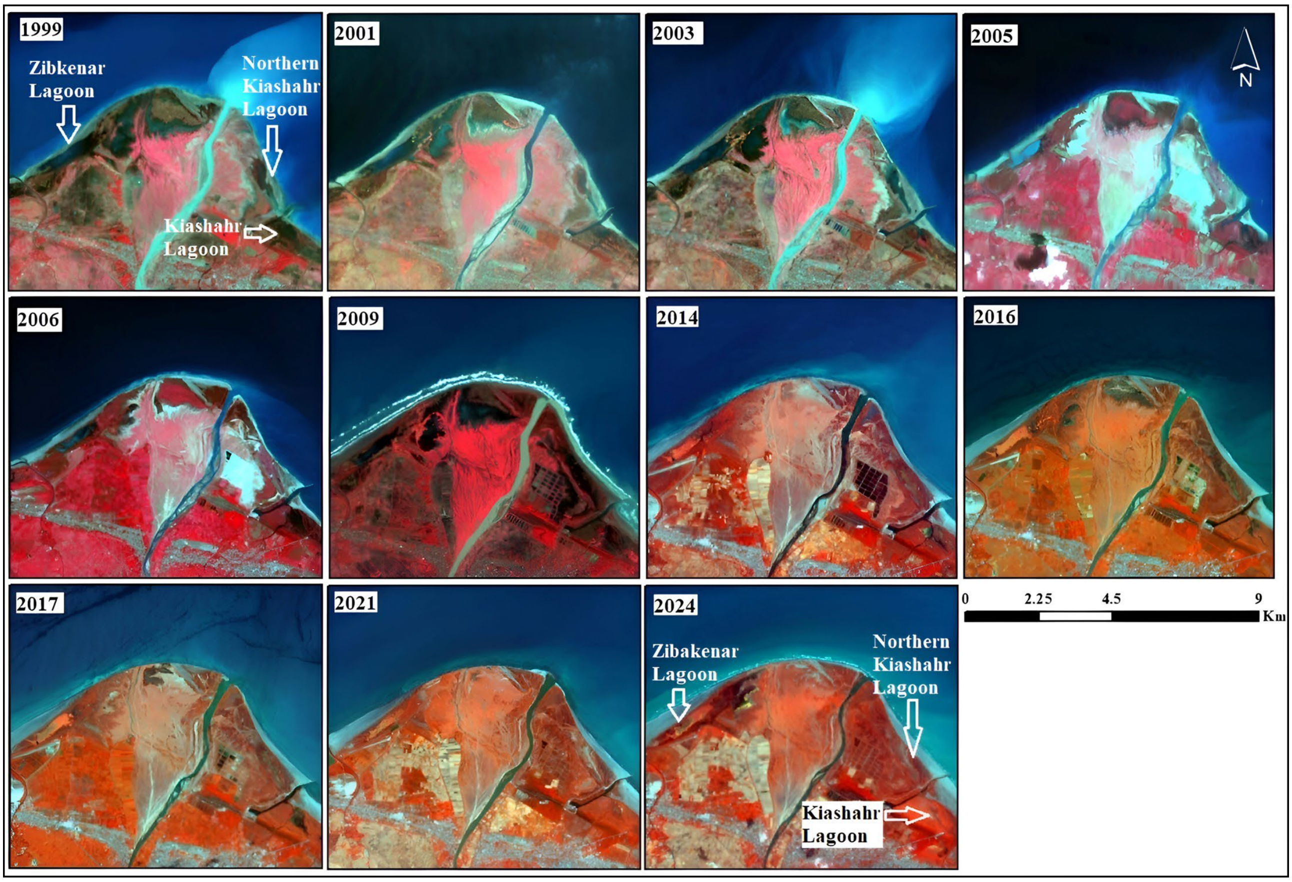


Figure 10. Morphological changes of the Sefidrud Delta from 1999 to 2024. During this period, the delta's morphology transitioned to a more flat arcuate shape. Due to the simultaneous decline in the Caspian Sea level and the reduction of Sefidrud River water discharge, all of the coastal lagoons shrank between 1999 and 2024.

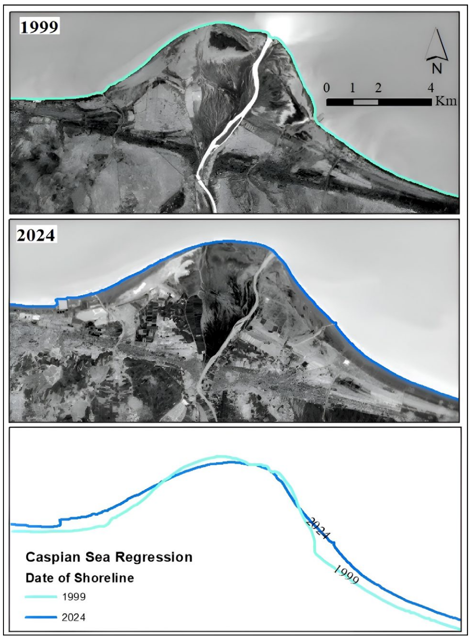


Figure 11. Shoreline progradation in both flanks of delta due to the decline in the CSL between 1999 and 2024. By 2024, the delta had taken on a more flat arcuate shape.

reduction in fluvial sediment supply, caused by damming and human mismanagement, has led to the loss of natural land gain in the Sefidrud Delta.

5. Discussion

The construction of the Manjil Dam and its sediment flushing operations have been the primary factors influencing the morphological changes of the Sefidrud Delta over the past seven decades. By altering the hydrometric regime of the river, the Manjil Dam transformed the delta from a river-dominated bird's foot into a wave-dominated cuspate shape, creating new shorelines and forming Kiashahr and Zibakenar lagoons. The large amount of sediment released during the flushing operation further transformed the delta, leading to the formation of a more pointy cuspate shape. Due to the similarity in sediment grain size distribution between the flushed sediments and the Sefidrud Delta (comprising clay, silt, and sand), the large volume of sediments released during the flushing operation has significantly contributed to the rapid expansion of the delta. The effect of the flushing operation on delta formation was so pronounced that, despite the rise in the Caspian Sea level, delta formation continued, and the delta's morphology changed from a wave-dominated arcuate shape in 1981 to a fluvial and wave-dominated pointy cuspate shape by 1990.

The substantial volume of sediment supplied by flushing operations between 1980 and 1998 contributed to the rapid expansion of the Boujagh point bar sedimentary lobe, leading to a 45˚ river channel migration. The rapid progradation of the Boujagh point bar within the delta following the construction of the Manjil Dam highlights the contribution of upstream sediments to the development of various parts of the delta under the river's altered hydrological regime. However, further investigation is required to understand all aspects of this process fully. The Kiashahr and Zibakenar coastal lagoons shrank significantly due to the influx of sediment. Additionally, the flushing operation contributed to the rapid formation of mouth bar complexes, resulting in the development of new shorelines and the formation of the Northern Kiashahr Lagoon. By the end of the flushing operation, the sediment load decreased by about 93.4%, leading to sediment starvation and erosion of approximately 1.166 km^2 of delta.

On the one hand, the Caspian Sea is non-tidal, allowing tides to be disregarded (Farley Nicolls et al., 2012). On the other hand, the dominant wave direction in the Sefidrud Delta area is NE-SW. However, the morphological changes of the Sefidrud Delta do not align with this wave direction, indicating that sediment discharge from the Sefidrud River is the primary factor driving these changes (Yamani et al., 2013). According to **Figure 12** during the Manjil Dam flushing period, the Caspian Sea level (CSL) rose by approximately 2 meters, which would typically be expected to cause significant erosion and delta destruction. In contrast, due to the substantial increase in sediment discharge from the Sefidrud Flushing Operation (SFO), the delta expanded by approximately 26 meters per year (Yamani et al., 2013). In comparison, during the same period, the Kura Delta in Azerbaijan (another delta in the southwestern Caspian Sea) experienced erosion of 10 to 15 meters annually due to the rise in the Caspian Sea level, with severe degradation observed in its eastern parts (Yamani et al., 2013; EU4Environment, 2023). The findings of this research demonstrate that the most critical factor controlling the development or degradation phases of the Sefidrud Delta is the volume of sediments transported by the Sefidrud River.

While the decline in the CSL (**Figure 12**, after 1998) may have reduced the erosion rate of the delta, the reduction in fluvial sediment supply, coupled with the decline in water discharge (**Figure 2**, after 1998), has exacerbated the delta's degradation.

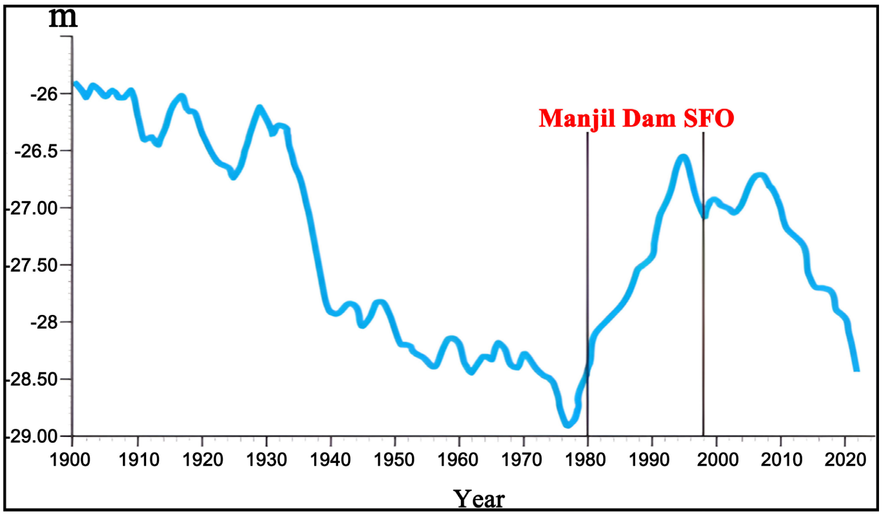


Figure 12. Caspian Sea level (CSL) graph from Lahijani et al. (2023). The SFO period highlighted in the graph by authors.

Due to the growing demand for water and energy in Iran, the construction of Shahr Bijar hydropower dam on the junction of two main tributaries of Sefidroud (Zalaki River and Do-aban River) began in 2004. This dam with a 105 Mm^3 reservoir capacity has aggravated the decrease of flow discharge and sediment load in the Sefidrud Delta since 2004 (**Figure 1(E)** and **Figure 2**). Although the impact of this dam is much smaller compared to the Manjil Dam in reducing the water flow and sediment discharge of the Sefidrud River, it underscores the inadequate attention given to managing the sediment budget necessary for maintaining the Sefidrud Delta. The continuation of reduced sediment supply from upstream and a lack of adequate water discharge in the third time interval (1999-2024) has led the Sefidrud Delta to become a more flat, arcuate shape. The combined effects of reduced sediment supply and sea-level decline have driven the delta into a state of erosion and ecological degradation. Based on the stability observed between 1962 and 1980, the critical sediment demand for maintaining the Sefidrud Delta is approximately 14 Mt/yr. During the period from 1999 to 2024, the mean annual sediment load delivered to the delta was 3.16 Mt/yr, which is only 23% of the required sediment load to sustain the delta (Table 2).

The contradiction between these coupled circumstances underscores that sediment supply is the primary factor driving the growth of the Sefidrud Delta:

- Delta expansion occurred during a rise in the CSL, with a positive fluvial sediment input from the Sefidrud River.
- Delta erosion occurred as the CSL fell, accompanied by a negative fluvial sediment input resulting from the substantial reduction in water discharge and sediment load from the Manjil Dam.

Therefore, the government must effectively manage water discharge and sediment load from upstream and the dam to safeguard the delta. The evolution of the Sefidrud Delta over the past 70 years can undoubtedly be considered a symbol of the Anthropocene in the southern Caspian Sea. Suppose the flushing operation of the Manjil Dam is to be repeated. In that case, careful consideration must be given to its impact on the morphology of the Sefidrud Delta, as the active lobe of the delta is highly sensitive to changes in hydrological parameters. The significant impact of the Manjil Dam's flushing operation on the Sefidrud Delta's morphology underscores the need for long-term studies on its environmental effects, water quality, and the health of the region's aquatic life. Flushing operations not only altered the morphological and hydrological characteristics of the Sefidrud Delta but also caused widespread environmental damage by filling coastal lagoons and shifting the river's main channel.

6. Conclusion

The evolutionary process of the Sefidrud Delta underscores the critical role of sediment budget alterations as the primary factor shaping delta formation, influenced by damming, flushing operations, and sea-level fluctuations over the past seven decades. Rapid changes in the Sefidrud Delta morphotype and alternating constructive-destructive phases make it a representative example of the degradation caused by human-induced interventions on deltaic systems. Although the hydrological regime and morphological type of the Sefidrud Delta were initially impacted by the Manjil Dam, sediment supply for delta development was maintained. Therefore, the delta continued to grow by forming new mouth bars. However, after the cessation of sediment flushing operations, the necessary sediment budget for delta sustainability was no longer supplied, resulting in sediment starvation and erosion.

The formation of mouth bars has been a critical indicator of the Sefidrud Delta's development, as delta growth has consistently been linked with the formation of mouth bar complexes, particularly after the construction of the Manjil Dam and the completion of the flushing operation. Since 1999, due to the lack of sufficient water discharge and sediment load, no new mouth bar complexes have formed.

While many deltas globally are eroding due to sea-level rise, the Sefidrud Delta has been severely impacted by human mismanagement and a drastic reduction in sediment supply, regardless of sea-level decline. Thus, effective management of the water discharge and sediment load of the Sefidrud River is critical for the preservation of the delta. The hybrid approach used in this research, combining continuous monitoring of physical changes in the delta through remote sensing and hydrological data, provides a practical methodology for studying deltaic systems worldwide. This approach can help detect both short and long-term changes in response to natural and anthropogenic factors that alter the hydrological regimes of deltaic systems. Expanding this model to other deltas can help simulate the time evolution of river delta formation processes and understand the compounded effects of destructive and constructive factors in deltas worldwide.

We believe that the current vulnerable state of the Sefidrud Delta is threatened by the continued reduction in fluvial sediment supply and the decline in the CSL. Excessive dam construction on the Sefidrud River's main tributaries after 2004 has further exacerbated the reduction in water discharge and sediment transport capacity. As a final point, the legacy of the Manjil Dam and its flushing operation must be carefully investigated to fully understand its negative impacts on water quality and the destruction of habitats in the region.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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