

## Article

# Hyper-Nutrient Enrichment Status in the Sabalan Lake, Iran

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**Abstract:** Lakes/reservoirs are rapidly deteriorating from cultural eutrophication due to anthropogenic factors. In this study, we aimed to (1) explore nutrient levels in the Sabalan dam reservoir (SDR) of northwest Iran, (2) determine the reservoir water fertility using the total phosphorus (TP) based and total nitrogen (TN) based Carlson trophic state indices, and (3) specify primary limiting factors for the reservoir eutrophication. Our field observations showed a state of hyper-nutrient enrichment in the SDR. The highest variation of TN in the reservoir water column happened when the reservoir was severely stratified (in August) while the highest variation of TP took place when the thermocline was attenuated with the deepening of the epilimnion (in October). Both TP and TN based trophic indicators classified the SDR as a hypereutrophic lake. TN:TP molar ratio averaged at the epilimnion indicated a P-deficiency in the reservoir during warm months whilst it suggested a co-deficiency of P and N in cold months. Given the hyper-nutrient enrichment state in the reservoir, other drivers such as water residence time (WRT) can also act as the main contributor of eutrophication in the SDR. We found that WRT in the SDR varied from hundreds to thousands of days, which was much longer than that of other reservoirs/lakes with the same and even much greater storage capacity. Therefore, both hyper-nutrient enrichment and WRT mainly controlled eutrophication in the reservoir. Given time consuming and expensive management practices for reducing nutrients in the watershed, changes in the SDR operation are suggested to somewhat recover its hypereutrophic state in the short-term. However, strategic long-term recovery plans are required to reduce the transition of nutrients from the watershed to the SDR.

**Keywords:** Carlson trophic state index; limiting factor; dam reservoir; fertilizers; Iran



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## 1. Introduction

Lake and reservoir water is rapidly deteriorating from cultural eutrophication driven by anthropogenic factors. Man-made activities compounded by severe rainfall in the basin have introduced intensive pollution loads such as nutrients into these bodies of water, leading to negative impacts on the ecological functions they deliver [1]. These anthropogenically driven nutrients in the Anthropocene have exposed many global lakes/reservoirs to eutrophication [2,3]. According to the Survey of the State of the World's Lakes in 2008, about half of Asian (~53%), European (~54%) and North American (48%) lakes were exposed to eutrophication ([www.lescienze.it](http://www.lescienze.it) (accessed on 28 February 2021)). This ratio is an underestimation of the number of lakes with eutrophication, as agricultural development in many developing countries such as Iran has intensified the nutrient transport to the terminal lakes/reservoirs [4]. Iran has 647, 146, and 537 dams in operation, under construction, and

under planning, respectively [5]. The large number of dams in Iran provides water supply to its growing population and expanding agriculture [4].

Although dams are useful for water supply, flood control, fisheries, recreational activities and hydropower generation, they increase water residence time (WRT) by the conversion of turbulent flow in running waters to a stable state in reservoirs [6–9]. River damming also creates a change in productivity from the river to the reservoir [10]. In general, these changes are associated to the conversion of a flowing (lotic) into a static (lentic) water environment, which results in extensive changes of the reservoir water quality such as nutrient enrichment and eutrophication [11–13]. The nutrient compounds (mainly N and P), as necessary elements for primary production (i.e., the conversion of inorganic into organic matter), are required for the growth and life of aquatic biota [14]. In a sustainable practice, nutrients are beneficial for aquatic ecosystems such as supporting primary production, and provide a suitable environment for fish and phytoplankton [15]. However, hyper-nutrient enrichment (HNE) can eventually lead to lake/reservoir eutrophication [16,17]. This process may eventually cause oxygen deficiency, overload macro-algal blooms, and finally decrease water transparency in the face of suspended vegetation [18].

Due to the discharge of large nutrient loads into Iran's lakes/reservoirs, the HNE and its consequences, such as eutrophication, have become a major national concern. Therefore, exploring the current state of nutrients and eutrophication in new dams helps to diagnose the reservoir water quality. In addition, reservoirs are economically important and are a major subject of public health. Hence, limnologists and water resources managers need proper tools to take necessary decisions about the trophic state of newly constructed reservoirs. This study aims to explore nutrient levels in the Sabalan dam, a relatively new dam impounded to supply water for domestic and agricultural uses in northwest Iran. To diagnose eutrophication in the Sabalan dam reservoir (SDR), we used the Carlson trophic state index (CTSI) [19]. The CTSI transforms eutrophication, as a multivariate and complex phenomenon, into numbers, helping water resources managers to understand and measure the state of reservoir fertility [20]. This index has been widely applied to specify the lake trophic state around the world [20–23].

## 2. Materials and Methods

### 2.1. Study Site

The Sabalan dam, with a mean elevation of one kilometer above sea level, was constructed on the Qareh-Su river to provide water for domestic (~10 million cubic meters (MCM)) and agricultural (~15,000 hectares of agricultural lands) applications. The SDR with a total volume of 105 MCM (active storage capacity is ~94 MCM) and an area of about 4.4 km<sup>2</sup> at the normal operating level, i.e., 1123 m, is located in the northwest of Iran (Figure 1) [24]. Thermal stratification in this warm mono-mictic reservoir begins from April and remains until November, leading to large variations in temperature between the top and bottom of the lake that can reach up to 15 °C in the summer season [11].

Potential evaporation is three times greater than precipitation in the Sabalan dam [25]. July and January are the warmest and coldest months in the study area, with a monthly average air temperature of about 20.8 °C and −0.7 °C, respectively. The warmest and coldest days during the sampling campaigns were on 21 July 2018 (around 28.7 °C) and 10 January 2018 (around −9.5 °C), respectively. The minimum and maximum monthly mean wind speeds during the sampling campaigns were around 2.5 m/s (September–October) and 3.4 m/s (February–March), respectively. According to long-term meteorological data from the dam location, the dominant wind direction is from the west-southwest to the east. Also, long-term hydrological data show that the average river inflow to the reservoir is about 2.12 m<sup>3</sup>/s [11].

Sabalan dam's basin area and its average slope are approximately 5366 square kilometers and 0.59%, respectively. About 34% and 35% of the basin area are covered by rain-fed and irrigated agricultural lands, respectively. Also, plains, populated areas, forests, rocks, and water cover around 29%, 1.1%, 0.6%, and 0.1% of the basin, respectively (Figure 1).

Although this dam was newly impounded, a number of studies reported serious concerns about its water quality deterioration due to nutrients [11], heavy metals [26], and dissolved oxygen deficiency [11].

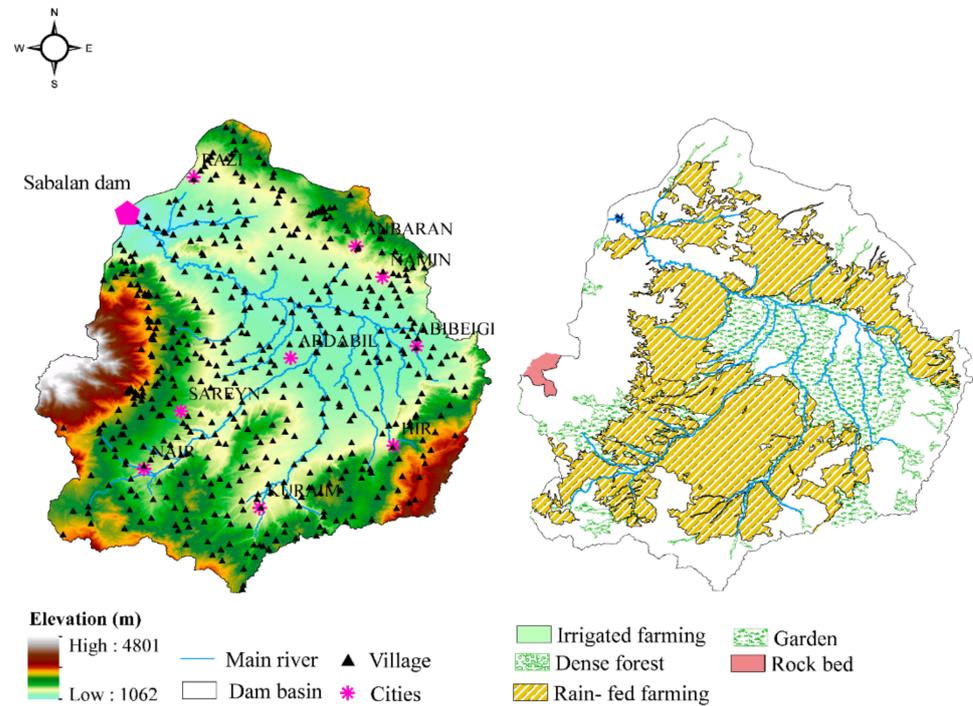


Figure 1. Basin of the Sabalan dam reservoir and digital elevation map of the basin.

### 2.2. Sampling

Based on the recommendations for selecting the sampling points in lakes/reservoirs, one sampling point was chosen at the deepest area of the reservoir and near the dam structure to investigate the nutrient concentration in SDR [27]. Sampling was performed during 12 occasions starting from 27 May 2017 to 5 August 2018. Due to sampling instrument constraints and weather conditions, sampling was not carried out in June 2017 as well as January and July 2018. TN and TP samples in the reservoir were taken at the depths of 0.5, 3, 6, 10, 15, 20, 25, and 35 m (Figure 2). Due to the dead storage zone in deep areas in the reservoir, we ignored sampling in depths >35 m.

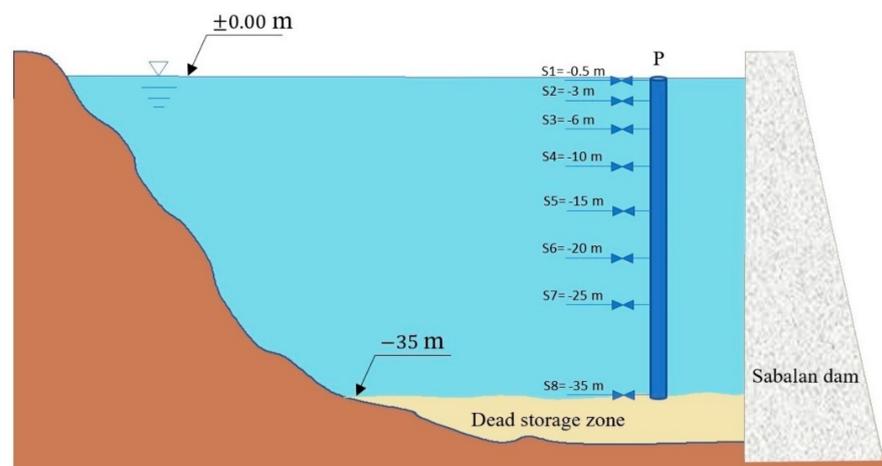


Figure 2. Schematic view of sampling points in different depths of the Sabalan dam reservoir.

To take TN and TP samples in different depths of the reservoir, a Hydro-Bios Water Sampler was used. All water samples were acidified by  $H_2SO_4$  to lessen the  $pH < 2$ , and kept in polyethylene containers. All water samples were stored in a refrigerator (with an ambient temperature around  $4\text{ }^\circ\text{C}$ ) during transportation to the certified laboratory by Iran's Department of Environment and analyzed within 48 h. Water sample analyses were performed based on the standard methods for the analyses of water-wastewater [28]. TN and TP were analyzed in the laboratory by 'Hach DR 5000™ UV-Vis Spectrophotometer'. Both TN and TP were measured in duplicate, and average values were used in this study.

To improve the accuracy of measurements in the laboratory, operating conditions (e.g., a comfortable and standard working environment for laboratory personnel and proper performance of instruments) were adjusted. To control the quality of the laboratory analyses, blanks (deionized water) were used, which showed an adequate recovery rate of 96–105% and a standard deviation of  $<5\%$ .

Detailed information on the samplings, analytical methods, data quality control, and TN and TP values measured are given in Noori et al. [11].

### 2.3. Nutrients and Trophic State Indices

The measured nutrient levels in the SDR were compared with those of the other reservoirs around the world. The eutrophication status was then investigated in the reservoir by averaging the nutrient levels in the epilimnion (depths of 0.5, 3, and 6 m). The trophic status in lakes is often specified by different indices such as nutrient concentration, Secchi depth, and the biomass concentration [29]. In this study, the lake fertility symptom was determined based on the CTSI [19]. This index is calculated based on TP, chlorophyll-*a* and Secchi depth, where TN is excluded. However, literature has shown that many lakes have co-deficiency of P and N and even N-deficiency [30–37]. To remedy this inconsistency in the assessment of trophic state in the SDR, we used nitrogen-based CTSI proposed by [38]. The TP- and TN- based Carlson trophic state indices are calculated via Equations (1) and (2), respectively [19,38].

$$CTSI(TP) = 10 \times \left[ 6 - \frac{\ln\left(\frac{48,000}{TP}\right)}{\ln(2)} \right] \quad (1)$$

$$CTSI(TN) = 10 \times \left[ 6 - \frac{\ln\left(\frac{1.47}{TN}\right)}{\ln(2)} \right] \quad (2)$$

where CTSI(TP) and CTSI(TN) are the TP- and TN- based Carlson trophic state indices, respectively.

In Equations (1) and (2), TP and TN should be given in mg/L. CTSI(TP) and CTSI(TN) range from 0 to 100. A lake is classified as 'oligotrophic', 'mesotrophic', 'eutrophic' and 'hypereutrophic' if they are less than 40, 40–50, 50–70, and 70–100, respectively [39].

The molar ratio of TN and TP, i.e., TN:TP, would specify which nutrient is the limiting factor and could cause a noticeable change in the intensity of production [40]. The eutrophication is limited by only N, or only P, and both of them when  $TN:TP < 10$ ,  $TN:TP > 21$ , and  $10 \leq TN:TP \leq 21$ , respectively [41]. Under particular circumstances, where TN and TP concentrations are more than 0.8 mg/L and 0.2 mg/L, respectively, eutrophication may not be controlled by nutrients. In these conditions, other environmental factors such as the WRT, sunlight, pH, and air temperature may boost eutrophication [42,43].

### 2.4. Statistical Analysis of the Data

In this study, we used all raw data measured during the 12 sampling occasions and no statistical reconstruction method was performed to fill the gaps. All calculations were done in the Microsoft Excel environment. Temporal variations in TP, TN, CTSI(TP), CTSI(TN), inflow to the reservoir and the elevation of water were plotted in the Microsoft Excel

environment. Spatiotemporal variation of TN:TP molar ratio in the SDR was plotted in the Python environment.

### 3. Results and Discussion

#### 3.1. Hyper-Nutrient Enrichment

The minimum, average, and maximum concentrations of TN measured in the SDR are 2.2 mg/L, 3.0 mg/L and 8.2 mg/L, respectively. Corresponding values of TP are 0.11 mg/L, 0.38 mg/L, and 1.85 mg/L. The highest variation of TN occurs in August 2018 with a standard deviation of 2.32 mg/L, when the reservoir is severely stratified (Figure 3A). The highest variation of TP throughout the water column is observed in November 2017 with a standard deviation of 0.63 mg/L, when the thermocline is attenuated by the deepening of epilimnion (Figure 3B).

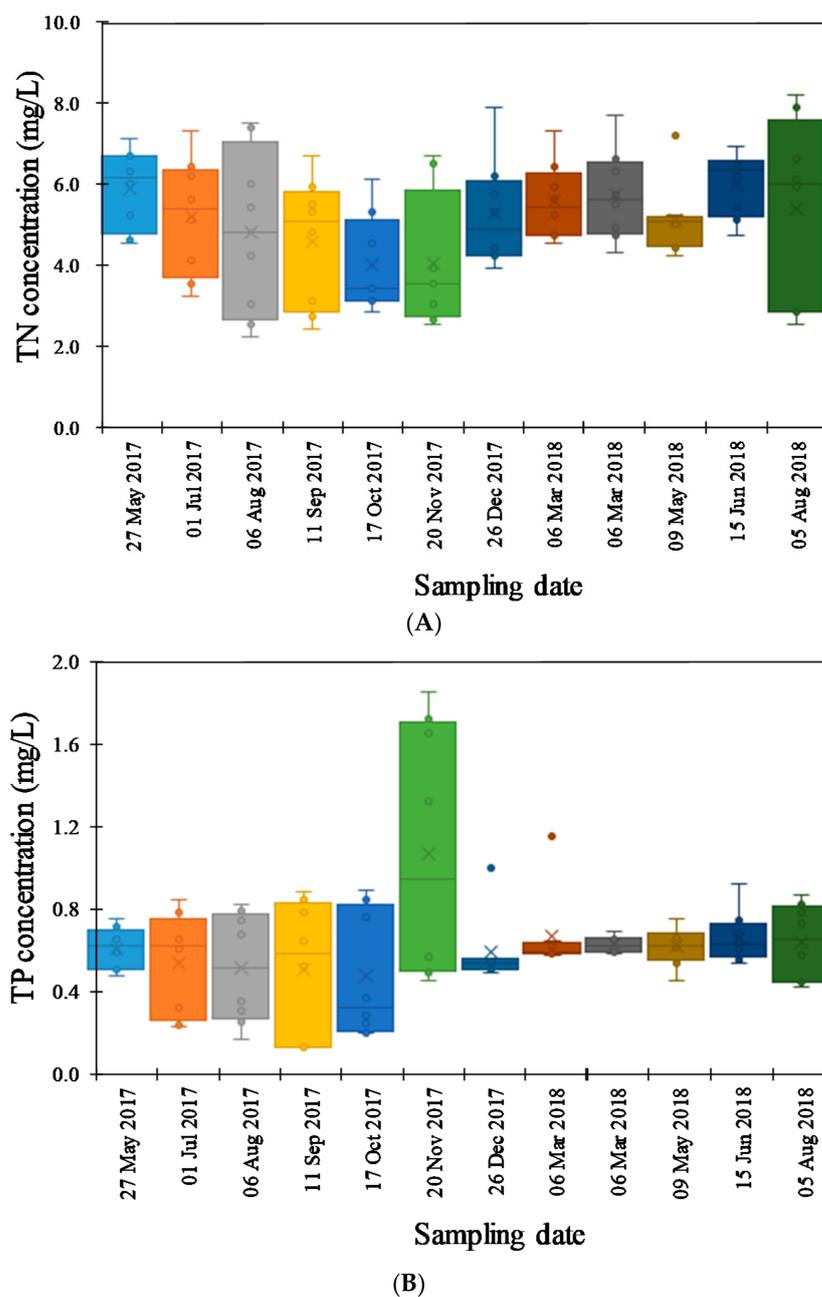


Figure 3. Variation of (A) total nitrogen (TN) and (B) total phosphorus (TP) concentrations throughout the water column in the Sabalan dam reservoir during the sampling periods.

Our findings clearly indicate the severity of nutrient enrichment in the reservoir. The HNE condition in the SDR is the result of agricultural activities in the dam watershed, leading to the discharge of large nutrient loads to the reservoir [11]. This is particularly important because fertilizers have often been overused in the reservoir watershed [4]. The utilized chemical fertilizers were doubled from 1990 to 2010 to increase the country's production [44]. In addition to fertilizers and manures, agricultural lands in different areas of Iran (such as the Sabalan reservoir watershed) are usually irrigated by nutrient-rich sanitary effluents. According to Thebo et al. [45], Iran has the highest number of croplands irrigated by effluents. This can increase the TN and TP concentrations in the reservoir watershed, and consequently the reservoir. In addition to the abovementioned nutrient external loads, in-reservoir (internal) loads can also contribute to the HNE in the SDR as suggested by Noori et al. [11]. In general, internal nutrient loads diffused out from the bed sediments can contribute to lake fertilizer even in the case of a reduction in external nutrients brought from the lake upstream [46–48].

The national policy on increasing domestic food production [4] as well as the fertilizer overuse to nourish nutrient-poor soil [49] can even further elevate nutrient inputs to the SDR in the future. Few wastewater treatment plants exist to purify the residential and industrial wastewaters in the study area. These residential, industrial and agricultural effluents directly discharge into both groundwater and surface water resources in the reservoir watershed. More specifically, the direct discharge of nutrient-rich fish farming effluents (located close to the reservoir inlet) also enriches the reservoir water by TN and TP. Due to a severe decline in the watershed groundwater table in the last decades [50,51], it is most likely that no groundwater discharge fertilizes the SDR water.

To clearly picture the HNE condition in the reservoir, we compared the TN and TP measurements in the SDR with those of the other reservoirs around the world (Table 1). According to this table, TN and TP levels in the SDR are more than those reported in all of the other reservoirs, except for Four Midwestern United States reservoirs.

**Table 1.** Total nitrogen (TN) and total phosphorus (TP) concentration in some selective reservoirs around the world.

Study Area	Sampling Details	Sampling Period (Interval)	TN (mg/L)	TP (mg/L)	Reference
Sabalan reservoir, Iran	Water column	2017–2018 (monthly)	Mean = 4.2 Max = 8.8 Min = 2.0	Mean = 0.61 Max = 1.85 Min = 0.11	This study
Sabalan reservoir, Iran	Surface layers	2017–2018 (monthly)	Mean = 3.1 Max = 4.6 Min = 2.0	Mean = 0.39 Max = 0.61 Min = 0.11	This study
Paldang reservoir, South Korea	Surface layers	1996–2019 (annually)	Mean = 2.3 Max = 2.8 Min = 1.9	Mean = 0.043 Max = 0.071 Min = 0.028	Mamun et al. [52]
Keban dam reservoir, Turkey	Water column	1991–1993 (seasonally)	Mean = 3.7 Max = 12 Min = 2	Mean = 0.11 Max = 0.175 Min = 0.025	Akbay et al. [53]
Dam reservoir of Sulejów, Poland	Water column	2009–2013 (monthly)	Mean = 2.46 Max = 6.72 Min = 0.1	Mean = 0.138 Max = 0.45 Min = 0.01	Mankiewicz-Boczek et al. [54]
Iron Gates I reservoir, Romania	Water column	2001 (bimonthly)	Mean = 1.35 Max = 1.6 Min = 0.7	Mean = 0.12 Max = 0.16 Min = 0.032	Teodoru and Wehrli [55]
Batman dam reservoir, Turkey	Surface layers	2008–2009 (bimonthly)	Mean = 0.67 Max = 1.088 Min = 0.217	Mean = 0.061 Max = 0.136 Min = 0.016	Varol [56]
Four Midwestern United States reservoirs	Surface layers	2001–2012 (monthly)	Mean = 1.68 Max = 7.96 Min = 0.16	Mean = 0.103 Max = 1.77 Min = 0.014	Harris et al. [57]

Table 1. Cont.

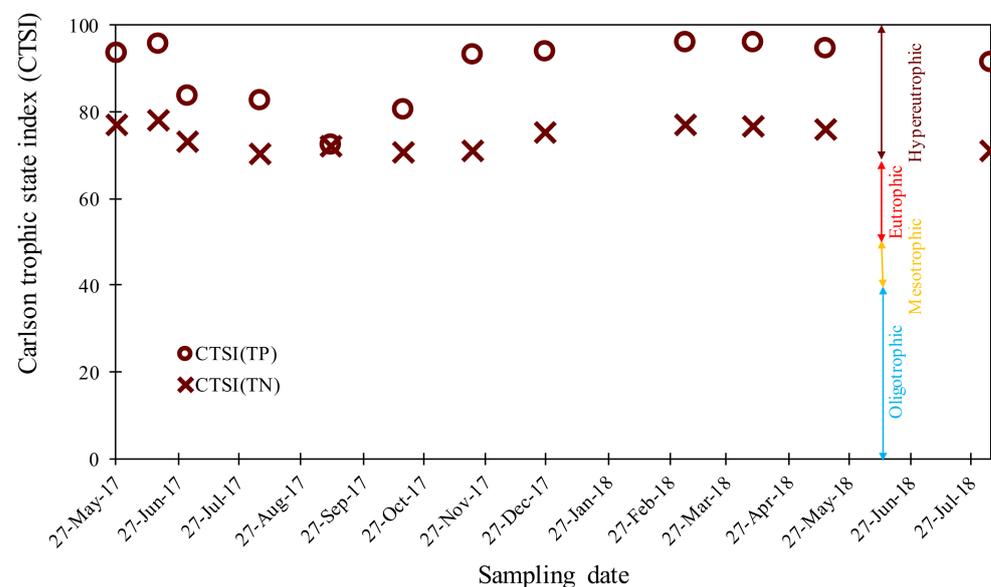
Study Area	Sampling Details	Sampling Period (Interval)	TN (mg/L)	TP (mg/L)	Reference
Gilgel Gibe reservoir, Ethiopia	Surface layers	2014–2015 (seasonally)	Mean = 1.606 StD = 0.17	Mean = 0.184 StD = 0.015	Woldeab et al. [58]
Seven reservoirs in subtropical southeast Queensland, Australia	Water column	2004–2005 (seasonally)	Mean = 0.48 StD = 0.066	Mean = 0.024 StD = 0.016	Burford et al. [59]
Three dams constructed over Mimi River, Japan	Surface layers	2012–2014	Mean = 0.25 Max = 0.40 Min = 0.15	Mean = 0.035 Max = 0.2 Min = 0.005	Nukazawa et al. [60]
Three Gorges Reservoir, China	Surface layers	2015 (autumn)	Mean = 1.485 StD = 0.309	Mean = 0.128 StD = 0.013	Huang et al. [61]
Xin'anjiang Reservoir, China	Surface layers	2013–2014 (randomly)	Mean = 1.017 Max = 1.783 Min = 0.661	Mean = 0.019 Max = 0.066 Min = 0.002	Li et al. [62]
Hanfeng dam reservoir, China	Surface layers	2013–2014 (seasonally)	Mean = 1.95 Max = 3.51 Min = 1.05	Mean = 0.138 Max = 0.33 Min = 0.05	Li et al. [63]
Dongting lake, China	Surface layers	2004–2018 (randomly)	Mean = 1.46 Max = 2.05 Min = 1.12	Mean = 0.1 Max = 0.17 Min = 0.03	Geng et al. [64]
Lake Cedrino, Italy	Water column	2010–2011 Monthly	Mean = 2.371 Max = 2.026 Min = 0.681	Mean = 0.101 Max = 0.296 Min = 0.027	Padedda et al. [65]
Klamath river dam, USA	Surface layers	2010–2011 (monthly)	Mean = 1.26 Max = 2.79 Min = 0.69	Mean = 0.10 Max = 0.15 Min = 0.07	Oliver et al. [66]
Missouri reservoir, USA	Surface layers	1978–2002 (annually)	Mean = 0.7 Max = 2.330 Min = 0.200	Mean = 0.045 Max = 0.182 Min = 0.006	Jones et al. [67]
Tenango Dam, Mexico	Surface layers	June 2015		Mean = 1.51 StD = 0.65	Muñoz-Nájera et al. [68]
Nigeen Lake, India	Surface layers	May to November 2015		Min = 0.104 Max = 0.688	Dar et al. [69]
Lhasa River Dam, Tibet	Sediment	August 2017	Mean = 1.5 StD = 0.057	Mean = 0.0512 StD = 0.0024	Tao et al. [70]
Nanla River, China	Surface layers	2019 Monthly	Mean = 1.37 StD = 1.13	Mean = 0.18 STD = 0.12	Wang et al. [71]
Delaware, USA	Water column	March 1982–October 1983	Mean = 0.035 StD = 0.012	Mean = 0.0014 StD = 0.003	Fisher et al. [72]
Mississippi River, USA	Surface layers	21 July–1 August 1987	Mean = 0.176 StD = 0.182	Mean = 0.319 StD = 182	Dortch and Whitlege [73]
Three Gorges Dam, China	Surface layers	2003–2015 monthly	Max = 1.3 Min = 0.64	Max = 0.110 Min = 0.046	Ding et al. [74]
Three Gorges Reservoir, China	Surface layers	April 2010	Mean = 0.865 Max = 1.903 Min = 0.127	Mean = 0.592 Max = 1.365 Min = 0.205	Zhang et al. [75]
4 Multipurpose Reservoirs, Korea	Surface layers	2015–2017 monthly	Mean = 1.85 Max = 3.45 Min = 0.57	Mean = 0.018 Max = 0.147 Min = 0.003	Mamun et al. [76]
Lake Taihu, China	Epilimnion layer	April 2017–September 2018 monthly	Mean = 0.70 Max = 1.40 Min = 0.32	Mean = 0.05 Max = 0.1 Min = 0.02	Yang et al. [77]
Bzura River, Poland	Surface layers	2010–2012 and 2014–2016 biweekly	Mean = 1.15 StD = 0.28	Mean = 0.26 StD = 0.09	Jurczak et al. [78]
Danjiangkou Reservoir, China	Surface layers	2015–2018 May and Sep	Mean = 1.69 Max = 5.99 Min = 0.76	Mean = 0.09 Max = 0.36 Min = 0.02	Li et al. [79]

Table 1. Cont.

Study Area	Sampling Details	Sampling Period (Interval)	TN (mg/L)	TP (mg/L)	Reference
Three Gorges Reservoir, China	Surface layers	August 19 e September 12, 2018	Mean = 1.49 StD = 0.031	Mean = 0.13 StD = 0.01	Nwankwegu et al. [80]
Grand Lake, Oklahoma, USA	Surface layers	June–October 2011 monthly	Mean = 0.642 Max = 1 Min = 0.3	Mean = 0.077 Max = 0.13 Min = 0.04	Nikolai and Dzialowski [81]
Jiangdong Reservoir, China	Surface layers	April to August 2016 daily	Mean = 2.53 StD = 0.33	Mean = 0.15 StD = 0.02	Yan et al. [82]
King Talal Dam, Jordan	Surface layer	2007–2008 (seasonally)	Mean = 59.1 StD = 8.23	Mean = 5.6 StD = 0.45	Abu Hilal et al. [83]
Gezhouba Dam, China	Surface layer	2008–2009 (Monthly)	Mean = 1.8 StD = 0.03	Mean = 0.18 StD = 0.01	Hu et al. [84]
Soyang reservoir, South Korea	Surface layer	1992–2013	Mean = 1.5 Max = 2.9 Min = 0.73	Mean = 0.017 Max = 0.237 Min = 0.001	HaRa et al. [85]

### 3.2. Trophic State of the Sabalan Reservoir

To determine the trophic status in the Sabalan reservoir, the mean values of TN and TP in the epilimnion (at the depths of 0.5, 3, and 6 m) were used during each sampling campaign. CTSI(TP) and CTSI(TN) varied from 72 to 96 and 68 to 78, respectively. CTSI(TP) was higher than CTSI(TN) in all of the sampling campaigns (Figure 4). The temporal variability of CTSI(TP) with the variation coefficient of about 8.6% was more than that of CTSI(TN). According to Figure 4, all CTSI(TP) and CTSI(TN) values exceed 70, putting the SDR in a hypereutrophic state. Similar results were reported by Noori et al. [11] where they used the TP and TN thresholds (suggested by Vollenweider [86]) to distinguish the eutrophication occurrence in the SDR.



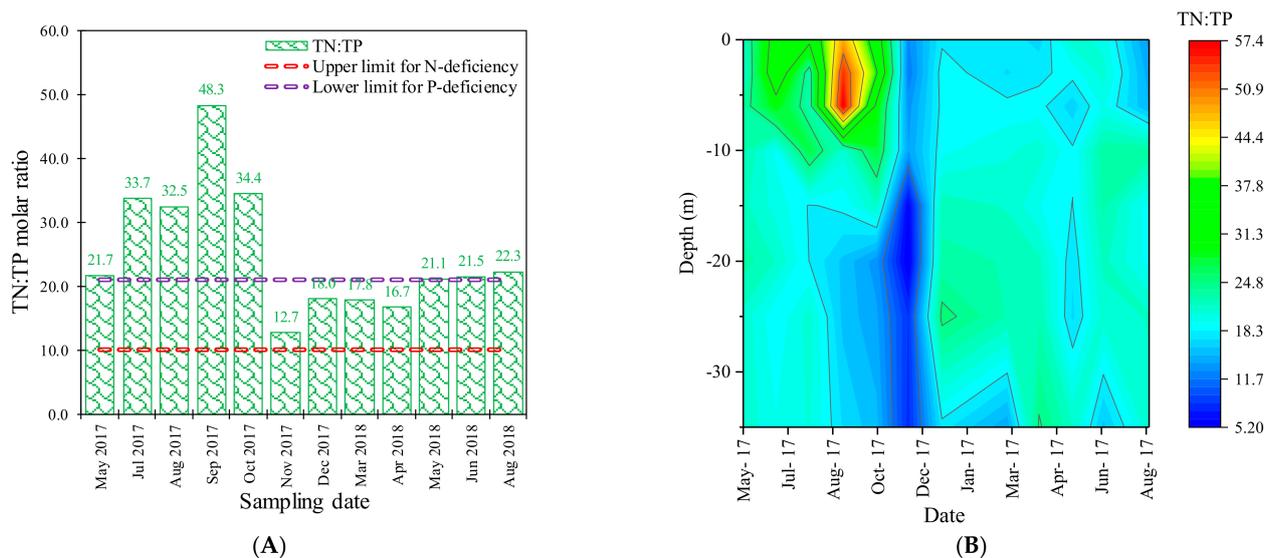
**Figure 4.** TP- and TN- based Carlson trophic state indices (CTSI(TP) and CTSI(TN)) calculated for mean values of TP and TN measurements in the epilimnion (at the depths of 0.5, 3, and 6 m) during each sampling campaigns.

CTSI(TP) and CTSI(TN) should be theoretically equal. However, CTSI(TP) and CTSI(TN) measurements in the SDR are unequal. The inconsistency between them is because CTSI(TP) was developed primarily based on the data on P-deficiency lakes [19], while the CTSI(TN) was mainly modified on the basis of the N-deficiency lakes [38]. However, in our case study, both indicators suggest that the SDR is a hypereutrophic lake.

It should be noted that no chlorophyll-*a* data, as the main indicator of eutrophication, was available to further verify the hypereutrophic state calculated based on TP and TN in the SDR. As described earlier, chlorophyll-*a* is a main factor in calculation of the CTSI in lakes. However, based on our field observations, the sampling device used (i.e., Hydro-Bios Water Sampler) was not visible at few meters below the water surface during 12 sampling occasions. This justifies the lack of effective light penetration due to the severe algal turbidity in the reservoir. In addition, unpublished field data and evidence declared by the dam operators confirm the hypereutrophic state in the SDR for almost the entire year.

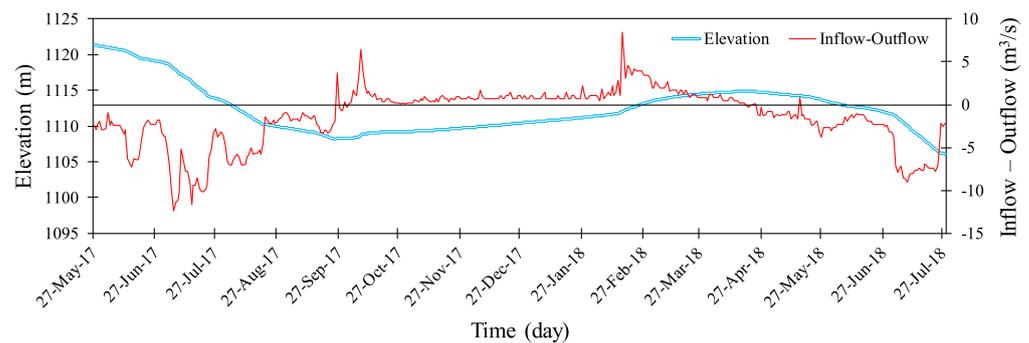
### 3.3. Limiting Factor

TN:TP (molar) ratios averaged at the epilimnion (at the depths of 0.5, 3, and 6 m) during the sampling periods are shown in Figure 5A. P-deficiency, i.e., TN:TP > 21, was observed in warm months (May to October), while the ratio suggests a co-deficiency of P and N in cold months (November to April), i.e.,  $10 \leq \text{TN:TP} \leq 21$ . Despite the common understanding about P-deficiency in inland waterbodies [18,87,88], a co-deficiency of P and N was dominant in the SDR. Figure 5B also shows a general decreasing trend for the TN:TP molar ratio with the depth of reservoir. Surface and bottom layers experienced the maximum and minimum values of TN:TP molar ratio, respectively. The same decreasing trend of TN:TP ratio with depth was also observed in some lakes such as Lake Victoria [88] and Lake Superior [89].



**Figure 5.** (A) Total nitrogen (TN) to total phosphorus molar ratio (TN:TP) averaged at the epilimnion (at the depths of 0.5, 3, and 6 m) in the Sabalan reservoir, and (B) TN:TP molar ratio through depth of the reservoir.

A relationship between TN:TP ratio, inflow to reservoir, and water level can be observed in Figure 6. The reservoir experiences a sharp drop in water level from May 2017 to the late September 2017 due to low inflow to the reservoir (inflow  $\sim 0$ ). During this period, P-deficiency can be observed in the SDR (Figure 5A). By the increase of inflow and water level in cold months, P-deficiency turns to the co-deficiency of P and N in the reservoir. Finally, P-deficiency in the reservoir is again dominated by the start of warm months and water level drop in May 2018. Phosphorus compounds are relatively less soluble in water than nitrogen compounds. Hence, they are transferred from watersheds to reservoirs/lakes in a more dissolved form compared to nitrogen compounds during the high flow events [90]. Therefore, the decline in inflow decreases TP more than TN in the SDR, leading to a P-deficiency in the reservoir during the warm months. It is worth noting that changes in the inflow may also contribute to the conspicuous differences in TN:TP molar ratios observed at the same months in Figure 5A.



**Figure 6.** Inflow to the reservoir and the elevation of water throughout the study period.

Given the high concentration of nutrients ( $TN > 0.8$  mg/L and  $TP > 0.2$  mg/L) in the SDR, other factors such as the WRT may contribute to eutrophication in the reservoir [42,43]. It should be noted that WRT in SDR varied from hundreds to thousands of days during the study period [11]. The increase of WRT in Iran's reservoirs such as the SDR is mainly due to significant changes in the quality of upstream flow in the planning and operation phases of dams, named as "mirage water" [91]. In this regard, it takes a long time to fill up the SDR because of low inflows. Meanwhile, reservoirs/lakes with the same and even larger storage capacity than that of the SDR have much smaller WRT, i.e., tens to at most a few hundred days [92–96]. The longer the WRT, the more suitable conditions for algal reproduction, colonization and growth in lakes/reservoirs [6,7,97]. In addition, the WRT is positively proportional to water level fluctuations as well as nutrient accumulation in the reservoirs. Therefore, the long WRT in the SDR can contribute to the nutrient accumulation and eutrophic condition in the reservoir. Hence, shortening the WRT constrains algal growth and reproduction in the SDR. The results reported for other lakes/reservoirs around the world also show that although nutrients are significant for eutrophication, the WRT is a more effective factor in controlling the lake/reservoir's trophic state than the nutrients [98–101]. It should be noted that no chlorophyll-*a* data was available to further verify which factor dominantly controlled eutrophication in the SDR. Thus, we suggest further investigation using chlorophyll-*a* data to undertake this process.

#### 4. Conclusions

Hyper-nutrient enrichment exposes the lakes/reservoirs to eutrophication. This study explored the state of nutrients in the SDR, Iran. Findings highlighted a state of the HNE in the SDR. Nutrient concentrations measured during the sampling periods in the SDR were higher than those reported in other reservoirs around the world. Our observations showed phosphorus was a limiting factor in warm months due to the severe decline of inflows to the reservoir from the upstream watershed. During cold months, the co-deficiency of phosphorus and nitrogen was observed in the SDR. Given the HNE state in the reservoir, we investigated other possible controlling factors in the SDR. We found the long WRT in the SDR could act as the main driver of eutrophication. Extensive agriculture developments as the primary nonpoint nutrient source, untreated wastewater inputs and nutrient-rich fish farming effluents contribute to the HNE in SDR. These drivers as well as the long WRT (induced by inappropriate operations undertaken to supply more water) have caused the hypereutrophic state of the reservoir, although it was impounded in 2006. Given time consuming and expensive management practices for reducing nutrients in the watershed, changes in the SDR operation are suggested to somewhat recover its hypereutrophic state in the short-term. However, controlling nutrients from the watershed should be undertaken in the long-term restoration of the SDR since it is the fundamental cause of the hypereutrophic state in the reservoir. Moreover, even if the nutrients are flushed out of the reservoir by modulating WRT, it would still create issues in the downstream receiving waters.

The findings from this study were based on the nutrient data in the SDR. No chlorophyll-*a* data, as the main indicator of eutrophication, was available to further verify the results on the trophic state and limiting factors. Thus, we suggest further investigation using chlorophyll-*a* data to clarify the causes of the alarming trophic state observed in the reservoir.

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