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A Computational and Applied Approach to Determining the Pollution Load in Urban Wastewater Management in Van Province

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ABSTRACT

This study evaluates pollution loads from point sources in the İpekyolu, Tuşba, and Edremit districts of Van Province by comparing both calculated and measured data. In this context, chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), and suspended solids (SS) loads were calculated using pollution design coefficients. The urban wastewater from these districts is also treated at the Van Central Advanced Biological Wastewater Treatment Plant (WWTP), and the pollution loads received and discharged from the plant were measured and compared with regulatory values. As a result, the total pollution load discharged into Lake Van was determined to be 4037 tons/year for COD, 576 tons/year for TN, 96 tons/year for TP, and 1121 tons/year for SS. The measured pollution load at the plant outlet was determined to be 2737 tons/year for COD, 391 tons/year for TN, 43 tons/year for TP, and 608 tons/year for suspended solids (SS). The calculated values for TN and TP loads exceed the specified limit values.

Van İli Kentsel Atıksu Yönetiminde Kirlilik Yükü Tespitine Yönelik Hesaplamalı ve Uygulamalı Yaklaşım

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ÖZ

Bu çalışmada; Van ilinin merkeze bağlı İpekyolu, Tuşba ve Edremit ilçelerinin noktasal kirlilik kaynaklarından kentsel atıksuların kirlilik yükleri hesaplamaya ve gerçek ölçüm verilerine dayalı karşılaştırılarak değerlendirilmiştir. Bu kapsamda kirlilik yüklerini temsilen kimyasal oksijen ihtiyacı (KOİ), toplam azot (TN), toplam fosfor (TP) ve askıda katı madde (AKM) yükleri kirlilik tasarım katsayıları kullanılarak hesaplanmıştır. Bu ilçelerin kentsel atıksuları aynı zamanda Van Merkez İleri Biyolojik Atıksu Arıtma Tesisi (AAT)'nde arıtılmakta olup, tesise gelen ve deşarj edilen kirlilik yükleri de ölçülmüş ve mevzuat değerleri ile mukayese edilmiştir. Sonuç olarak Van Gölü'ne deşarj edilen; KOİ için hesaplanan toplam kirlilik yükü miktarı 4037 ton/yıl, TN için 576 ton/yıl, TP için 96 ton/yıl ve AKM için 1121 ton/yıl olarak belirlenmiştir. Tesis çıkışında KOİ için ölçülen kirlilik yükü miktarı 2737 ton/yıl, TN için 391 ton/yıl, TP için 43 ton/yıl ve AKM için 608 ton/yıl olarak tespit edilmiştir. TN ve TP yükleri için hesaplanan değerler belirlenen sınır değerlerin üzerindedir.

1. INTRODUCTION

Today, rapid population growth, industrialization, and urbanization have led to significant decreases in both the quantity and quality of available water [1]. In our country, groundwater and surface water are exposed to pressure from natural and human-induced (anthropogenic) pollution sources. The Mediterranean Basin, including Türkiye, is facing serious effects of climate change. In the worst-case scenario, Türkiye is projected to face water scarcity as early as 2040 [2]. Considering these critical assessments of water resources, watershed-scale water resource management is becoming increasingly important. The concept of a watershed encompasses the entire drainage area from a river's source to its point of discharge. Effective watershed management is vital for the conservation and sustainable use of water resources, both in terms of quantity and quality [3,4]. The first step in improving and protecting water quality is to identify and control point and diffuse sources of pollution. To determine pollution from these sources, various methods are used, ranging from simple calculations based on unit pollution loads to complex models with varying sensitivities [5,6]. Point source discharges generally originate from municipal and industrial wastewater. Since municipal wastewater is transported through sewer systems, these types of discharges are classified as point sources. In contrast, wastewater from settlements without sewerage and infrastructure systems is considered a diffuse source. Assessing the amount of pollutants transported from point sources to receiving environments is crucial for the protection and sustainable management of water resources and ecosystem health. In systems in which urban or industrial wastewater is discharged directly after treatment, annual pollution loads should be calculated by considering both pollutant concentrations and discharge flow rates. There must be sufficient facilities to treat wastewater classified as point sources of pollution, and these facilities must demonstrate effective treatment performance to ensure that treated water is safely discharged into surface and groundwater. Such load calculations are necessary for assessing the carrying capacity of water bodies, understanding ecosystem pressures, and formulating effective water quality management plans [7].

Nitrogen and phosphorus pollution in aquatic environments can originate from point sources such as wastewater treatment plants and diffuse sources such as agricultural runoff. Nutrients enter receiving water bodies through atmospheric deposition, point sources, and land use activities. Among these, agriculture and livestock farming contribute most significantly to the pollution of receiving environments. Additionally, wastewater from settlements without sewage connections and water leaking from waste disposal areas contribute to the accumulation of nutrients in receiving water bodies [8]. Therefore, it is necessary to calculate the quantitative loads of diffuse and point source pollution that exert pressure on surface and groundwater bodies. However, a review of the literature reveals that most studies focus either on assessing water quality [9,10] or identifying pollution originating from specific sources [11]. This situation negatively impacts biological diversity and water quality, reducing the recreational and water supply value of water bodies. Due to increasing risks to water resources, one of the fundamental elements of life, the European Parliament and Council published the Water Framework Directive (WFD) 2000/60/EC on October 23, 2000, which "establishes a framework for Community action in the field of water policy management." The primary objective of this directive is to establish a legal framework for the protection of surface and groundwater, as well as coastal and transitional waters; to protect water ecosystems and prevent their pollution; to ensure sustainable water use; to improve the quality of water ecosystems; and to develop a comprehensive approach to mitigate the potential impacts of disasters such as floods and droughts [12]. Türkiye, which is a candidate for European Union (EU) membership, must bring its water legislation into line with the EU Water Framework Directive (WFD) [13].

Existing studies evaluating urban water and wastewater infrastructure in the region address criteria such as infrastructure services, treatment rates, and per capita wastewater volume. However, these studies primarily focus on infrastructure or service levels; they do not sufficiently evaluate post-treatment discharge loads and the ecological pressures on the lake. This situation reveals a mismatch between water quality and ecosystem health on the one hand, and the performance of wastewater infrastructure on the other [14]. There are a limited number of studies examining the relationship between pollution sources and water quality. In the international literature, nutrient loads (nitrogen and phosphorus) from point sources in closed and river basin systems are generally determined using mass balance methods and various modeling approaches. These models incorporate components such as soil-water transport, flow dynamics, and characteristics of the receiving environment to accurately quantify the contribution of wastewater discharged from wastewater treatment plants to the total nutrient load [15]. Furthermore, determining the nutrient composition (organic, inorganic, and bioavailable fractions) in treated wastewater is crucial for assessing the risk of eutrophication in the receiving water body [16].

Lake Van is designated as one of five sensitive basins in the Urban Wastewater Treatment Regulation. Due to its closed-basin structure, high alkalinity (sodium carbonate composition), and limited water circulation, the Lake Van Basin is highly sensitive to changes in water quality and pollutant accumulation. Due to its closed nature and lack of any natural outlets, its pollution potential is significantly increased. The chemical properties and flow rate or volume of water resources in the basin are crucial for assessing the potential impacts of pollutant loads entering the lake. For example, when the water chemistry of saline resources in the basin is examined, the large differences in parameters such as pH, electrical conductivity, and dissolved oxygen highlight the sensitivity of the water body [17]. Many factors contribute to the pollution of water resources in the Lake Van basin. Among these, the inadequate treatment and subsequent discharge of wastewater from settlements around the lake is prominent [18].

This study investigated, through calculations and measurements, whether point source urban wastewater from the districts of Tuşba, İpekyolu, and Edremit in Van province has a significant impact on the organic load of Lake Van, located within the Lake Van Basin. In this context, pollution loads resulting from organic pollutant parameters such as chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), and suspended solids (SS) were both calculated and evaluated by comparing measurement-based data. Furthermore, discharge data obtained from the calculation and measurement of pollution load parameters were compared with the limit values specified in the Water Pollution Control Regulation (WPCR) and the Municipal Wastewater Treatment Regulation (MWWTR). This study aims to determine the carrying capacity of the receiving environment, specifically in the Van Lake Basin, and to identify potential harmful effects on the lake ecosystem. It is expected that these results will inform water quality management in the region, improve treatment processes, support lake protection strategies, and guide regulatory decision-making.

2. METHOD

2.1. Study Area

Van Province is located between 42° 40' and 44° 30' east longitude and 37° 43' and 39° 26' north latitude. Located in southeastern Eastern Anatolia, the basin encompasses the catchment areas of rivers that flow into Lake Van. In Türkiye, it is located in the Upper Murat-Van section of the Eastern Anatolia Region, within the closed basin of Lake Van. Lake Van is a volcanic lake formed by the accumulation of water in a crater created by the volcanic eruption of Mount Nemrut, located on the border between the provinces of Bitlis and Van [19]. Lake Van, known as the world's largest soda lake, also has saline water properties and is located at an elevation of approximately 1,725 meters above sea level [20]. The Van Lake Basin covers an area of 17,964 km² and has an average annual rainfall of 474 mm and an average annual flow rate of 95.32 m³/s. The annual precipitation in the basin is 6.25 L/s/km^2, with a precipitation ratio of 0.42% and a contribution to runoff of 1.64%. The Van Lake Basin covers the provinces of Van, Bitlis, and Ağrı [18]. The sewer network in Van Province, approximately 1,960 kilometers long, collects wastewater from various sources, directs it to collector lines, and transports it to treatment plants. Construction work on the sewer networks and collector lines is still ongoing. Van Metropolitan Municipality VASKİ General Directorate is conducting operational activities at existing wastewater treatment plants in various districts to prevent pollution caused by wastewater. Extended aeration activated sludge treatment plants are in operation in Van (Center), Edremit, Başkale, Erciş, Gevaş, and Çelebibağı. The system, which operates using the activated sludge process, consists of mechanical and biological units, and the treated wastewater from the treatment plant is discharged into the lake. During treatment, a portion of the sludge generated is transported to conventional storage areas, while another portion is stored in drying beds. Efforts to dispose of the mud are ongoing. The wastewater treatment plant project for Çatak District has been completed, and construction is ongoing. Similarly, wastewater treatment plant projects for Bahçesaray, Çaldıran, Gürpınar, Muradiye, and Saray Districts have also been completed. All wastewater from the central districts of Van Province, namely İpekyolu and Tuşba, and part of the wastewater from Edremit District is treated at the Van Central Advanced Biological Wastewater Treatment Plant in Tuşba District and then discharged into the lake (Figure 1) [21].

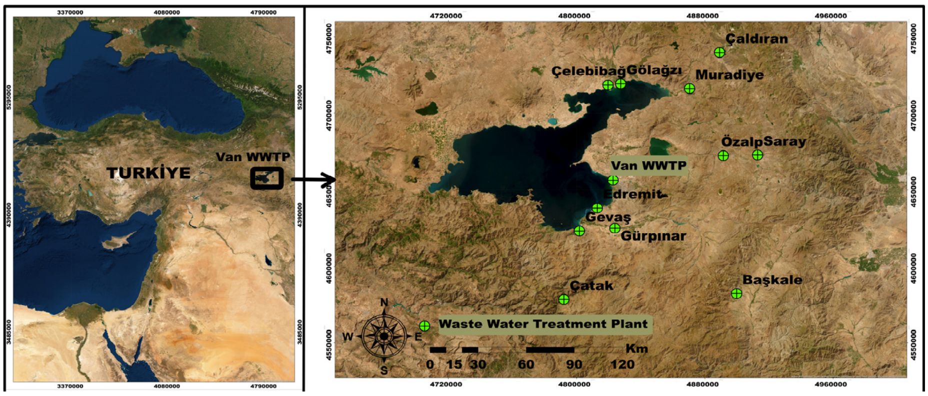

Figure 1. Location of wastewater treatment plants in van province and districts

2.2. Van Central Advanced Biological Wastewater Treatment Plant

The Van Central Advanced Biological Wastewater Treatment Plant was commissioned in 2021 and is located in the İskele neighborhood of Tuşba district. It was designed to serve a population equivalent of approximately 1,050,000 people and was constructed with a design capacity of 114,000 m³/day. In line with future flow projections, the plant is designed to reach a maximum capacity of 193,000 m³/day by 2026. The wastewater treatment plant is designed in two phases, 2026 and 2046, to meet long-term needs. The flow diagram of the Van Central Advanced Biological Wastewater Treatment Plant is shown in Figure 2, and images of the plant are shown in Figure 3. The facility has a pretreatment unit comprising a stone trap, a coarse screen, and perforated screens, as well as an inlet pumping station. This is followed by an aerated sand-and-oil trap, a flow-meter structure, anaerobic tanks, aeration tanks, and final settling tanks. Another component of the treatment process is the return-and-excess-sludge pumping station, which includes a chlorine contact tank. The sludge line also features sludge dewatering units. The facility also includes a transformer-generators building, workshop building, blower building, administration building, and a continuous wastewater monitoring system (CWMS) cabin. The 93.44 m³ stone trap, positioned before the coarse and perforated screens at the plant entrance, forms the first stage of the pre-treatment process by retaining large materials such as sand, gravel, and similar substances. Six mechanical cleaning grates, one of which is spare, are designed with ropes. The grate bars are made of 10x50 mm stainless steel plates and are designed at a 75 ° angle to the horizontal, with 40 mm spacing between bars. Fine grates are located after the inlet pumping station. The spacing of the fine perforated screens selected as the perforated type has been set to 8.0 mm to ensure efficient operation of biological treatment units and the sludge process. The screen structure is equipped with a waste conveyor and a screen press. The perforated screens are designed to allow five units to operate simultaneously at the Q_{max} flow rate in the second stage and two units at the Q_{min} flow rate. In the first stage, four screens are designed to operate continuously, while one screen is designed to be used alternately for maintenance and malfunction situations. The intake pumping station is designed with six pumping units, each with a capacity of 109 kW, to handle the total hydraulic load.

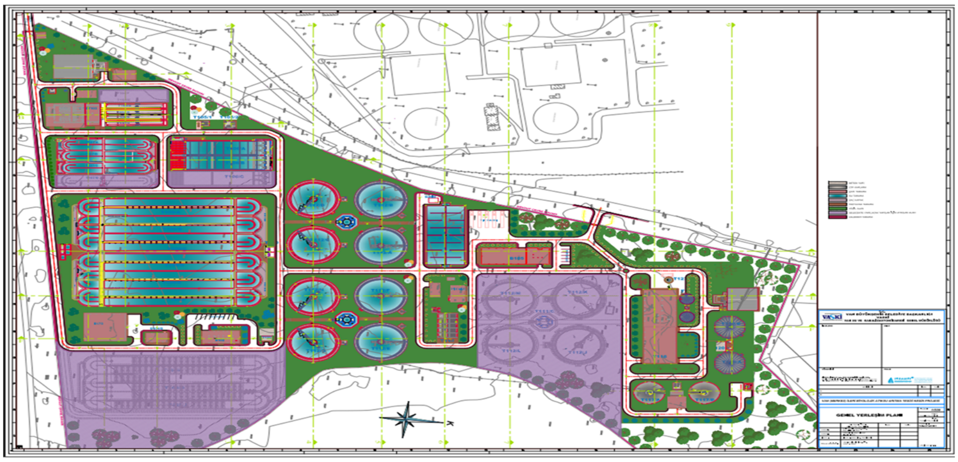

Figure 2. Van Central Advanced Biological WWTP flow diagram

Aerated sand and oil separators are designed to separate sand, gravel, and similar materials from wastewater entering the treatment plant, and to remove oils present in the wastewater, preventing their passage to downstream units. Four sand separators have been sized for the first stage, and six sand separators have been sized for the second stage. The volume of the aerated sand and oil separators has been designed as 315.12 m³. To minimize filamentous bacterial growth in wastewater entering the treatment system and to homogenize the wastewater, selector tanks with a total volume of 3062.12 m³ have been used. Anaerobic phosphorus tanks have been designed with a volume of 3062.12 m³, with 2 for Stage I and 3 for Stage II. Aeration tanks have been designed with 6 for the first stage and 9 for the second stage, each with a volume of 11333 m³ and capable of operating independently.

The process tanks are designed for the pre-denitrification A^2O system and are planned to operate as simultaneous denitrification (stepwise feeding) systems when required. Settling tanks are planned for 8 units in the first-stage year (2026) and 12 units in the second-stage year (2046), with each settling tank designed to have a volume of 3,889.66 m³. The recirculation unit is designed to be equipped with 6 lift pumps, each with a capacity of 109 kW. The chlorine contact tank is sized to a volume of 2,817 m³, based on a 20-minute retention time, to ensure completion of chemical reactions. A mechanical thickener was used to thicken the sludge taken from the final settling tank. The mechanical thickener was designed to bring the excess sludge taken from the settling tank, which had a dry matter content of 1% 1000 mg/L; SVI (sludge volume index) = 110 mL/g) to 5%. Mechanical sludge thickener: A total of 3 units will be commissioned in Stage I (2 main + 1 spare), and a total of 4 units will be commissioned in Stage II (3 main + 1 spare). The RWMS (Remote Wastewater Monitoring Station) cabin continuously measures pH, temperature, conductivity, COD, BOD, and dissolved oxygen in wastewater and transmits the data to the Ministry's system. Two peristaltic suction pumps operating in shifts convey wastewater to the sample-filling cell, which allows vertical flow via PPR-T lines. The flow rate on the line is measured using a flow meter, transmitted to the SCADA screen, and simultaneously sent to the Ministry system.

Figure 3. Van Central Advanced Biological WWTP visuals

2.3. Methodology

Van Province comprises 13 districts, 3 of which are central districts. The 2025 population data for the districts of Edremit, İpekyolu, and Tuşba, which are affiliated with the central district, were obtained from the district-based demographic data of the Turkish Statistical Institute [21] and are shown in Table 1.

Table 1. TSI population data for the central districts of Van province [22]

District	Number of people	Percentage (%)
Tuşba	165 885	15
İpekyolu	356 977	32
Edremit	130 768	12
Van province total	1.118.087	100

The pollution loads for the central districts of Van Province were calculated using four parameters: COD, TN, TP, and SS. For these, the removal efficiencies reported in Table 2 and the design coefficients, such as pollution load, reported in Table 3, from the literature were used [23-26].

Pollution loads for the central districts of Van Province were calculated using four parameters: COD, TN, TP, and SS. The calculations were based on the values specified in the "Technical Procedures Circular for Wastewater Treatment Plants" dated March 20, 2010. According to Table 2.1 of this Circular, titled "Variation of Wastewater Generation and Pollution Loads Depending on Population," removal efficiencies representing wastewater and per capita pollution loads based on population values are provided (Table 2) [23]. For these, design coefficients, such as removal efficiencies (Table 2) and pollution load (Table 3), were obtained from the literature [23-27]. For the pollution removal efficiencies in the wastewater treatment plants (WTPs) in Table 3, the calculations were performed using the assumptions for the Van Central Advanced Biological Wastewater Treatment Plant, which has an advanced biological treatment type: 80% for COD, 70% for TN, 70% for TP, and 90% for SS. [24-26]. The formulas used in the calculations are given below.

Table 2. Removal efficiencies found in the literature for pollution load calculations [23-26]

Population	Unit flow rate L/person/day	Unit COD load gr/person/day	Unit TN load gr/person/day	Unit TP load gr/person/day	Unit SS load gr/person/day
50000-100000	150	90	7	1,1	50
>100000	150	90	7	1,1	50

Table 3. Pollutant load coefficients found in the literature for pollutant load calculations [24-26]

Treatment type	COD removal efficiency (%)	TN removal efficiency (%)	TP removal efficiency (%)	SS removal efficiency (%)
Biological	80	25	10	90
Advanced biological (Removing N and P)	80	70	70	90

The following formula is used to calculate the pollution load per person per day for each parameter, i.e., the calculated pollution load entering the facility [26,27].

$$L_{ann} = \frac{N \times k}{10^6} \times 365 \quad (1)$$

Here, L_{ann} denotes the annual pollution load (tons/year), N denotes the population, and k denotes the per-capita pollution generation coefficient (g/person-day) [26,27].

For an urban wastewater treatment plant, the pollution load is calculated as L_{eff} (tons/year) of discharged wastewater (the load delivered to the receiving environment), L_{inf} (tons/year) of inlet wastewater (the load arriving at the plant), and n (%) of removal efficiency [26,27].

$$L_{inf} = \begin{cases} L_{inf}\left(1 - \frac{n}{100}\right), If\ treatment\ exists \\ L_{inf}, Otherwise \end{cases} \quad (2)$$

The calculated and measured values to be discharged were compared with the limit values in Table 4 of the "Water Pollution Control Regulation", "Table 21: 4. Discharge Standards of Domestic Wastewater into Receiving Environments" and the "Urban Wastewater Treatment Regulation", "Table 2: Discharge Limits for Advanced Treatment from Municipal Wastewater Treatment Plants" [28,29].

Table 4. National legislation limits values for the discharge of urban wastewater into receiving environments

Pollution load parameter	Limit value	Legislation
COD (mg/L)	120	WPCR, Table 21:4
TN (mg/L)	10	MWTR, Table 2
TP (mg/L)	1	MWTR, Table 2
SS (mg/L)	35	WPCR, Table 21:4

Wastewater pollution parameters were analyzed in accordance with standard methods at the Environmental Chemistry Laboratory of the Central Advanced Biological Wastewater Treatment Plant [30]. Samples were collected using an Endress Hauser sampling device in accordance with the TS ISO 5667-10 standard. Samples were taken from the inlet and outlet points of the plant as 24-hour time-weighted composite samples, and sample containers and volumes specified in the TS EN ISO 5667-3 standard were used for the analyses. pH measurements were performed using a WTW 110 pH meter. Suspended solids (SS) analyses were conducted according to the TS EN872 standard using the SM 2540 D gravimetric method. COD analysis was performed spectrophotometrically (Hach Lange Dr5000) using ready-made kits according to the SM 5220 D closed reflux method. TN analyses were performed in accordance with TS EN 12260, based on persulfate oxidation, using ready-made kits on a Hach Lange Dr5000 spectrophotometer. Total phosphorus analysis was performed according to Standard Methods 4500-P B, based on the conversion of phosphorus to orthophosphate in an acidic environment and colorimetric measurement, using ready-made kits on a Hach Lange Dr5000 spectrophotometer [30].

3. RESULTS AND DISCUSSIONS

3.1. Comparative Evaluation of Calculated and Measured Pollution Load Parameters

The domestic wastewater from the central districts of Van province, Tuşba, İpekyolu, and Edremit, is treated at the Van Central Advanced Biological Wastewater Treatment Plant. This study evaluates organic pollution load parameters in wastewater entering the plant and in wastewater discharged into the receiving environment, accounting for point-source pollutants from the three central districts. Calculations were made assuming that all wastewater from the Tuşba and İpekyolu districts, and approximately 70% of wastewater from the Edremit district, arrive at the plant. First, the pollution load parameters specified in the legislation were calculated using coefficients from the literature. In addition, actual measurement data were obtained from influent and effluent wastewater at the Central Advanced Biological Wastewater Treatment Plant. Daily data from March, April, and May 2025 were used for this purpose. Descriptive statistical evaluations of these data on a monthly basis are also presented. In the comparative evaluation of the calculated data, the "average values of the measured parameters" were used. The calculated and measured data were compared, and the discharged data were compared with the values specified in the legislation.

Figure 4 shows the variation in urban-sourced pollution loads, specifically a) COD (chemical oxygen demand), b) TN (total nitrogen), c) TP (total phosphorus), and d) SS (suspended solids), calculated on a central district basis for the influent and effluent wastewater from the plant. The highest pollution load parameter values are observed in influent wastewater, with changes noted in the districts of İpekyolu, Tuşba, and Edremit. Under normal conditions, design coefficients used to obtain actual data for pollution load calculations are expected to be higher for influent wastewater than for measurement data [31]. Following wastewater treatment, the pollution load of the treated effluent is lower than that of the influent wastewater. In the district-based assessment, the highest values for all calculated pollution load parameters were found in the districts of İpekyolu, Tuşba, and Edremit, respectively, based on population density. Similar studies have shown that pollution loads increase with population density [5,31]. In the parameter-based evaluation, the difference between the input wastewater data and the discharge data is most significant for the calculated SS parameter values. The subsequent ranking continues with the parameters COD, TN, and TP. According to Uysal and Cebe [32], the parameter ranking is COD, SS, TN, and TP.

In Figure 5 (a,b), changes in the pollution loads of raw wastewater entering wastewater treatment plants and discharged wastewater are shown. Accordingly, the measured pollution load values (COD, TN, TP, and SS) are higher than the calculated values. In Figure 5a), it was observed that only the calculated influent WW pollution loads, TN and TP (excluding the COD and SS parameters), had lower ratios than the measured values.

Determining existing pollution loads from domestic wastewater within the scope of the river basin management plan and identifying the ultimate effects of the pressures it will exert on surface water bodies are crucial for basin management. In this regard, comprehensive studies are underway, and legislation is being updated regarding both discharge criteria and the protection of the receiving environment. Therefore, it is essential to disseminate these studies, taking into account their contributions to the literature. Within the scope of this study, calculations were performed using population data and design coefficients from the literature to assess the extent to which the results matched the actual data. Finally, averages were calculated from measurements taken in March, April, and May for comparison. The influent wastewater and effluent wastewater pollution load data for this study were compared with the calculated data. Accordingly, the calculated values were higher than the measured pollution load. The reasons for this can be listed as follows: i) the theoretical pollution coefficients being set too high for design purposes, ii) the discrepancy between the actual population data and the design population, iii) the increase in per capita water consumption and the dilution effect, iv) infiltration into the sewer system and the entry of rainwater, v) lower-than-expected industrial load values or the application of pretreatment processes, vi) differences arising from sampling and analysis methods, vii) reasons such as pre-sedimentation and biochemical decomposition in the sewage system [33,34]. Additionally, population-based pollution load estimates are derived from assumptions and standard coefficients to ensure design safety. In contrast, measured input values are affected by actual hydraulic and operational conditions, network status, and analytical processes. The fact that calculated loads are higher than measured concentrations in short, that calculated pollution loads, especially in terms of COD, suspended solids, TN, and TP parameters, are higher than measured discharge loads is a normal outcome from an engineering and design perspective. This is related to the conservative approach widely adopted in the design of wastewater treatment plants. The per capita pollution load coefficients used in design generally aim to plan for maximum-load conditions (i.e., upper-limit values), minimize risk, and include a safety margin. While this approach reflects a cautious planning approach to protecting the receiving environment, it can lead to discrepancies between the design values and the measured loads under actual operating conditions [34-36].

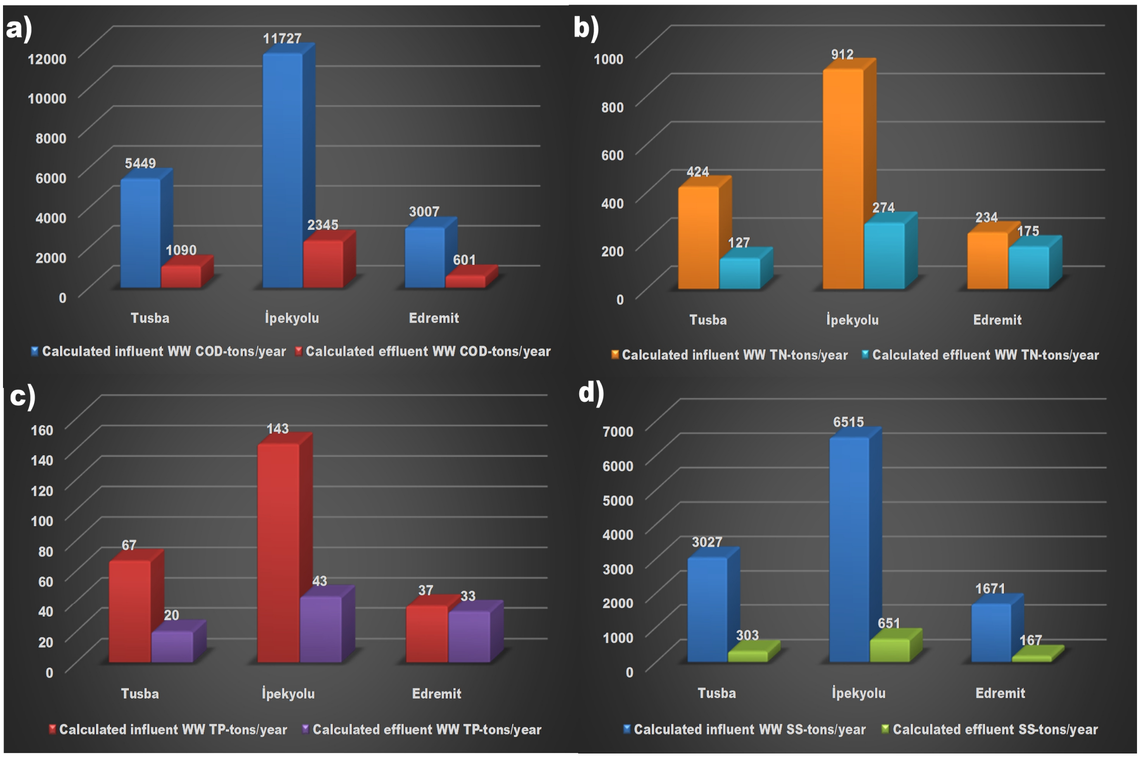

Figure 4. Distribution of pollution loads calculated in urban wastewater for the central districts of Van province (İpekyolu, Tuşba, and Edremit) according to some parameters: a) COD (tons/year), b) TN (tons/year), c) TP (tons/year), and d) SS (tons/year)

The characterization of urban wastewater varies with multiple parameters, including water consumption habits, industrial contribution rates, infiltration and exfiltration effects, seasonal variations, and socio-economic factors [34]. Therefore, while calculations based on theoretical coefficients are important for planning and capacity forecasting, they may not fully reflect local conditions if not calibrated with actual measurement data. The fact that the calculated TN and TP loads in this study exceed the regulatory limits, whereas the measured values are within the limits, indicates that the design coefficients are protective; however, operational performance should be evaluated more realistically using monitoring data. On the other hand, the difference between design and actual loads has significant consequences not only in terms of mass load balance but also for energy consumption [37].

In wastewater treatment plants, 45–75% of total energy consumption occurs in biological treatment processes, particularly aeration systems [38]. In advanced biological wastewater treatment plants, nitrification-denitrification and biological phosphorus removal processes are used for the removal of nitrogen and phosphorus, leading to significant energy consumption due to their high dissolved oxygen demand [39]. High TN and COD loads selected during the design phase can lead to parameters such as blower capacity, aeration time, and reactor volume being set at their upper limits. If the actual organic and nitrogen loads remain below the design values, and dissolved oxygen control is not optimized based on load, blower systems may operate at unnecessarily high capacities. This situation can lead to an increase in energy consumption per unit of pollutant removal (kWh/kg COD or kWh/kg TN) and a decrease in the plant's specific energy performance. It can also cause biological treatment units to operate at relatively low organic loading rates (F/M) [40]. Low F/M rates can lead to increased sludge age and the dominance of endogenous respiration processes in activated sludge systems, causing biomass metabolism to shift to a less energy-efficient range [34,41]. Similarly, while lowering the nitrogen load than the design assumptions reduces the theoretical oxygen demand required for nitrification, it can also prevent the full realization of energy saving potential due to fixed aeration strategies. The nitrification process is one of the energy-intensive processes in biological treatment systems, and changes in oxygen transfer efficiency and organic and nitrogen loadings directly affect energy consumption [30].

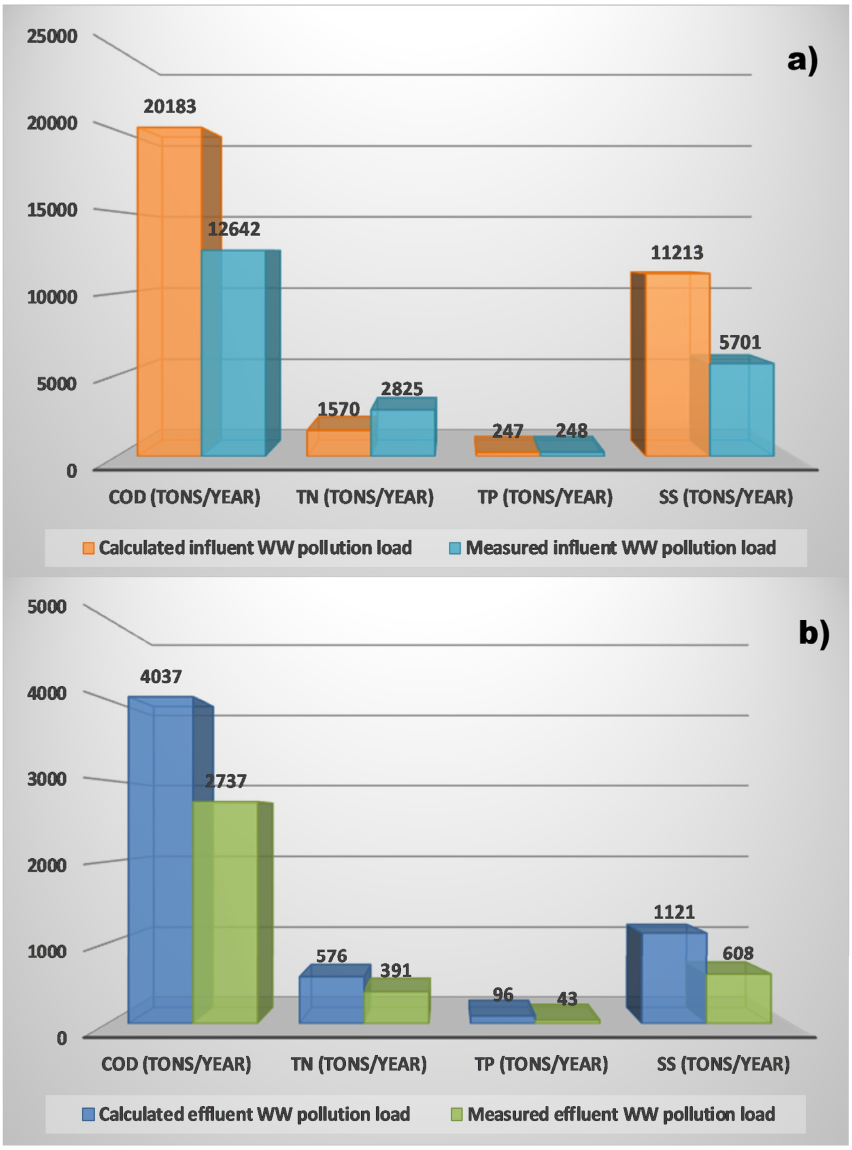

Figure 5. Comparison of a) influent wastewater and b) effluent wastewater pollution loads of Van central advanced biological wastewater treatment plant based on calculated and measured values of COD, TN, TP, and SS (tons/year) parameters

Therefore, analyzing actual load conditions relative to design assumptions is important not only for regulatory compliance but also for energy optimization and the development of sustainable operating strategies. Increasing energy efficiency is considered one of the fundamental components of sustainable wastewater management [42]. Applications such as dynamic process control based on the actual load profile, in-cycle dissolved oxygen sensors, pumping, sludge line and minimization, ammonium-based aeration control, variable speed blower use, and biogas production offer significant potential for energy savings [43-47]. In this context, revealing the difference between estimated and measured pollution loads is important not only for planning accuracy but also for energy optimization, greenhouse gas emission reduction, and lower operating costs [48].

Given the closed and sensitive basin nature of Lake Van, while protecting the receiving environment is a primary objective, the energy-efficient operation of wastewater treatment plants is also a critical element for sustainability. The European Union Water Framework Directive (2000/60/EC) aims to improve the condition of water bodies while adopting holistic basin management [12]. In this context, monitoring plant performance and evaluating it within the energy-efficiency framework are as important as accurately estimating point-source pollution loads [37].

3.2. Evaluation of Influent and Effluent Wastewater Parameters Measurement Data

Table 5 presents descriptive statistics (minimum, maximum, mean, and standard deviation) for pollution load parameters in the plant influent and effluent wastewater for March, April, and May. For the base parameters in the table, the minimum and maximum influent wastewater values were 182 mg/L (March) and 537 mg/L (May), respectively, while the plant effluent wastewater values were 45 mg/L (May) and 80 mg/L (May). All daily measurement values at the COD plant effluent wastewater (over a 3-month period) did not exceed the limit values set for discharge. The minimum and maximum influent wastewater TN values were 27 mg/L (March) and 84 mg/L (May), respectively, whereas the effluent TN values were 6 mg/L (March) and 10 mg/L (May). The daily TN measurement values at the plant influent wastewater (over a 3-month period) did not exceed the specified discharge limit, remaining at the limit threshold for 1 day each in March and April, and 3 days in May. The minimum and maximum TP values in the influent wastewater were 3 mg/L (March) and 7 mg/L (April and May), respectively, while the minimum and maximum TP values in the effluent wastewater were 1 mg/L across all months. All daily TP measurements in the plant effluent wastewater (over 3 months) remained within the set discharge limits. For SS, the minimum and maximum influent wastewater concentrations were 56 mg/L (March and April) and 190 mg/L (May), respectively, while the plant effluent concentrations were 2 mg/L (March and April) and 25 mg/L (March). All daily SS measurement values in the plant effluent wastewater (over a 3-month period) did not exceed the specified discharge limit. Table 5 presents the calculated results for discharged wastewater and compares them with the limit values specified in the legislation for each measurement obtained at the facility. According to this, only the calculated TN and TP values for the discharged wastewater exceed the specified limits in the legislation, while the measured (mean) values do not exceed these limits and remain within them.

Table 5. Descriptive statistics of organic pollution parameters measured in the wastewater treatment plant

Values	Period	WWTP influent				WWTP effluent			
		COD (mg/L)	TN (mg/L)	TP (mg/L)	SS (mg/L)	COD (mg/L)	TN (mg/L)	TP (mg/L)	SS (mg/L)
Min	March	**182**	**27**	**3**	***56***	53	6	***1***	***2***
	April	197	54	5	***56***	48	8	***1***	***2***
	May	193	39	4	108	**45**	8	***1***	9
Mean	March	208	57	5	76	65	8	1	16
	April	279	62	6	119	60	9	1	11
	May	289	54	5	153	62	9	1	14
Max	March	258	75	6	100	79	10	***1***	***25***
	April	426	**84**	***7***	179	72	10	***1***	16
	May	**537**	65	***7***	***190***	**80**	10	***1***	17
SD	March	23	13	1	13	8	1	0	6
	April	71	11	1	49	9	1	0	5
	May	104	10	1	27	11	1	0	2
General mean		255	57	5	115	63	9	1	14
Limit value		120	10	1	35	120	10	1	35

4. CONCLUSIONS

Lake Van, a closed basin, is one of the five sensitive basins specified in the Urban Wastewater Treatment Regulation - Sensitive and Less Sensitive Water Areas Circular. The fact that this basin is closed, with no outflow, increases its potential for pollution. The primary sources of pollution in the basin are wastewater from settlements surrounding the lake. Therefore, wastewater should not be discharged into the receiving environment without adequate treatment and removal efficiency. The final discharge of wastewater from the Van Central Advanced Biological Wastewater Treatment Plant is also made to the shore of Lake Van. VASKİ carries out the operation, maintenance, and repairs of WWTPs located on the coast to protect the health of the receiving environment. To support sustainable water use through the long-term protection of the coastal waters of Lake Van, a closed basin, the watershed protection action plan and drought and flood management plan studies have been completed, and implementation program monitoring meetings are ongoing.

As a result, among the central districts of Van Province, the highest pollution load was calculated in the district of İpekyolu, which has the most densely populated area, while the lowest pollution load values were calculated in the district of Edremit. In general, when calculating the pollution load, the calculated values were higher than the measured values because the theoretical pollution coefficients were selected high for design purposes, in line with the assumptions. COD is the pollutant parameter with the highest pollution load, while TP is the parameter with the lowest load. Compared with the legislative limit values, the measured values were within acceptable limits, whereas the calculated values for TN and TP exceeded the limits. It is important to develop management and planning strategies within the scope of action plans and river basin management plans to reduce pollution loads.

Furthermore, the difference between the calculated and measured pollution loads represented in the study demonstrates the need to calibrate design assumptions against local data. Optimization studies based on actual measurement data will make significant contributions to both maintaining regulatory compliance and increasing energy efficiency. The main reason for limiting the study's scope to three central districts is that these districts are connected to an advanced biological wastewater treatment plant that discharges directly into Lake Van and that houses a large share of the urban population in the basin. Therefore, rather than representing all pollution sources at the basin scale, the study focuses on quantitatively identifying point sources that exert a high degree of pressure. Considering the current state of Lake Van and its basin, the impacts of point and diffuse pollution sources should be investigated on a basin-wide basis, and detailed periodic monitoring studies should be conducted. The pollution load values calculated in this study constitute an important basis for the proposed applications and future studies. In this respect, the study offers a holistic approach to the literature by presenting not only the environmental but also the technical and energy-based consequences of pollution load calculations.

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