



OPEN Impact of temperature and flow rate on oxygen dynamics and water quality in major Turkish rivers

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This study investigates the effects of temperature and flow variations on dissolved oxygen and biochemical oxygen demand across four major Turkish rivers: Kızılırmak, Sakarya, Seyhan, and Yeşilirmak. An Extended Streeter-Phelps Model, incorporating temperature-dependent deoxygenation and flow-sensitive reoxygenation rates, was employed to simulate oxygen dynamics under diverse environmental condition. Results indicate that increased temperature generally reduces oxygen levels due to lower solubility, while biochemical demand initially rises, reflecting accelerated organic decomposition. Higher flow rates, however, help sustain oxygen levels by enhancing mixing and dilution. Each river exhibited unique responses to these factors, influenced by its hydrological and anthropogenic characteristics. The model demonstrated strong predictive accuracy, with R^2 values ranging from 0.80 to 0.95 and RMSE values generally below 5.5, effectively capturing complex interactions that traditional models often overlook. These findings underscore the importance of managing flow and temperature impacts on river ecosystems, particularly under seasonal and human-induced pressures. This study provides valuable insights for water quality management and conservation strategies, emphasizing the utility of dynamic modeling frameworks in diverse river systems.

Keywords Biochemical oxygen demand, Dissolved oxygen, Flow rate, River water quality, Temperature effects, Water quality modeling

Rivers are vital ecosystems that provide essential resources, such as drinking water, habitat for biodiversity, and recreational opportunities. Monitoring and understanding river water quality is essential for managing water resources effectively, particularly in the context of growing anthropogenic pressures^{9,49}. Rivers receive inputs from diverse sources, including agricultural runoff, industrial discharge, and urban effluents, which influence various water quality parameters such as dissolved oxygen (DO), biochemical oxygen demand (BOD), temperature, and turbidity^{1,30}. In addition to classical analyses, recent studies have introduced explainable machine learning approaches that predict water quality trends while also identifying the most influential environmental factors²⁰. Widespread recognition of the adverse impacts of river pollution—such as reduced water availability, aquatic habitat degradation, and public health risks—has led to the development of integrated monitoring frameworks and data-driven management tools in many countries^{2,37}. These efforts are particularly evident in regions facing growing anthropogenic stress, where maintaining ecological integrity has become a core component of water policy.

Water quality modeling plays a crucial role in understanding the interactions and trends among these parameters, helping predict changes under different conditions. A variety of analytical and numerical models have been developed to simulate river water quality, each providing insights into the impacts of environmental and anthropogenic factors^{12,46}. Water quality models range from mechanistic frameworks such as QUAL2K and AQUATOX to advanced machine learning (ML) techniques. The QUAL2K model provides detailed simulations of hydrological and chemical processes in river systems³⁶, while AQUATOX incorporates ecological and toxicological interactions to assess ecosystem impacts³⁵. In parallel, data-driven methods like artificial neural networks (ANNs) and support vector machines (SVMs) have gained popularity for their ability to capture complex, non-linear relationships where traditional models often fall short^{27,42}. Recent studies further highlight the superior predictive capabilities and generalizability of ANN- and SVM-based models across diverse aquatic systems, including rivers, aquifers, and coastal environments^{3,23}. Complementary modeling innovations have also emerged in recent years, such as Kolmogorov–Arnold networks for chlorophyll-a prediction in large lakes³⁹, web-GIS integrated tools for spatial water resources assessment⁴⁰, reduced-order neural network models for

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real-time BOD₅ monitoring³³, and probabilistic frameworks for uncertainty analysis in dispersion modeling³¹. These approaches expand the methodological landscape of water quality assessment by incorporating efficiency, spatial integration, and robust uncertainty quantification.

Among the numerous factors influencing river water quality, flow rate (Q) and temperature are recognized as key determinants of DO and BOD levels due to their direct effects on oxygen solubility, organic matter decay, and mixing processes^{13,25,28,54}. Q affects the physical dispersion and residence time of pollutants, influencing the rates of dilution and reoxygenation³⁴. Higher flow rates often enhance DO levels by increasing aeration, whereas lower flows can exacerbate oxygen depletion due to reduced turbulence and increased residence time for organic matter degradation⁵. Temperature, on the other hand, impacts biochemical reaction rates, directly affecting BOD decay and DO saturation levels⁷. As temperature rises, oxygen solubility decreases, and the rate of organic matter breakdown increases, intensifying DO depletion⁴³. Numerous studies have highlighted the importance of accounting for these factors in water quality modeling to capture seasonal and diurnal variations in river systems^{4,8,48,50}. Recent advancements in ensemble machine learning approaches, such as the AR-RBF and MLP-RF models, have shown high accuracy in forecasting daily dissolved oxygen levels in large river systems, underscoring the importance of integrating environmental factors like water temperature for improved river conservation and management²¹.

The Extended Streeter-Phelps Model offers an advanced approach to simulating DO and BOD dynamics by incorporating the effects of flow rate and temperature on deoxygenation and reoxygenation rates. Originally developed to describe oxygen sag curves downstream of pollution sources, the Streeter-Phelps Model has since been adapted to capture the complex interactions of temperature and flow in influencing oxygen dynamics^{12,44}. The extended version modifies the classical equations to account for temperature-sensitive decay rates (kd) and flow-dependent reoxygenation rates (kr), allowing for a more accurate representation of riverine oxygen conditions under varied environmental circumstances^{6,45}. This extended model has proven valuable in a wide range of studies, from evaluating lowland river pollution¹⁶ to assessing nutrient impacts in diverse river systems³⁸. Numerous other studies have demonstrated the model's adaptability and effectiveness across various environmental contexts, solidifying its role as a versatile tool for river water quality assessment^{14,26,29,32,52}.

In this study, the Extended Streeter-Phelps Model is applied to analyze DO and BOD dynamics in four major Turkish rivers—Kızılırmak, Sakarya, Seyhan, and Yeşilirmak—each with distinct hydrological characteristics. While the model itself is well-established, its application across multiple basins under a structured combination of environmental scenarios remains limited in the literature. This study addresses this gap by applying a comprehensive 3 × 3 simulation matrix (three temperatures × three flow rates) to evaluate oxygen dynamics under diverse thermal and hydraulic regimes. The model is calibrated and validated using over 30 years of observed data, and its performance is assessed using a range of statistical metrics (R², RMSE, MAE, MAPE, RMSLE). By providing a comparative, scenario-based assessment across variable river systems, this work advances the practical application of oxygen modeling and supports adaptive water quality management in the face of increasing climatic and anthropogenic pressures.

Specifically, this study addresses the lack of multi-scenario applications of the Extended Streeter-Phelps Model across diverse river basins. Unlike prior research that often focuses on single systems, our approach systematically evaluates DO and BOD dynamics under three temperatures and three flow conditions across four major rivers in Türkiye. Using over 30 years of observational data and multiple performance metrics, this work offers a novel, comparative insight into oxygen behavior under hydrologically and climatically variable regimes. These findings support both model advancement and practical applications in river basin management under changing environmental conditions.

Materials and methods

Study area

The study area includes four major rivers in Türkiye: Sakarya, Yeşilirmak, Kızılırmak, and Seyhan Rivers (Fig. 1). The Sakarya River, originating in Central Anatolia, supports agriculture, industry, and domestic water supply, flowing into the Black Sea^{41,53}. The Yeşilirmak River is a vital source for irrigation and hydroelectric power, characterized by a temperate climate and diverse agricultural activities²². The Kızılırmak River, Türkiye's longest river, plays a significant role in agriculture, drinking water, and industrial use¹⁸. Lastly, the Seyhan River, with a Mediterranean climate, supports irrigation, drinking water, and hydroelectric power in the Çukurova region^{10,24}.

Data collection

Monthly water quality data for the four major rivers—Sakarya, Yeşilirmak, Kızılırmak, and Seyhan—were obtained from monitoring stations operated by the General Directorate of State Hydraulics Works of Türkiye (DSİ) over a 30-year period on a seasonal basis. The data included measurements of DO, BOD, temperature, and flow rate for each river. These parameters were selected due to their relevance to modeling water quality dynamics, particularly for understanding the impacts of temperature and flow rate on DO and BOD levels within the Extended Streeter-Phelps framework.

Including a summary table of the collected data enhances the understanding of the distributional characteristics of key water quality parameters (Table 1). The mean BOD concentrations vary from 2.75 mg/L in Sakarya to 4.87 mg/L in Kızılırmak, with higher values in Kızılırmak and Yeşilirmak likely reflecting increased organic inputs from agricultural and industrial activities. DO concentrations are more stable across systems, with Sakarya showing the highest mean (10.19 mg/L) and Seyhan the lowest (8.01 mg/L), suggesting differing balances between re-aeration and oxygen demand.

Flow rate and temperature exhibit substantial variability; Seyhan's high flow (99.42 m³/s) and elevated temperature (18.54 °C) reflect its Mediterranean climatic regime, whereas Sakarya displays cooler, more temperate conditions. The broad standard deviations and percentile spreads—particularly for BOD and flow—

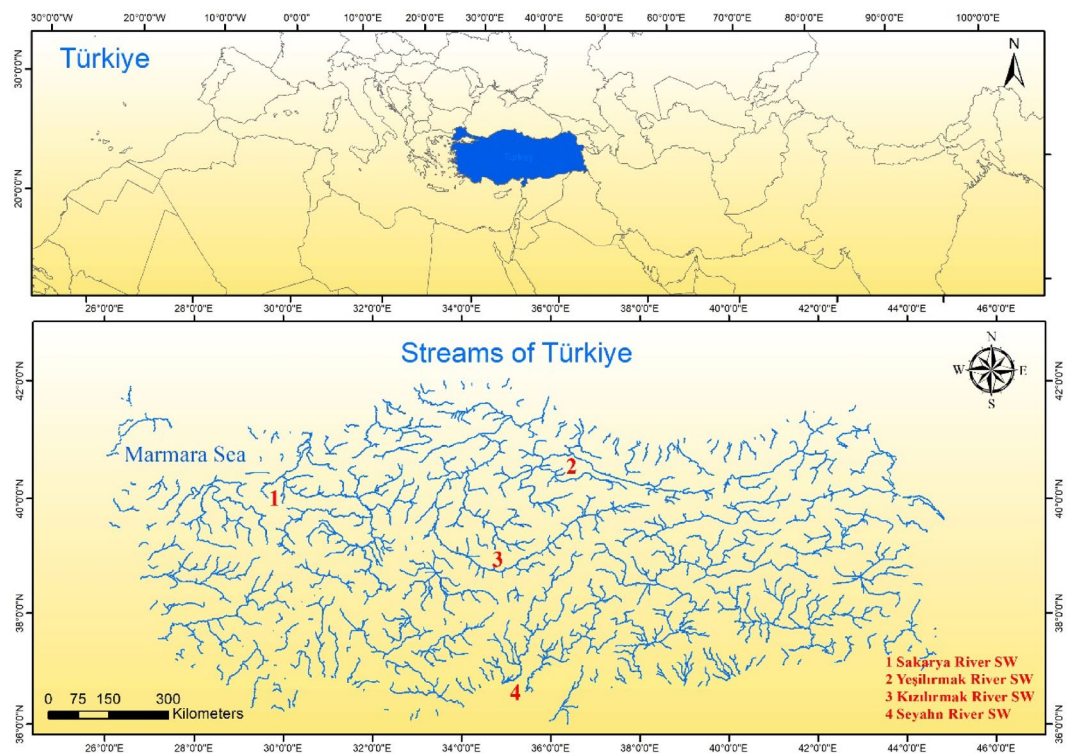


Fig. 1. Study area.

Rivers	Feature	Mean	Standard Deviation	Min.	25th Percentile	Median	75th Percentile	Max.
Kızılırmak	BOD	4.87	2.68	0.00	3.00	4.05	6.32	14.00
	DO	9.03	1.70	5.80	8.00	8.90	10.10	12.90
	Q	48.35	44.45	0.60	21.38	28.00	63.94	210.00
	T	16.52	4.66	6.00	14.00	17.10	19.00	26.00
Sakarya	BOD	2.75	1.13	0.97	2.00	2.78	3.16	7.00
	DO	10.19	1.21	7.22	9.45	10.25	11.06	13.20
	Q	56.50	54.21	2.87	26.73	48.42	66.37	366.05
	T	14.45	4.78	7.00	10.00	14.75	18.13	24.00
Seyhan	BOD	2.80	6.70	0.00	1.00	1.10	2.93	52.00
	DO	8.01	1.57	1.70	7.50	8.40	8.90	10.10
	Q	99.42	111.06	2.40	20.00	54.64	125.30	448.17
	T	18.54	6.26	4.00	14.00	19.00	22.25	30.00
Yeşilirmak	BOD	3.19	2.02	0.10	1.58	2.60	4.23	8.00
	DO	9.48	2.27	5.00	8.15	9.13	10.40	22.70
	Q	58.36	51.85	0.60	21.98	37.80	80.38	234.00
	T	15.79	6.34	5.00	11.75	15.50	21.25	27.00

Table 1. Statistical summary of water quality parameters across major Turkish Rivers.

highlight the seasonal and anthropogenic variability influencing each river. These insights directly informed model calibration by contextualizing the environmental heterogeneity within and among the river systems.

Extended Streeter-Phelps model: theoretical basis and implementation

The Streeter-Phelps Model, initially developed in 1925, has served as a cornerstone for studying oxygen sag curves, especially in rivers affected by organic pollution⁴⁴. This classical model operates on the premise that oxygen dynamics in streams are primarily driven by deoxygenation due to organic matter decay and reoxygenation from atmospheric exchange. However, to address the complexity of real-world aquatic systems, the model has since been expanded to incorporate additional environmental factors, such as temperature and flow rate, both of which can influence oxygen dynamics substantially^{12,46}.

To explicitly incorporate these influences, two adjustment factors were applied in the model: a temperature correction factor $f(T)$, and a flow-based reoxygenation adjustment factor $g(Q)$.

The temperature adjustment was modeled using an Arrhenius-type formulation as recommended by¹²:

$$f(T) = \theta^{(T-20)}$$

where T is the water temperature in °C and $\theta = 1.047$.

The flow rate adjustment was introduced into the reoxygenation rate calculation following¹⁶:

$$k_r(Q) = k_{r0} \cdot \left(\frac{Q}{Q_0}\right)^\beta$$

where k_{r0} is the base reoxygenation rate, Q , is the river discharge, Q_0 is the reference discharge, and $\beta = 0.5$.

These theoretical formulations allowed the model to dynamically adjust deoxygenation and reoxygenation rates under varying thermal and hydraulic conditions, improving its applicability to natural river systems.

In particular, temperature variations can alter reaction rates of biological and chemical processes affecting DO, while flow rates can impact the physical dispersion and replenishment of oxygen. Therefore, the Extended Streeter-Phelps Model is better suited for simulating DO and BOD in a dynamic context, especially in rivers with highly variable hydrological conditions⁴⁵.

The Extended Streeter-Phelps Model used in this study integrates temperature and flow rate factors to improve the accuracy of DO and BOD predictions. This model is mathematically represented as follows:

DO Equation:

$$\frac{dDO}{dt} = -k_d \cdot BOD + k_r \cdot (DO_{sat} - DO) \cdot f(T) \cdot g(Q)$$

where: k_d represents BOD decay rate influenced by temperature, k_r reoxygenation rate, impacted by flow rate, DO_{sat} is oxygen saturation level, dependent on water temperature, $f(T)$, temperature adjustment factor, $g(Q)$ is flow rate adjustment factor.

BOD Equation:

$$\frac{dBOD}{dt} = -k_d \cdot BOD$$

The decay rate, k_d , varies with temperature according to:

$$k_d(T) = k_{d0} \cdot e^{\alpha T}$$

The reoxygenation rate, k_r , is similarly dependent on flow rate:

$$k_r(Q) = k_{r0} \cdot Q^\beta$$

The temperature and flow adjustments incorporated into k_d and k_r enable the model to capture fluctuations in DO and BOD levels that respond to seasonal or episodic changes in temperature and river flow. This approach enhances the model's suitability for assessing water quality under variable environmental conditions¹².

The full methodological workflow implemented in this study is summarized in Fig. 2. This visual representation captures each phase of the modeling framework, from data acquisition to result analysis, providing a structured overview of the simulation pipeline.

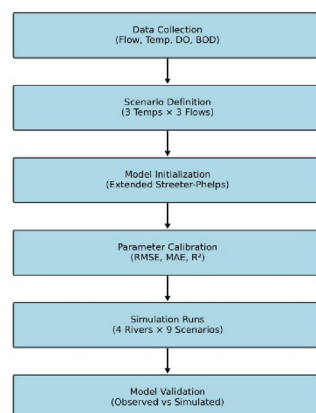


Fig. 2. Flowchart representing the modeling framework and simulation process used in the study.

Model calibration and validation

The model calibration process aimed to fine-tune the parameters k_d and k_r for each river, accommodating their unique hydrological characteristics. Using historical data, the model was calibrated to reduce the discrepancy between observed and predicted DO and BOD levels. Following the methodologies outlined by^{12,16}, initial values for k_d and k_r were adjusted by optimizing against the monthly observed DO and BOD data over a 30-year period. Based on reported values in the literature for similar river systems^{12,16}, the initial deoxygenation rate constant (k_d) was set at 0.3 day⁻¹, and the reoxygenation rate constant (k_r) at 0.5 day⁻¹. The organic loading coefficient (k_3) was set within the range of 0.1–0.3 depending on seasonal BOD trends. These values served as the initial conditions for manual calibration. Calibration was achieved through iterative simulations, with error metrics such as Mean Squared Error (MSE) and Root Mean Squared Error (RMSE) used to evaluate the alignment between observed and predicted values. MAE, RMSE, and MAPE were selected as key performance metrics to evaluate model accuracy and reliability in predicting DO and BOD levels. MAE provides a straightforward measure of average error magnitude, offering insight into the model's overall accuracy^{15,51}. RMSE, a more sensitive metric that emphasizes larger errors, allows for the identification of potential outliers affecting model predictions¹¹. Lastly, MAPE, expressed as a percentage, contextualizes prediction accuracy relative to actual values, facilitating a comparative understanding of model performance⁴⁷.

Post-calibration, the model's performance was validated against an independent dataset not utilized during the calibration process. This validation ensures the model's robustness across different seasonal and hydrological conditions, as suggested by¹⁷. Additionally, model accuracy was assessed through the calculation of performance metrics, including the coefficient of determination (R^2), MAE, MAPE, and RMSLE, to provide a comprehensive understanding of the model's effectiveness.

Table 2 summarizes the final calibration values used in the simulations. With the model successfully calibrated for each river, the subsequent section presents the results of scenario-based simulations under varying temperature and flow conditions.

Results

Simulations were conducted across three temperature settings (10 °C, 20 °C, and 30 °C) and three flow rates (50, 150, and 250 m³/s) for each river. This design allowed for a comprehensive assessment of how temperature and flow independently and interactively influence DO and BOD concentrations. The calibrated model was applied to simulate water quality dynamics in the four river systems under these varying conditions.

Tables 3, 4, 5 and 6 summarize the model's performance metrics, including R^2 , MSE, RMSE, MAE, MAPE, and RMSLE, for each of the four rivers. The results indicate consistently high performance across all rivers, with R^2 values generally exceeding 0.80 and RMSE values remaining below 5.5. These tables confirm the model's ability to accurately reproduce observed DO and BOD levels under diverse environmental conditions. They also offer comparative insights into prediction variability and reliability, supporting the model's applicability to systems with differing hydrological and anthropogenic characteristics.

The findings further indicate that increasing temperature generally leads to a reduction in DO levels due to decreased oxygen solubility, while BOD levels tend to rise initially, reflecting enhanced microbial decomposition. However, variations in flow rate significantly modulate these temperature-driven responses. Higher flow conditions improve oxygenation and dilute organic loads, thereby influencing both DO and BOD concentrations in river-specific ways.

Overview of River-Specific responses

While each river exhibited distinct hydrological characteristics, several consistent patterns were observed across the four systems. Increasing temperature universally led to a decrease in DO concentrations, primarily due to the thermodynamic principle that oxygen solubility in water declines as temperature rises⁷. Moreover, higher temperatures increase microbial respiration and biochemical reaction rates, further depleting oxygen availability⁴³.

BOD levels generally increased with temperature, which can be explained by the acceleration of microbial decomposition processes under warmer conditions, leading to higher oxygen demand¹². Flow rates between 150 and 250 m³/s mitigated these effects through increased mixing, reduced residence time, and greater atmospheric re-aeration³⁴.

Kızılırmak river

The Kızılırmak River exhibits distinct trends in DO and BOD concentrations under varying temperatures and flow conditions, highlighting the river's unique response to these environmental factors. At 10 °C, DO levels remain consistently high across all flow rates (50, 150, and 250 m³/s), which can be attributed to the higher solubility of oxygen at lower temperatures. Low temperatures reduce the kinetic energy of water molecules,

Parameter	Description	Initial Value	Calibrated Value	Units	Source
k_d	Deoxygenation rate	0.3	0.25–0.35	day ⁻¹	Chapra ¹² ; adjusted
k_r	Reoxygenation rate	0.5	0.45–0.55	day ⁻¹	Cox ¹⁶ ; adjusted
k_3	Organic load decay (BOD)	0.1–0.3	0.15–0.28	dimensionless	Empirical tuning

Table 2. Summary of initial and calibrated parameter values used in the extended Streeter-Phelps model for all rivers.

T (°C)	Q (m ³ /s)	Metric	R ²	MSE	RMSE	MAE	MAPE	RMSLE
10	50	DO	0.931	6.879	2.623	2.274	0.318	0.276
10	150	BOD	0.855	18.073	4.251	3.972	0.777	1.274
10	250	DO	0.931	6.9	2.627	2.279	0.319	0.276
10	50	BOD	0.855	18.073	4.251	3.972	0.777	1.274
10	150	DO	0.931	6.909	2.629	2.281	0.319	0.276
10	250	BOD	0.855	18.073	4.251	3.972	0.777	1.274
20	50	DO	0.950	3.685	1.92	1.526	0.177	0.224
20	150	BOD	0.846	19.471	4.413	4.148	0.812	1.363
20	250	DO	0.950	3.676	1.917	1.524	0.177	0.224
20	50	BOD	0.846	19.471	4.413	4.148	0.812	1.363
20	150	DO	0.950	3.672	1.916	1.523	0.177	0.224
20	250	BOD	0.846	19.471	4.413	4.148	0.812	1.363
30	50	DO	0.800	28.91	5.377	5.175	0.651	0.917
30	150	BOD	0.838	20.694	4.549	4.3	0.842	1.439
30	250	DO	0.800	28.918	5.378	5.176	0.651	0.917
30	50	BOD	0.838	20.694	4.549	4.3	0.842	1.439
30	150	DO	0.800	28.921	5.378	5.177	0.651	0.917
30	250	BOD	0.838	20.694	4.549	4.3	0.842	1.439

Table 3. Water quality metrics for Kızılırmak River.

T (°C)	Q (m ³ /s)	Metric	R ²	MSE	RMSE	MAE	MAPE	RMSLE
10	50	DO	0.933	6.627	2.574	2.224	0.312	0.272
10	150	BOD	0.867	16.222	4.028	3.732	0.729	1.153
10	250	DO	0.932	6.648	2.578	2.229	0.312	0.272
10	50	BOD	0.867	16.222	4.028	3.732	0.729	1.153
10	150	DO	0.932	6.658	2.58	2.232	0.313	0.272
10	250	BOD	0.867	16.222	4.028	3.732	0.729	1.153
20	50	DO	0.950	3.71	1.926	1.53	0.178	0.225
20	150	BOD	0.858	17.55	4.189	3.905	0.764	1.24
20	250	DO	0.950	3.702	1.924	1.528	0.177	0.225
20	50	BOD	0.858	17.55	4.189	3.905	0.764	1.24
20	150	DO	0.950	3.698	1.923	1.527	0.177	0.225
20	250	BOD	0.858	17.55	4.189	3.905	0.764	1.24
30	50	DO	0.800	28.834	5.37	5.158	0.649	0.919
30	150	BOD	0.850	18.775	4.333	4.061	0.795	1.319
30	250	DO	0.800	28.842	5.37	5.16	0.649	0.919
30	50	BOD	0.850	18.775	4.333	4.061	0.795	1.319
30	150	DO	0.800	28.846	5.371	5.16	0.649	0.919
30	250	BOD	0.850	18.775	4.333	4.061	0.795	1.319

Table 4. Water quality metrics for Sakarya River.

enhancing oxygen's ability to remain dissolved. The BOD values show a steady decrease with increasing flow rates, indicating that dilution plays a significant role in reducing organic matter concentration under these conditions, thereby limiting microbial oxygen demand (Fig. 3).

At 20 °C, DO levels decrease as temperature affects oxygen solubility. However, higher flow rates (150 and 250 m³/s) help to stabilize the DO concentrations, reflecting the influence of increased mixing and oxygenation due to flow. BOD values are moderately high at this temperature but decline with rising flow rates, balancing the effects of enhanced microbial activity and dilution (Fig. 4). At 30 °C, the DO concentrations are notably lower across all flow rates, primarily due to reduced oxygen solubility at higher temperatures. The highest flow rate (250 m³/s) provides some mitigation but does not fully offset the effects of high temperature. BOD levels initially peak at this temperature due to increased microbial decomposition but decrease with higher flow rates, showcasing the interplay between temperature-driven organic decomposition and flow-driven dilution (Fig. 5). At higher temperatures, increased microbial metabolism accelerates organic matter decomposition, thus increasing BOD. However, high flow enhances turbulence and mixing, countering some of the oxygen loss.

T (°C)	Q (m ³ /s)	Metric	R ²	MSE	RMSE	MAE	MAPE	RMSLE
10	50	DO	0.930	7.052	2.656	2.311	0.323	0.279
10	150	BOD	0.850	18.871	4.344	4.073	0.797	1.325
10	250	DO	0.930	7.068	2.659	2.314	0.323	0.279
10	50	BOD	0.850	18.871	4.344	4.073	0.797	1.325
10	150	DO	0.930	7.075	2.66	2.316	0.324	0.279
10	250	BOD	0.850	18.871	4.344	4.073	0.797	1.325
20	50	DO	0.950	3.643	1.909	1.518	0.176	0.223
20	150	BOD	0.841	20.306	4.506	4.251	0.833	1.415
20	250	DO	0.950	3.636	1.907	1.517	0.176	0.223
20	50	BOD	0.841	20.306	4.506	4.251	0.833	1.415
20	150	DO	0.950	3.633	1.906	1.516	0.176	0.222
20	250	BOD	0.841	20.306	4.506	4.251	0.833	1.415
30	50	DO	0.800	28.948	5.38	5.185	0.652	0.916
30	150	BOD	0.833	21.525	4.639	4.402	0.863	1.489
30	250	DO	0.800	28.954	5.381	5.186	0.652	0.916
30	50	BOD	0.833	21.525	4.639	4.402	0.863	1.489
30	150	DO	0.800	28.956	5.381	5.186	0.652	0.916
30	250	BOD	0.833	21.525	4.639	4.402	0.863	1.489

Table 5. Water quality metrics for Seyhan River.

T (°C)	Q (m ³ /s)	Metric	R ²	MSE	RMSE	MAE	MAPE	RMSLE
10	50	DO	0.930	6.938	2.634	2.292	0.32	0.277
10	150	BOD	0.861	17.251	4.153	3.866	0.756	1.221
10	250	DO	0.930	6.953	2.637	2.295	0.321	0.277
10	50	BOD	0.861	17.251	4.153	3.866	0.756	1.221
10	150	DO	0.930	6.96	2.638	2.297	0.321	0.277
10	250	BOD	0.861	17.251	4.153	3.866	0.756	1.221
20	50	DO	0.950	3.63	1.905	1.513	0.176	0.222
20	150	BOD	0.851	18.66	4.32	4.046	0.792	1.312
20	250	DO	0.950	3.624	1.904	1.512	0.176	0.222
20	50	BOD	0.851	18.66	4.32	4.046	0.792	1.312
20	150	DO	0.950	3.621	1.903	1.511	0.175	0.222
20	250	BOD	0.851	18.66	4.32	4.046	0.792	1.312
30	50	DO	0.800	28.943	5.38	5.179	0.651	0.918
30	150	BOD	0.843	19.919	4.463	4.203	0.823	1.391
30	250	DO	0.800	28.948	5.38	5.18	0.651	0.918
30	50	BOD	0.843	19.919	4.463	4.203	0.823	1.391
30	150	DO	0.800	28.95	5.381	5.181	0.651	0.918
30	250	BOD	0.843	19.919	4.463	4.203	0.823	1.391

Table 6. Water quality metrics for Yeşilırmak River.

3.3. Sakarya river

In the Sakarya River, the relationship between temperature, flow rates, and their combined effect on DO and BOD concentrations reveals unique patterns due to the river’s specific ecological conditions. At a lower temperature of 10 °C, DO levels remain relatively high, due to low water temperature improving oxygen retention. However, slight DO decline at higher flows may be attributed to a reduced residence time, limiting atmospheric reoxygenation. This is because lower temperatures enhance oxygen solubility, but higher flow rates introduce mixing, which slightly offsets DO levels. Meanwhile, BOD levels show a consistent decline as flow increases, suggesting a strong dilution effect that limits the concentration of biodegradable organics available for microbial decomposition (Fig. 6).

At 20 °C, the DO levels exhibit a noticeable decline due to reduced oxygen solubility. However, the increased flow rates from 50 to 250 m³/s appear to buffer this effect, helping maintain higher DO levels than would be expected at a static condition. BOD levels follow a similar trend, decreasing with higher flow rates, but they begin at a slightly higher baseline compared to 10 °C, reflecting increased microbial activity at this temperature (Fig. 7).

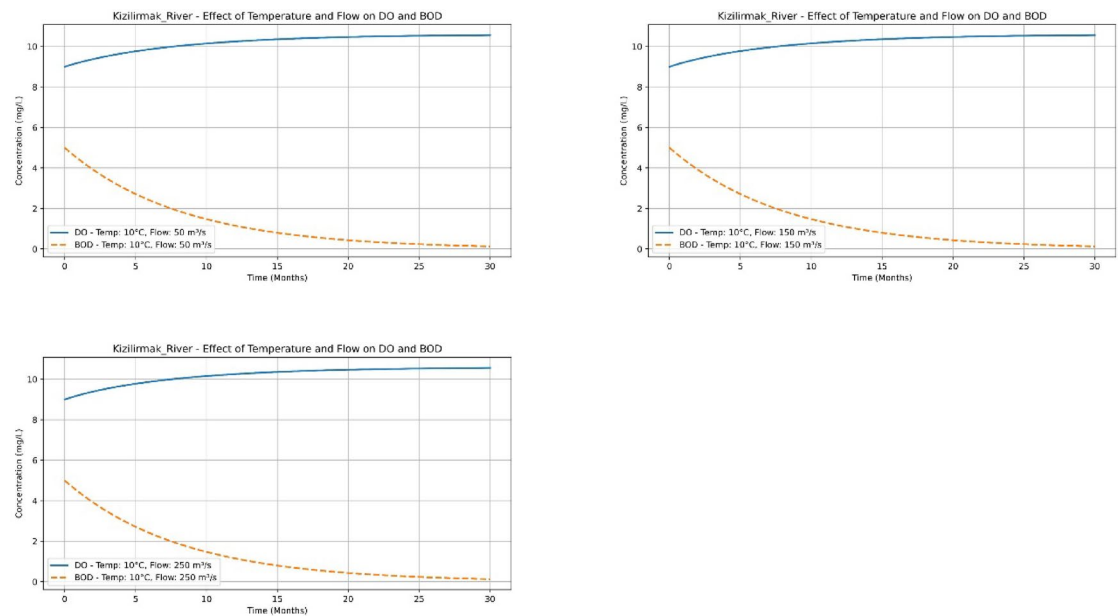


Fig. 3. DO and BOD in the Kızılırmak under Different Flow Conditions (10 °C).

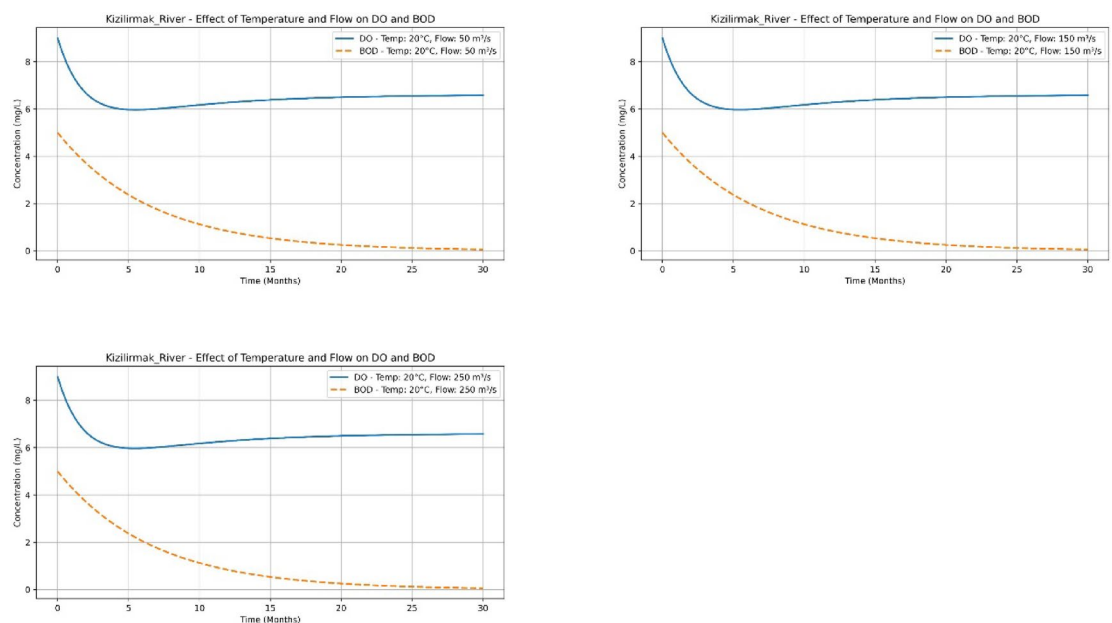


Fig. 4. DO and BOD in the Kızılırmak under Different Flow Conditions (20 °C).

At 30 °C, DO levels are significantly lower across all flow rates, primarily due to reduced oxygen solubility at higher temperatures. The highest flow rate (250 m³/s) mitigates this effect to some extent, but overall, the DO concentration remains low. BOD levels are highest in the initial months at this temperature but decline rapidly as flow rates increase, showing the combined effects of temperature-driven microbial activity and flow-driven dilution (Fig. 8). The notable DO depletion is linked to reduced oxygen solubility and elevated microbial respiration at higher temperatures, while increased flow supports reoxygenation via surface aeration and pollutant dispersion.

Seyhan river

In the Seyhan River, the interplay between temperature and flow exhibits distinct trends that contrast with those observed in the Sakarya River, highlighting the influence of river-specific factors on DO and BOD dynamics. At 10 °C, as colder temperatures enhance DO saturation, and Seyhan's relatively consistent flow facilitates natural aeration. This is due to the high oxygen solubility at lower temperatures and the river's ability to sustain aeration

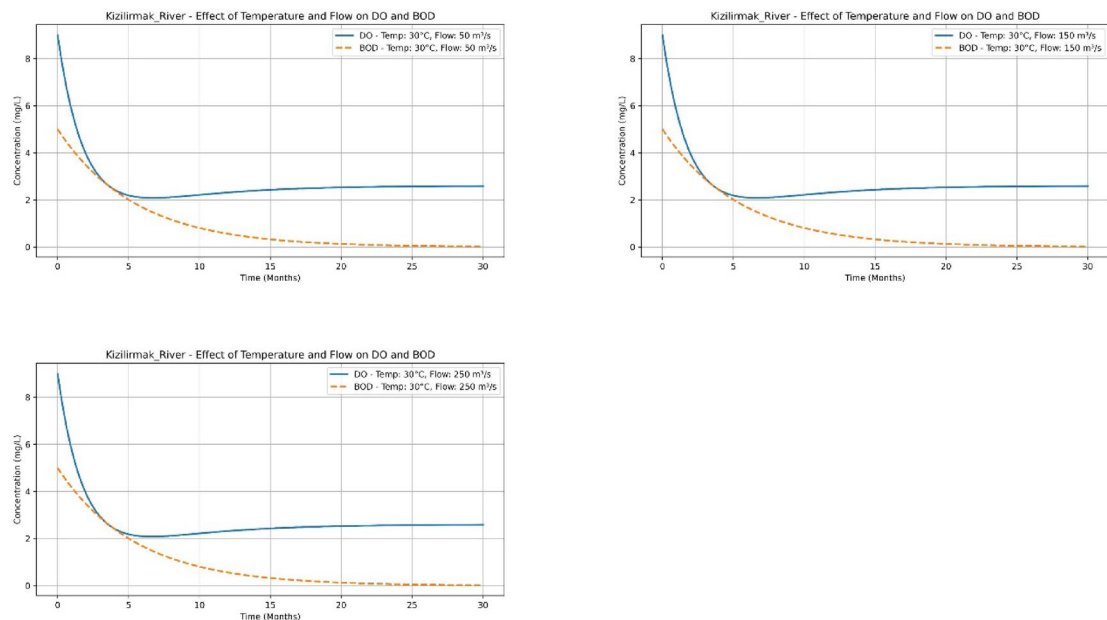


Fig. 5. DO and BOD in the Kizilirmak under Different Flow Conditions (30 °C).

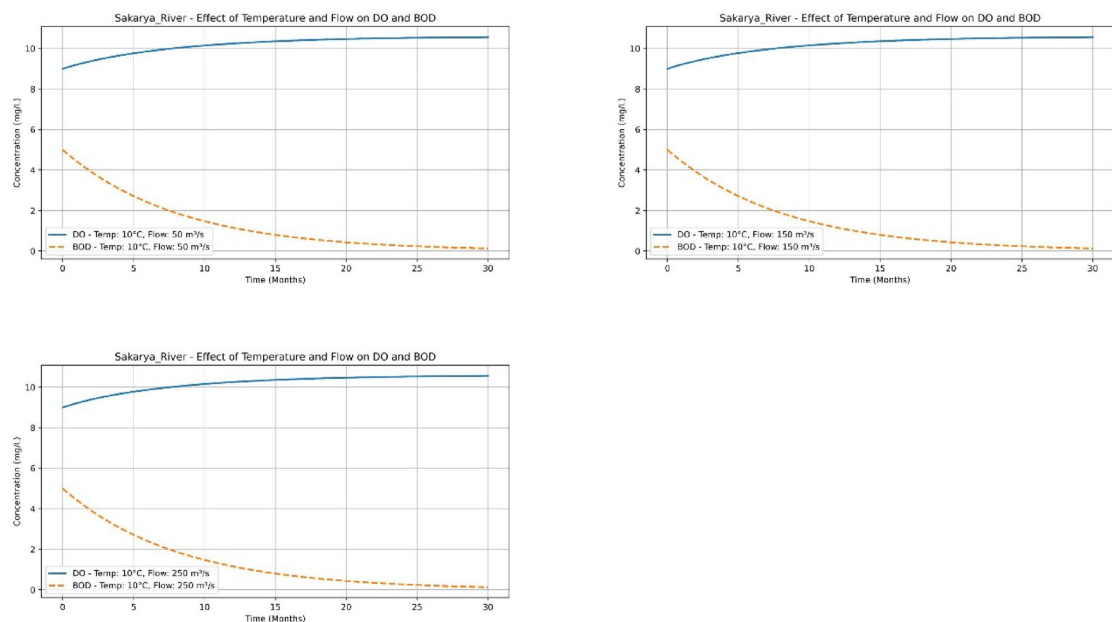


Fig. 6. DO and BOD in the Sakarya under Different Flow Conditions (10 °C).

under flow conditions. BOD levels consistently decrease with higher flow rates, indicating effective dilution of organic load (Fig. 9).

At 20 °C, DO concentrations start to drop, particularly at lower flow rates (50 m³/s), due to the reduced solubility of oxygen. However, as flow rates increase to 150 and 250 m³/s, DO levels stabilize, showing the moderating effect of flow on oxygen levels. BOD values show an initial increase compared to 10 °C but decline with increasing flow, indicating a balance between enhanced microbial activity and flow-driven dilution (Fig. 10). The drop in DO at elevated temperatures is driven by two mechanisms: reduced gas solubility and increased oxygen consumption from microbial respiration. Flow offsets this by promoting turbulent mixing and shortening pollutant residence time.

At 30 °C, DO levels are lowest, especially at low flow rates, reflecting the combined effect of high temperature and reduced oxygen solubility. The highest flow rate (250 m³/s) helps maintain moderate DO levels. BOD levels at this temperature are elevated initially but decrease as flow rates increase, showing the temperature's influence

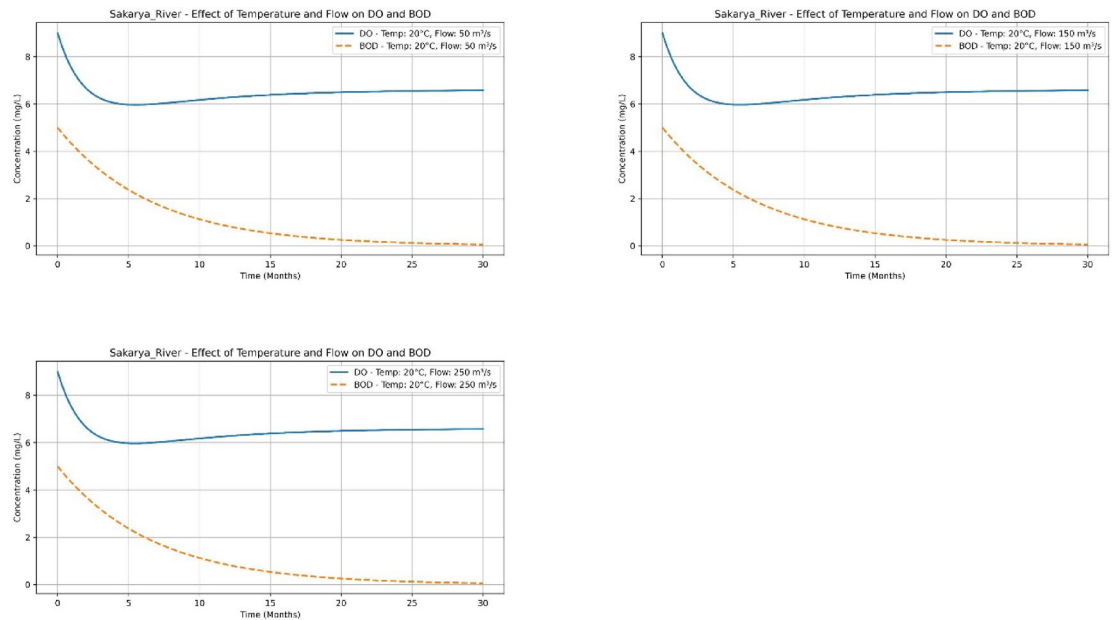


Fig. 7. DO and BOD in the Sakarya under Different Flow Conditions (20 °C).

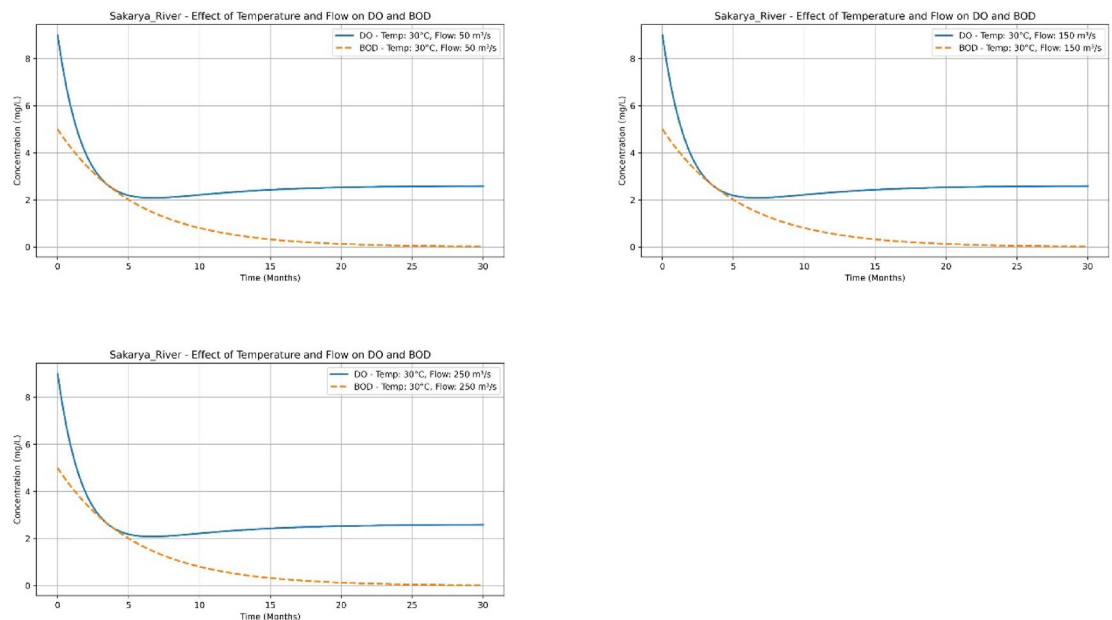


Fig. 8. DO and BOD in the Sakarya under Different Flow Conditions (30 °C).

on organic decomposition rates and the flow's impact on dilution (Fig. 11). Higher temperatures increase enzymatic activity in bacteria, raising BOD levels unless moderated by high flows that disperse organics and reduce their availability in localized zones.

Yeşilırmak river

The Yeşilırmak River exhibits patterns in DO and BOD levels that further underscore the river-specific responses to temperature and flow variations. At 10 °C, DO levels are high across all flow rates, similar to the other rivers, due to the increased solubility of oxygen at low temperatures. BOD values decrease as flow rates rise, showing effective dilution of organic content (Fig. 12). The high DO is attributed to favorable thermal conditions that promote gas solubility. The consistent DO levels across flows reflect a balance between oxygen retention and low biochemical activity.

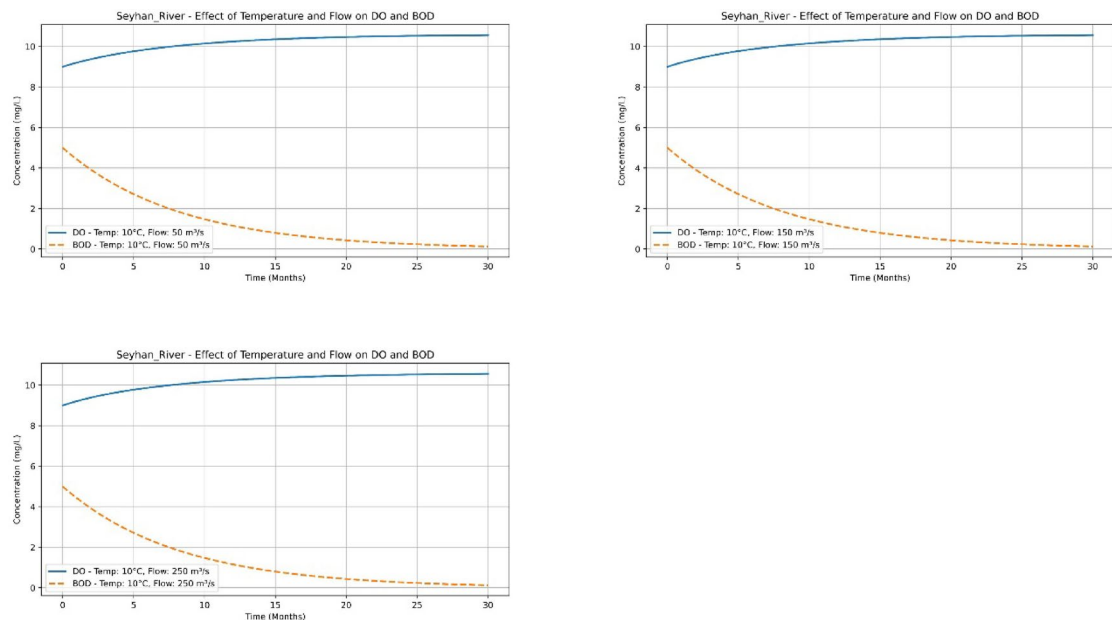


Fig. 9. DO and BOD in the Seyhan under Different Flow Conditions (10 °C).

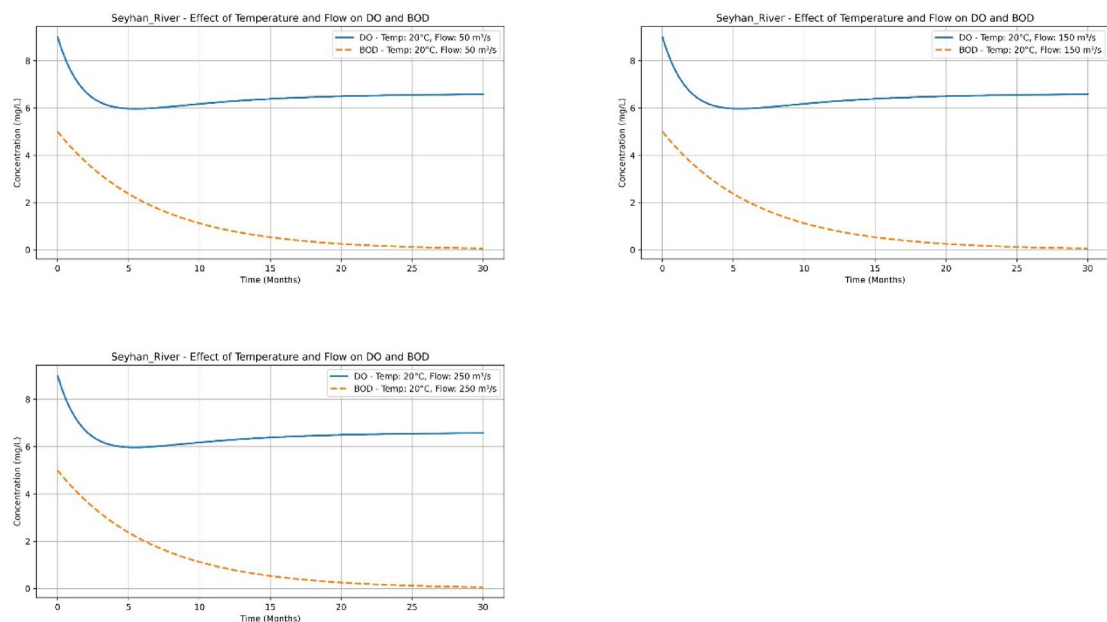


Fig. 10. DO and BOD in the Seyhan under Different Flow Conditions (20 °C).

At 20 °C, DO levels show a moderate decline, particularly at lower flow rates, as temperature impacts oxygen solubility. However, as flow increases, DO levels stabilize, demonstrating the positive effect of higher flows on oxygenation. BOD levels are moderately high initially, reflecting the enhanced microbial activity at this temperature, but decrease with increasing flow rates (Fig. 13). Flow-induced mixing likely compensates for moderate DO depletion, indicating a strong coupling between hydrodynamic conditions and biogeochemical processes.

At 30 °C, DO levels are generally lower across all flow conditions, with the highest flow rate of 250 m³/s providing some mitigation. BOD levels begin high but decrease significantly as flow rates increase, showcasing the balance between high-temperature decomposition and flow dilution (Fig. 14). The elevated BOD at low flows indicates intense microbial activity, while higher flows dilute organic matter and increase oxygen renewal, reducing BOD and partially restoring DO.

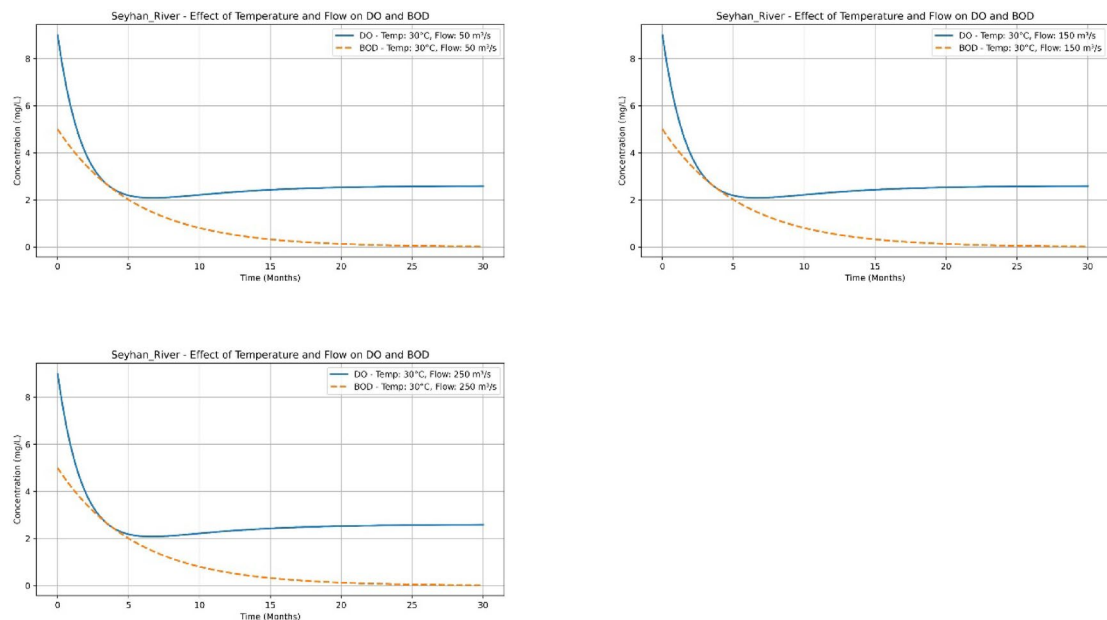


Fig. 11. DO and BOD in the Seyhan under Different Flow Conditions (30 °C).

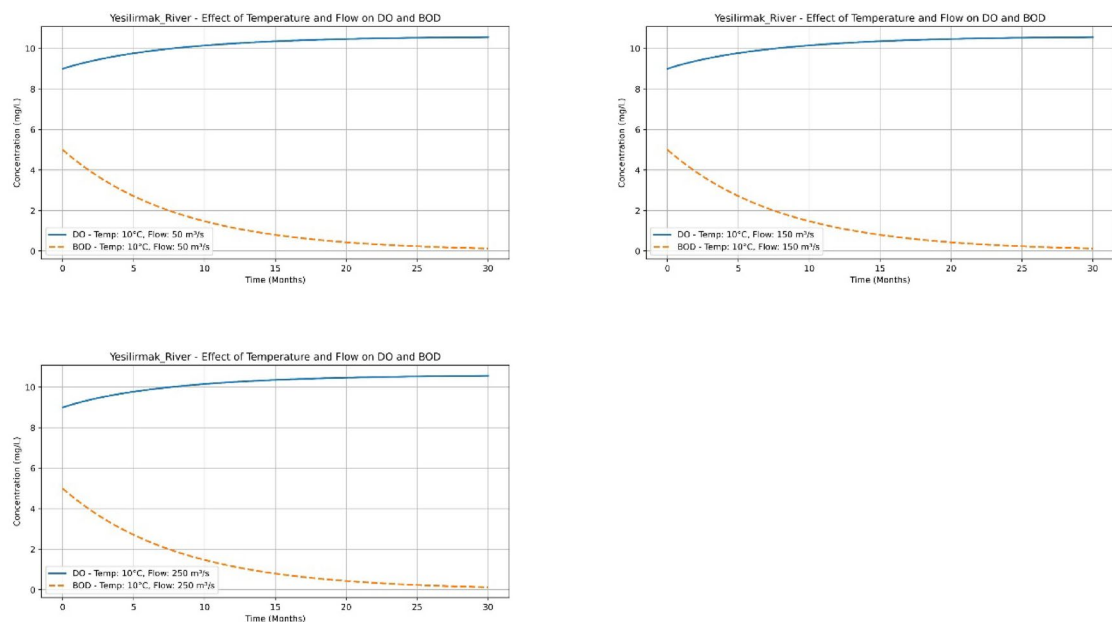


Fig. 12. DO and BOD in the Yeşilirmak under Different Flow Conditions (10 °C).

Discussion

The findings of this study underscore the critical role of temperature and flow rate in influencing the DO and BOD dynamics across four major Turkish rivers—Kızılırmak, Sakarya, Seyhan, and Yeşilirmak. The Extended Streeter-Phelps Model enabled a nuanced understanding of how these parameters interact to affect oxygen availability, which has implications for water quality management in regions with varying seasonal and anthropogenic pressures.

Impact of temperature and flow on DO and BOD

The study demonstrates that DO levels generally decrease with increasing temperature, aligning with previous research indicating reduced oxygen solubility at higher temperatures^{7,43}. This relationship was evident across all rivers, with DO concentrations declining significantly at 30 °C. Higher temperatures also accelerated microbial activity, as reflected in the initial increase in BOD levels, a finding consistent with studies highlighting

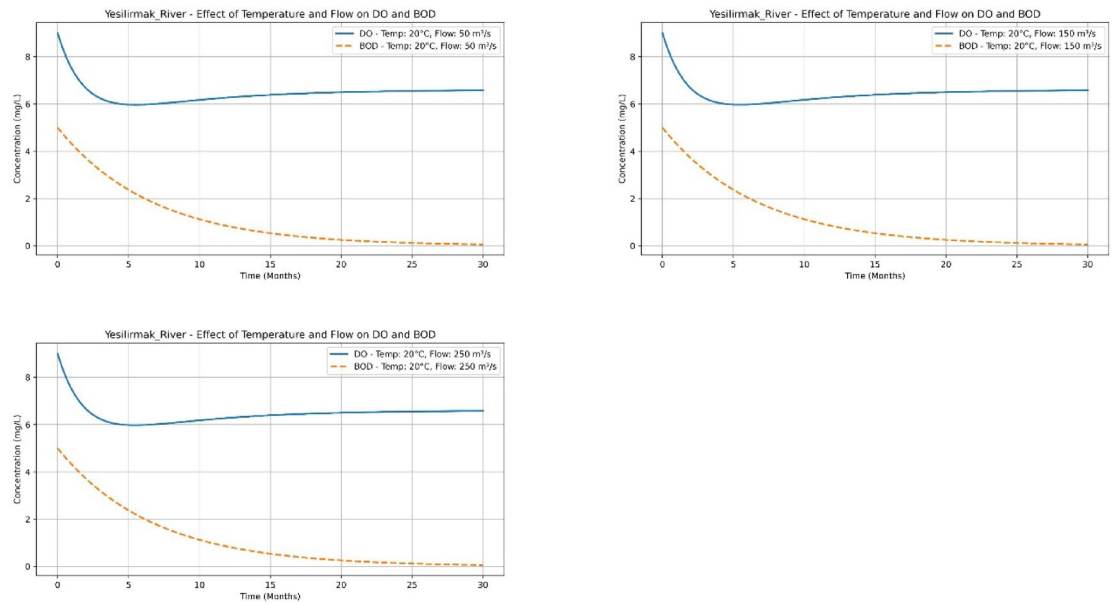


Fig. 13. DO and BOD in the Yeşilirmak under Different Flow Conditions (20 °C).

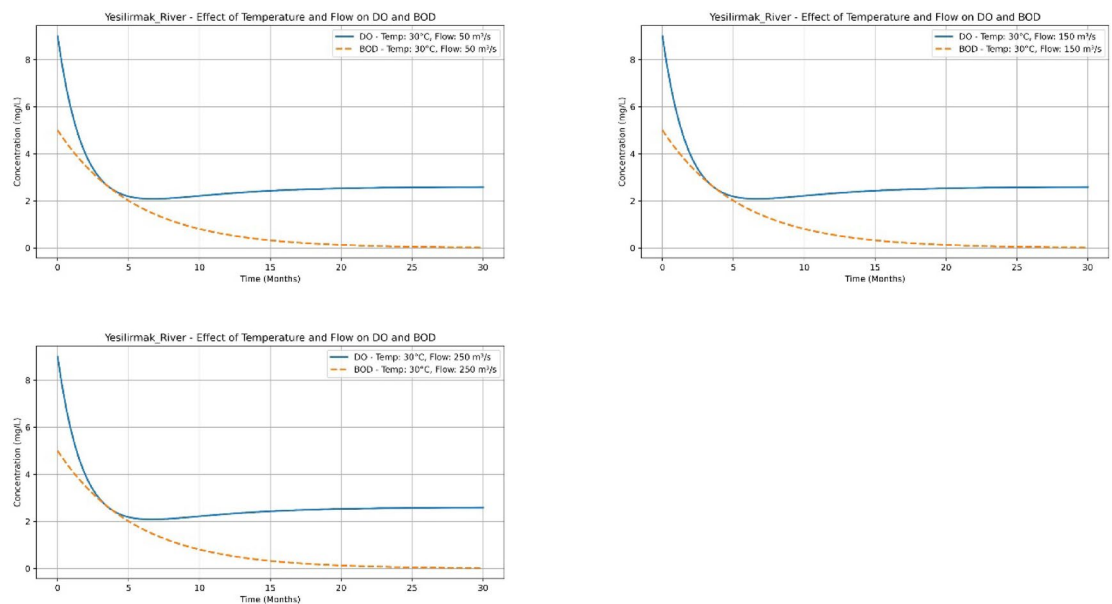


Fig. 14. DO and BOD in the Yeşilirmak under Different Flow Conditions (30 °C).

the temperature-dependency of organic matter decay rates^{12,19}. However, flow rate mitigated some of these temperature effects, as higher flow rates enhanced DO levels through increased mixing and aeration, in agreement with the observations of Owens et al.³⁴.

Each river exhibited unique responses to temperature and flow variations due to distinct hydrological characteristics and land use influences. For example, the Kızılırmak River showed relatively stable DO levels at lower temperatures, but significant reductions at higher temperatures and flow rates, indicating sensitivity to thermal changes. This variability may be attributed to the river's agricultural and industrial inputs, which affect oxygen dynamics and organic loads¹⁸. Similarly, the Sakarya River demonstrated notable fluctuations in DO and BOD levels, particularly at 20 °C, reflecting the influence of agricultural runoff and urban discharge in modulating oxygen dynamics⁴¹.

A comparative evaluation of the four rivers reveals that their responses to temperature and flow variations differ due to unique hydrological, morphological, and anthropogenic characteristics. For instance, the Kızılırmak River, which receives substantial agricultural and industrial input, exhibited sharper BOD increases at elevated temperatures, likely due to higher baseline organic loads. In contrast, the Yeşilirmak River showed more stable

DO levels across scenarios, suggesting a better natural buffering capacity, possibly due to higher base flows and lower anthropogenic pressures. The Sakarya River demonstrated moderate DO fluctuations, reflecting its mixed land use and relatively urbanized catchment, while the Seyhan River, influenced by both urban and seasonal irrigation discharge, showed more variable behavior depending on flow regime. These inter-river differences emphasize the role of both natural flow dynamics and localized pollution pressures in shaping oxygen-related water quality responses.

The utility of the extended Streeter-Phelps model

The model's incorporation of temperature and flow adjustments for decay and reoxygenation rates proved valuable in capturing the complex interactions influencing DO and BOD under diverse environmental conditions. Studies have shown that traditional models often fall short in representing dynamic river systems with variable flow and temperature regimes^{16,45}. By accounting for these factors, the Extended Streeter-Phelps Model provided a more accurate simulation of DO and BOD variations, which is critical for rivers with significant seasonal fluctuations or anthropogenic impacts. This study's findings support the model's application in water quality assessments, as suggested by Nas and Nas^{32,52}, particularly in Mediterranean climates where temperature and flow extremes are common.

While the Extended Streeter-Phelps Model successfully captured temperature and flow-related dynamics, it is important to acknowledge certain limitations. Specifically, the model does not explicitly account for additional sources and sinks of dissolved oxygen such as sediment oxygen demand (SOD), algal photosynthesis, or nitrification processes. These factors can influence DO concentrations, especially in eutrophic or stratified river segments. Although their exclusion simplifies the model and allows a focused evaluation of thermal and hydraulic effects, it introduces a degree of uncertainty that should be considered when interpreting the results.

Implications for river management and conservation

The insights gained from this study can inform river management practices aimed at maintaining oxygen levels essential for aquatic ecosystems. For instance, the results suggest that managing flow rates, especially during warmer months, could mitigate the adverse effects of high temperatures on DO concentrations. This approach aligns with conservation strategies that prioritize adaptive management in response to climatic variability, as emphasized in recent literature⁴⁸. Additionally, targeted efforts to reduce organic load inputs, particularly in regions with agricultural and industrial activities, could help control BOD levels and preserve oxygen availability.

For example, in Kızılırmak and Seyhan Rivers, where BOD levels rise more sharply under high temperatures and low flows, summer-season flow support and stricter regulation of wastewater discharge may help maintain oxygen thresholds. In contrast, Yeşilırmak River, which demonstrated more stable DO under varying conditions, could benefit from preservation of its natural flow regime and catchment protection. Management interventions could include adaptive reservoir releases to maintain flows above 150 m³/s when ambient river temperatures exceed 25 °C, which was found to significantly reduce DO decline in several simulations. Such river-specific, threshold-informed actions offer a practical application of modeling insights for real-time water quality management under climate stress.

Conclusion

In conclusion, this study demonstrates the applicability of water quality modeling approaches that explicitly incorporate temperature and flow adjustments—variables already considered in many process-based models—for analyzing oxygen dynamics in large river systems under varied environmental scenarios. The Extended Streeter-Phelps Model, with its adaptability to variable hydrological contexts, provides a robust framework for simulating oxygen dynamics in rivers facing seasonal and anthropogenic pressures. Future research could expand on these findings by examining the model's application in other river systems with distinct climatic and land use characteristics, contributing to global efforts to manage and protect freshwater resources.

Data availability

The research data supporting the findings of this study are not publicly available due to proprietary restrictions and further data can be made available from the corresponding author on reasonable request.

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Author contributions

CRedit authorship contribution statement Veysel Süleyman Yavuz: Conceptualization, Investigation, Methodology, Data Curation, Formal Analysis, Visualization, Writing – original draft, Writing – review & editing.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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