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Modeling the Effect of WWTP Bypass Events on Water Quality in Sebou River Estuary, Morocco

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ABSTRACT

Historically, urban wastewater from Kenitra was directly discharged into the Sebou estuary (68 km) through six collectors, producing environmental degradation and prompting the Kenitra wastewater treatment plant (WWTP) in 2020. Although designed to treat all urban wastewater before discharge, WWTP (19.4 km from the mouth) experiences bypass events during Eid al-Adha when organic loads surge due to widespread animal slaughter. This study aims to model the Bypass impact on Sebou estuary water quality, focusing on biochemical oxygen demand (BOD_5) as a key indicator. Given the strong dependence of water quality on hydrodynamics, a one-dimensional hydraulic model (HEC-RAS5.0.6) was used, calibrated, and validated using morphological datasets. The hydraulic simulation outputs (water levels and flow velocities) were then used in the water quality module to simulate BOD_5 dynamics. Three scenarios were examined: untreated discharge, discharge after treatment at WWTP, and Eid al-Adha bypass event. The results indicated a 90% BOD_5 reduction post-treatment, confirming WWTP efficiency. However, during the bypass event, BOD_5 surged to 4.3 $mg.L^{-1}$, significantly deteriorating Sebou estuary water quality. The pollution residence time varied from 3 days under high freshwater flow (300 $m^3.s^{-1}$) to 9 days under tidal dominance (0 $m^3.s^{-1}$). These findings highlight the urgent need for adaptive wastewater management (pre-treatment during peak periods and public awareness campaigns) during peak-load events to mitigate ecological risks and safeguard downstream communities relying on the estuary for water and livelihoods.

INTRODUCTION

Estuaries are dynamic environments where freshwater and seawater meet, creating complex ecosystems that are highly sensitive to variations in water quality (Robins et al. 2016, Zedler 2017). Pollution peaks, often due to untreated discharges or exceptional events, can severely disrupt these fragile balances, threatening biodiversity and ecosystem services (Nizar et al. 2022a). One of the main objectives is to establish sustainable management policies and governance rules to preserve estuarine health and ensure water resource sustainability (Kettab 2014). In this context, the present study aims to address the following research question: How do pollution peaks caused by exceptional events, particularly temporary discharges of untreated wastewater with a focus on biochemical oxygen demand (BOD_5) levels, affect estuarine water quality and pollutant residence time under varying hydrodynamic conditions?

The Sebou Estuary, a vital transition zone between the freshwater of the Sebou River and the saltwater of the Atlantic Ocean, supports a rich biodiversity and is essential for maintaining the region's ecological equilibrium (Haddout et al. 2016). However, like many estuarine systems worldwide, the Sebou Estuary faces increasing pressure from anthropogenic activities, including the discharge of urban wastewater (Nizar et al. 2022a). In Kenitra, Morocco, the Kenitra Wastewater

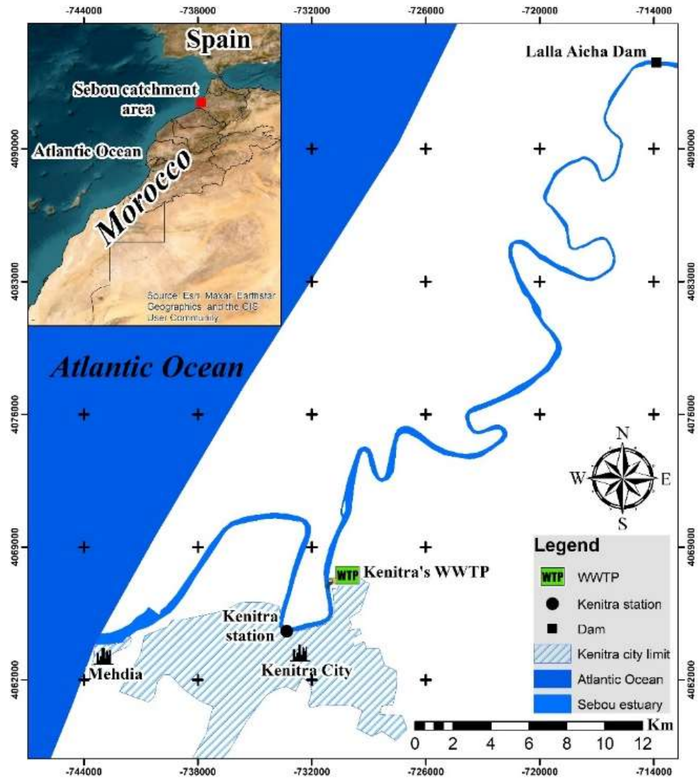

Fig. 1: Study area location.

Treatment Plant (WWTP) serves as the primary point source for treated wastewater discharge into the estuary. While the WWTP significantly improves water quality under normal operating conditions, it experiences periodic bypass events during the Eid al-Adha religious holiday due to the dramatic increase in organic loading from widespread animal slaughter. These bypass events, where untreated wastewater is directly released into the estuary, pose a significant threat to the estuarine ecosystem, raising concerns about the long-term impacts on water quality, ecosystem health, and disruption to the economic and agricultural activities in the region (Nizar et al. 2022b).

The challenge of managing wastewater during Eid al-Adha is not unique to Kenitra. As El Allaoui et al. (2017) highlight in their study of Fez city effluents, the surge in organic waste during this period can exceed the capacity of wastewater treatment facilities. Similar issues related to slaughterhouse waste management during Eid al-Adha have been highlighted by Salehin et al. (2021), emphasizing the need for effective strategies to mitigate the environmental impact of this important cultural event. The vulnerability of WWTPs to operational failures and their subsequent impact on receiving waters has also been demonstrated. For instance, Jaskulak et al. (2022) analyzed a major WWTP failure in Warsaw, Poland, where a collection system malfunction led to the release of more than 4.8 million m^3 of untreated discharge into the Vistula River. Their study revealed significant and prolonged deterioration of water quality in both the estuary and the Baltic Sea, even more than 400 km downstream from the unloading location. While the context of a system malfunction differs from the bypass events during Eid al-Adha in Kenitra, Jaskulak et al. (2022) underscore the potential for large-volume releases of untreated wastewater to have substantial and far-reaching consequences for aquatic ecosystems. These studies, including those focused on Eid al-Adha waste management, highlight the importance of understanding the consequences of such events and developing robust management plans to protect aquatic ecosystems.

Before the construction of the Kenitra WWTP in 2020, untreated wastewater from the city was discharged directly into the Sebou Estuary through six separate collectors (Nizar et al. 2022c). This situation led to significant environmental and health problems, prompting the development of a strategic plan (2015-2020) that included the construction of the WWTP to reduce pollution in the Sebou basin (Nizar et al. 2022c). The WWTP now collects and treats wastewater from Kenitra, becoming the single discharge point for treated effluent into the estuary. However, the challenge of managing the peak organic load during Eid al-Adha remains.

The Sebou River, one of Morocco's largest waterways alongside the Moulouya and Oum Er-Rbia rivers, drains a watershed of about 40,000 km^2 (5.5 % of the country's total area) in the northwest between 4° and 7° W and 33° and 35° N. Originating in the Middle Atlas Mountains under the name Oued Guigou (Combe 1966), it flows over 600 km before emptying into the Atlantic Ocean at Mehdia, near Kenitra. The Sebou estuary, the focus of this study, covers approximately 70 km between the Lalla Aicha guard dam and the river mouth (Fig. 1). Tidal forces and freshwater releases govern its dynamics from the dam (Mergaoui et al. 2003). The Lalla Aicha guard dam plays a vital role in limiting saltwater intrusion, which historically affected upstream irrigation zones (Haddout et al. 2016).

The hydrodynamics of the estuary, including tidal influence and freshwater flow, govern the transport and fate of pollutants. The semi-diurnal sinusoidal tide, with a cycle of 12.17 hours and an amplitude of 0.97 to 3.11 meters, creates an average discharge of approximately 250 $m^3.s^{-1}$ at the mouth (Touazit et al. 2024). Tidal influence extends 45 km upstream, with patterns of filling at high tide and emptying at low tide (Mergaoui et al. 2003). The effect of wind on the flow is negligible due to the narrowness of the estuary (Haddout et al. 2016). The Sebou estuary is classified as partially mixed, reflecting the balance between river discharge and tidal mixing (Thatcher & Harleman 1981).

Previous studies on the Sebou Estuary (Combe 1966, Mergaoui et al. 2003, Palma et al. 2012, Haddout et al. 2016, Nizar et al. 2022a, 2022b, 2022c, Ech-chayeb et al. 2023, Touazit et al. 2024) have primarily focused on field measurements and the general assessment of pollution levels. While these works provide valuable baseline data, they did not investigate the combined influence of morphological and hydrodynamic conditions on pollution dynamics, nor did they address the specific impact of bypass events from the Kenitra WWTP. This gap is significant, especially considering that although the WWTP has proven effective under normal operation (Nizar et al. 2022a), it remains vulnerable to bypass events during exceptional circumstances, which can temporarily undermine its environmental benefits. The present study contributes new insights by modeling the spatial-temporal evolution of BOD_5 pollution during such events, taking into account hydrodynamic variability. This approach supports environmental managers with rapid and reliable tools for evaluating pollutant dispersion in the estuary and developing adaptive strategies under stress conditions.

One-dimensional mathematical models offer a valuable tool for this purpose due to their relative simplicity, ease of application, and suitability for management scenarios. Furthermore, a methodological approach that begins with simpler representations of the phenomena under study, such as 1D models, is often preferred. This allows researchers to evaluate the limitations of these approximations before progressing to more complex and computationally demanding models, ensuring a balanced approach between model complexity and practical applicability.

This paper aims to model Sebou water quality during WWTP bypass events at Eid al-Adha. The hydraulic regime of the Sebou River estuary was modeled using a one-dimensional model (HECRAS 5.0.6). Calibration and validation of the HEC-RAS model were performed using hydraulic and morphological datasets from 2020. The evolution of hydrodynamic variables (water levels and flow velocities) was simulated by the hydraulic model and used to model the dissolved oxygen (DO) and the biochemical oxygen demand (BOD_5) in the water-quality HEC-RAS module. Three scenarios were analyzed: discharge without treatment, reflecting pre-WWTP conditions (mean BOD_5 of 414.13 $mg.L^{-1}$), discharge after treatment, representing the standard WWTP operation (mean BOD_5 of 21 $mg.L^{-1}$), and the exceptional Eid al-Adha period, during which the WWTP is bypassed (mean BOD_5 of 990 $mg.L^{-1}$). The results highlighted the role of tidal dynamics and upstream freshwater flows in shaping pollutant dispersion. They confirmed that the WWTP significantly reduced BOD_5 levels in the estuary and offered insights into pollutant dispersion patterns and residence times.

This study is the first to assess the impact of WWTP bypass events during Eid al-Adha on water quality in the Sebou Estuary, addressing concerns highlighted by earlier works (Haddout et al. 2016, Nizar et al. 2022a) regarding periods of exceptional organic load that exceed treatment capacity. It offers new perspectives on the performance of the Kenitra WWTP, the risks linked to peak pollution episodes, and the need to incorporate such events into coastal management planning.

MATERIALS AND METHODS

Kenitra's WWTP

The Kenitra WWTP (Fig. 2) employs an activated sludge process with medium load to treat urban wastewater before discharge into the Sebou Estuary. This modern facility, covering 6 hectares, has a current treatment capacity of 700,000 equivalent inhabitants (EH) and is projected to reach 1,050,000 EH by 2030. The treatment process is divided into three modules: water treatment, sludge treatment, and biogas production. The plant also includes a control room and an analytical laboratory for process monitoring and optimization. A key feature of the WWTP is its focus on energy sustainability. Biogas cogeneration covers over 45% of the plant's electricity needs, and photovoltaic panels provide 100% of the lighting requirements. Treated wastewater is classified as "urban wastewater" (Nizar et al. 2022b).

Normally, treated effluent is discharged into the Sebou Estuary. However, during Eid al-Adha, the Kenitra WWTP often experiences a significant surge in organic load due to widespread animal slaughter. This sudden increase exceeds the facility's treatment capacity (0.7 $m^3.s^{-1}$), resulting in a hydraulic overflow. Consequently, unplanned bypass events occur, during which untreated wastewater is directly released into the estuary (Nizar et al. 2022b).

In 2021, the WWTP conducted a trial to assess its ability to handle the Eid al-Adha wastewater flow. During this year only, the WWTP successfully treated the Eid al-Adha wastewater flow, which reached 0.6 $m^3.s^{-1}$, a level within the plant's capacity. However, during the Eid al-Adha periods of 2020, 2022, 2023, and 2024, the organic load exceeded the WWTP's capacity, resulting in bypass events. The 2021 dataset is thus used as a baseline reference to characterize treated discharges and assess their impact on estuarine water quality. Three simulation scenarios were developed to explore the influence of WWTP operations. This comparative approach provides a clearer understanding of the potential consequences of WWTP performance or failure during high-load periods and helps quantify the environmental risk associated with bypass events.

Biochemical Oxygen Demand (BOD_5) Measurement

Biochemical Oxygen Demand (BOD_5) represents the amount of dissolved oxygen consumed by bacteria to partially degrade or fully oxidize biodegradable organic matter in water (Das et al. 2024). In this study, BOD_5 analyses at the WWTP were conducted daily at the RAK laboratory (Régie Autonome de Kénitra) using water samples collected with the Endress+Hauser XE4302.2, an instrument designed for continuous water monitoring and automatic sampling. BOD_5 was determined using the OxiTop® system, a manometric respirometric technique based on pressure changes in a closed system. As microorganisms consume oxygen and produce CO_2, which is absorbed by sodium hydroxide (NaOH) pellets, allowing indirect measurement of oxygen uptake via the resulting pressure drop (Rahmati et al. 2021). Two measurement modes were employed: for raw wastewater, 164 mL of sample was analyzed and the result multiplied by 10, for treated wastewater, 43.5 mL was used and the result multiplied by 50. Since BOD_5 levels are inherently dependent on the amount of available organic matter, the measurement system was calibrated based on the volumes of the analyzed samples. Temperature stabilization is crucial for accurate BOD_5 measurements due to its influence on biological activity (Maddah 2022). All BOD_5 measurements were performed at a controlled temperature of 20°C within a thermostatically controlled cabinet.

Mathematical Hydraulic Model

The one-dimensional approach was applied in this study, as it is suitable for long-distance river courses. The HEC-RAS (5.0.7) mathematical model, developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers (Brunner 2016), was used to simulate open-surface flows. This integrated hydraulic analysis software can simulate steady and unsteady flows, sediment transport, and other functions that aid in the design and analysis of hydraulic

Fig. 2: Overview of the location of the Kenitra's WWTP.

structures (Nizar et al. 2022a). It is important to note that while the 1D HEC-RAS model is well-suited for simulating longitudinal flow and pollutant transport in elongated estuarine systems, it does not account for lateral mixing or vertical stratification. These limitations may affect the spatial accuracy of water quality predictions in areas where multidimensional flow dynamics are significant. The Sebou estuary's water quality is strongly influenced by its hydraulic regime. The one-dimensional Saint-Venant equations, which govern the conservation of mass and momentum, form the basis of the HEC-RAS model and are expressed as follows (Brunner 2016):

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}-q_1=0 \qquad ...(1)$$

$$\frac{\partial (VA)}{\partial t}+\frac{\partial (QV)}{\partial x}+gA\left(\frac{\partial Z}{\partial x}+S_f\right)=0 \qquad ...(2)$$

Where V is the velocity ($m.s^{-1}$), Q is river flow ($m^3.s^{-1}$), A denotes the cross-section area (m^2), q_l represents lateral inflow ($m^2.s^{-1}$), x and t are the distance of the estuary (m) and time (s), respectively, g indicates acceleration of gravity (9.81 $m.s^{-2}$), $\partial Z/\partial x$ refers to the flow surface slope (m), and S_f (Dimensionless) is the frictional slope expressed as (Nizar et al. 2022a):

$$S_f=\frac{Q|Q|n^2}{2.208\,A^2R^{\frac{4}{3}}} \qquad ...(3)$$

Where R (m) is the hydrodynamic radius, and n represents Manning's roughness coefficient ($1.m^{-1/3}.s^{-1}$). The initial estimation of Manning's roughness coefficient integrated into equation (3) is obtained using the empirical equation discovered by Chow (1973), expressed as:

$$n=(n_0+n_1+n_2+n_3+n_4).m_5 \qquad ...(4)$$

Where n_0 represents the correction factor for river bed granularity, n_1 refers to the correction factor of the influence of irregularity in river, n_2 refers to the correction factor for cross-section type and shape, n_3 refers to the correction factor for the effects of obstacles, n_4 means the correction for the effect of the presence of vegetation on the banks, and m_5 denotes the correction factor for the degree of meandering in the river. The n_0 factor was assessed based on the granulometric data collected along the estuary. The other factors were also assessed during the field visits, cross-section, available photos, and aerial photos. Equations (1) and (2) were solved using the four-point implicit box finite difference scheme. The commonly used forms of the derived equations for a function *f* are presented below. The time and spatial derivatives are given in equations (5) and (6):

$$\frac{\partial f}{\partial t}\approx\frac{\Delta f}{\Delta t}=\frac{0.5\left(\Delta f_{j+1}+\Delta f_j\right)}{\Delta t} \qquad ...(5)$$

$$\frac{\partial f}{\partial x}\approx\frac{\Delta f}{\Delta x}=\frac{\theta\left(\Delta f_{j+1}-\Delta f_j\right)+\left(f_{j+1}-f_j\right)}{\Delta x} \qquad ...(6)$$

The value of the function f is given in equation (7):

$$f\approx\bar{f}=0.5.\theta.\left(\Delta f_j+\Delta f_{j+1}\right)+0.5\left(f_{j+1}+f_j\right) \qquad ...(7)$$

Where θ represents the weighting factor, its default value in HEC-RAS is 1 (Brunner 2016). Solving the system of equations needs spatial discretization of the river estuary into characteristic grids and determining the geometry of the river, upstream and downstream boundaries, and initial river flow. The Sebou estuary was divided into 1310 grids, each ranging from 46 to 49 meters in length, with an average of 48 meters. For each grid, the length, cross-sectional area, and Manning friction factor were specified.

Transport Model

In the HEC-RAS model, the water quality transport module uses the advection-dispersion equation, based on the mass balance equation, with supplementary terms to incorporate lateral inflows (Brunner 2016). For BOD_5 simulation, the transport equation is expressed as follows (Brunner 2016):

$$\frac{\partial (AC_{BOD})}{\partial t}=-\frac{\partial (QC_{BOD})}{\partial x}+\frac{\partial}{\partial x}\left(AD_x\frac{\partial C_{BOD}}{\partial x}\right)-AK_1C_{BOD}+AR_{BOD} \qquad ...(8)$$

Where C_{BOD} represents the organic matter concentration ($kg.m^{-3}$), R_{BOD} denotes the organic matter release ($mg.L^{-1}$), K_1 indicates the coefficient of oxidation ($1.days^{-1}$), which was empirically calibrated using field observations, and D_x is the dispersion coefficient ($m^2.s^{-1}$), which is the key parameter that must receive appropriate evaluation. The HEC-RAS water quality module utilizes the ULTIMATE QUICKEST explicit numerical scheme developed by Leonard to solve the advection-dispersion equation. The resulting finite difference solution for equation (8) is given as follows (Brunner 2016):

$$V^{n+1}C^{n+1}=V^nC^n+\Delta t\times\left(Q_{up}C^*_{up}-Q_{dn}C^*_{dn}+D_{dn}A_{dn}\left.\frac{\partial C^*}{\partial x}\right|_{dn}-D_{up}A_{up}\frac{\partial C^*}{\partial x}\left.\frac{\partial C^*}{\partial x}\right|_{up}\right) \qquad ...(9)$$

Where V^{n+1} and V^n (m^3) are the water quality cell volumes at the next and current time steps, respectively, C^{n+1} and C^n ($kg.m^{-3}$) represent the constituent concentration at the current and preceding time step, respectively, C^*_{up} denotes the upstream face QUICKEST concentration ($kg.m^{-3}$), Q_{up} refers to the flow of the upstream face ($m^3.s^{-1}$), $(\partial C^*/\partial x)_{up}$ indicates the QUICKEST derivative at the upstream face ($kg.m^{-4}$), D_{up} refers to the upstream face dispersion coefficient ($m^2.s^{-1}$), and A_{up} refers to the upstream face area (cross-sectional) (m^2). The water quality module inputs are the initial concentration, boundary conditions concentrations,

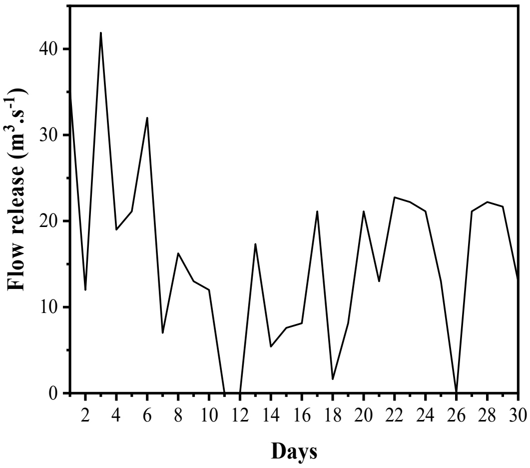

Fig. 3: Flow release by Lalla Aicha dam (upstream boundary condition), June 2021.

and dispersion coefficient. This parameter was computed using the Fischer equation (Fischer et al. 1979):

$$D_x = 10.62\left(\frac{U^2 w^2}{U^* h}\right) \quad ...(10)$$

Where w is the mean channel width (m), U denotes the flow velocity ($m.s^{-1}$), U* corresponds to the shear velocity ($m.s^{-1}$), and h represents the mean channel depth (m).

RESULTS AND DISCUSSION

Calibration and Validation of Hydraulic Model

The boundary conditions of the hydrodynamic model are constituted by the flows released by the Lalla Aicha guard dam (upstream condition) obtained from the Hydraulics Directorate of Kenitra (Fig. 3) and the temporal evolution of the water level at the estuary mouth (Port of Mehdia) (downstream condition) obtained from SHOM (Maritime Hydrographic and Oceanographic Service) (Fig. 4).

In the hydraulic simulation, the hydrodynamic model was subjected to calibration and validation. The Manning roughness coefficient in the estuary is the parameter used for calibration. Calibrating a model consists of simulating a given period, knowing the initial and boundary conditions, and comparing the model outputs (water level, flow, etc.) with field measurements by adjusting the Manning coefficient, which is initially estimated by the Cowan and Chow formula. This coefficient was uniformly adjusted along the entire study reach, assuming that the sources of error influencing its variation were consistent across all grid cells.

Water level data from the Kenitra station (Fig. 1) were used to calibrate and validate the model, as these measurements can be obtained there by the National Ports Agency (ANP). The calibration process utilized data from June 1st, 2021, to June 15th, 2021. A strong agreement was obtained between the water level simulated by the model and that measured at Kenitra station (Fig. 5). To confirm the calibration results, a model validation test is usually performed. This test consists of simulating the flow regime over a period other than the one used in the calibration while keeping the same Manning coefficient values. In this study, the validation test was performed for the period ranging from June 15th, 2021, to June 30th, 2021. The output variables are well reproduced, which attests to the performance of the model.

The performance of the hydraulic model was evaluated using statistical indicators, including the root-mean-squared error (RMSE), normalized objective function (NOF), and Nash-Sutcliffe coefficient (NSC) (Abbi et al. 2025). The RMSE gives a measure of the model error, with a value of 0 indicating perfect agreement between measured and

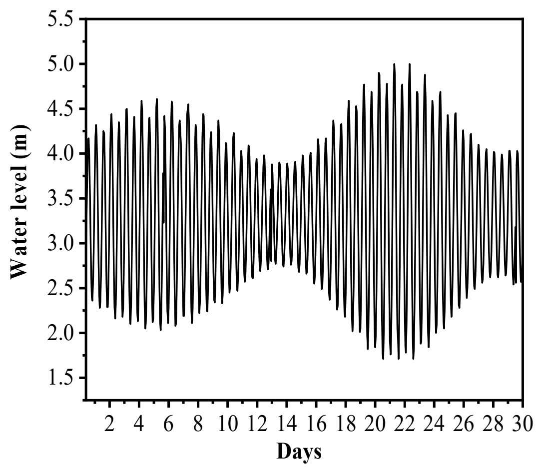

Fig. 4: Semi-diurnal tide at estuary mouth (Downstream boundary condition), June 2021.

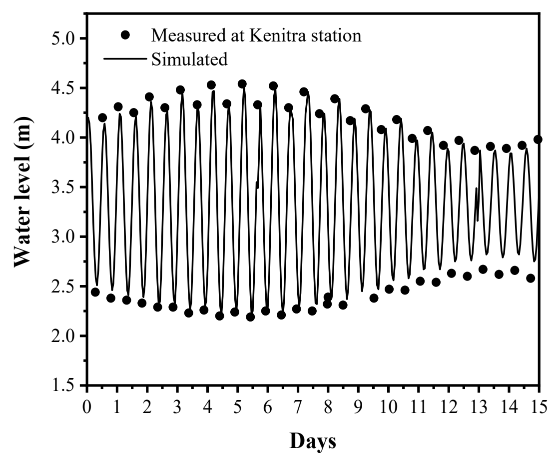

Fig. 5: Hydraulic calibration using water level from Kenitra station (from 1st to 15th June 2021).

Table 1: Statistical indicators used to assess the performance of the model.

Statistical indicators	RMSE	NOF	NSC
Calibration phase	0.18	0.05	0.98
Validation phase	0.11	0.04	0.99

simulated values. For NSC, it ranges between -∞ and 1, with values tending towards 1 indicating the strong performance of the model, and the NOF, with a value less than 1 indicating negligible model error (Abbi et al. 2025). The statistical analysis revealed an NOF value below 1, a low RMSE, and an NSC value near 1, indicating the model's efficiency and confirming the success of its calibration and validation (Table 1).

The outputs of the HEC-RAS model make it possible to estimate the spatiotemporal evolution of numerous hydraulic parameters, such as river velocity, water level, and river flow. Fig. 6 shows the velocity evolution from downstream to upstream in the section subject to study for both tide states (high tide and low tide) during spring and neap tides. A strong fluctuation is observed in the flow velocity, which is due to the influence of the estuary's morphology and bottom. The spring tide period's velocities are higher than those of the neap tide, especially downstream. At high tide, the velocities are also significant but in the opposite direction. Also, the results show sites with high velocity values (from 3 to 8 km, 15 km, 20 km).

Water Quality Simulation Results

Water quality simulations for the Sebou Estuary were conducted between June and August 2021. The dispersion coefficient, calculated using the Fischer equation, was estimated at 150.27 $m^2.s^{-1}$. Three scenarios were analyzed: untreated urban wastewater discharge, treated effluent discharge from the WWTP, and a bypass event scenario during peak pollution periods such as Eid al-Adha, where treatment is temporarily suspended.

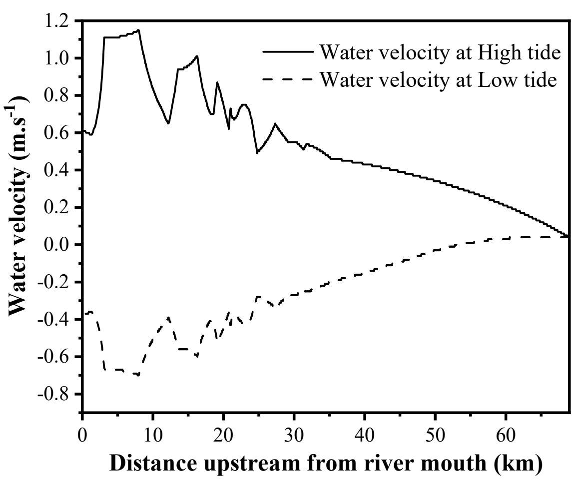

Fig. 6: Velocity profile estimated at high and low tides along the Sebou estuary.

In the primary simulation, the inflow of urban wastewater into the Sebou estuary is shown in Fig. 7, while the corresponding BOD_5 concentrations are illustrated in Fig. 8. On the day of Eid al-Adha, the discharge flow reached to 0.55 $m^3.s^{-1}$, reflecting a 14% increase compared to the average flow observed during the monitoring period (Fig. 7). Simultaneously, the BOD_5 concentration rose to 990 $mg.L^{-1}$, representing a 139% increase relative to the average concentration recorded during the same period (Fig. 8).

Fig. 9 shows the longitudinal variation of BOD_5 concentrations from the river mouth up to the Lalla Aicha guard dam under four tidal phases: high tide, falling tide, low tide, and rising tide. BOD_5 levels increase both upstream and downstream, but are significantly higher in the downstream

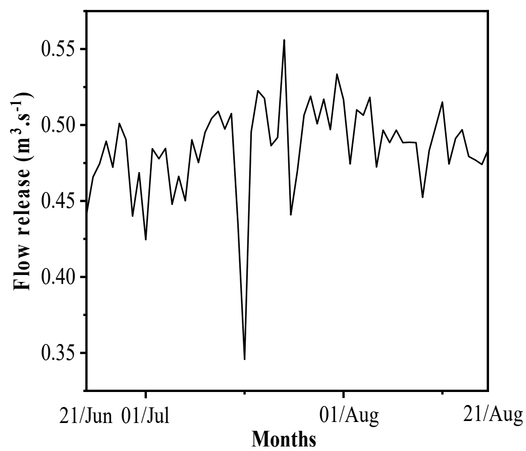

Fig. 7: Evolution of raw water flow discharged from Kenitra's WWTP (June 21st to August 21st, 2021).

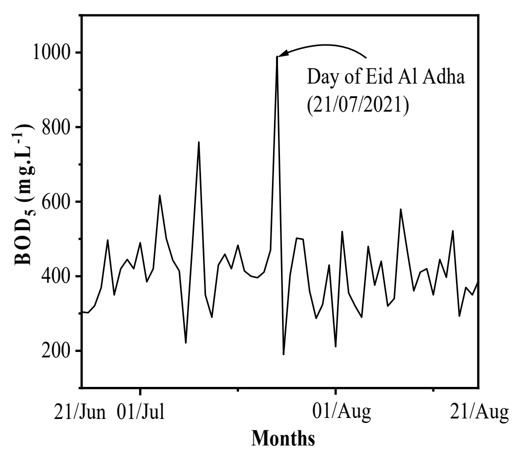

Fig. 8: BOD_5 concentration in raw water flow (lateral condition) (June 21st to August 21st, 2021).

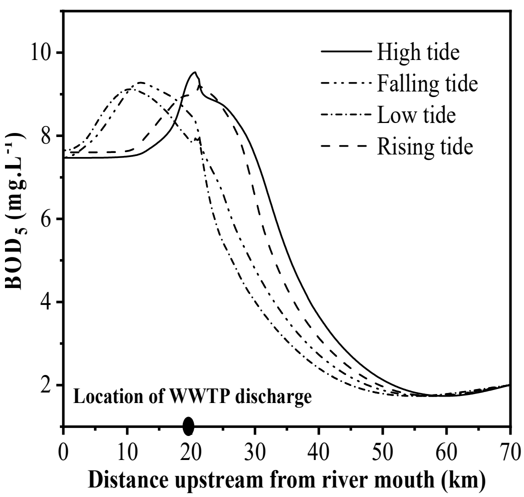

Fig. 9: Longitudinal evolution of BOD_5 along the Sebou estuary for untreated urban waters on July 21st, 2021.

sections. The BOD_5 concentrations at downstream from the WWTP during high tide exceed those observed during low tide, with a mean increase of 0.64 $mg.L^{-1}$ attributed to the dilution effect of cleaner continental waters. The movement of pollutants discharged into the estuary follows the tidal rhythm, transported downstream at low tide and driven upstream at high tide, resulting in pollutant accumulation downstream. However, this accumulation gradually decreases as a result of biochemical reactions and dispersion. Importantly, the increase in BOD_5 does not affect areas beyond 35 km from the river mouth.

The second simulation focuses on urban wastewater after treatment at the WWTP. The concentration of BOD_5 for treated urban wastewater at WWTP and discharged into the estuary is shown in Fig. 10. This reveals a considerable reduction of the BOD_5 concentration in the discharge. Previously, the untreated discharge ranged from 200 $mg.L^{-1}$ to 1000 $mg.L^{-1}$ (Fig. 8), which fails to comply with WHO guidelines for discharges into aquatic ecosystems. The installation of the WWTP significantly reduces pollution, so the BOD_5 concentrations typically do not exceed 20 $mg.L^{-1}$, except on Eid al-Adha, when they peaked at 50 $mg.L^{-1}$, which corresponds to 5% of the BOD_5 levels found in untreated discharge. This indicates that the WWTP reduced the BOD_5 levels during Eid al-Adha by 95%.

Fig. 11 highlights the progressive reduction of BOD_5 concentrations from upstream to downstream, primarily due to biochemical degradation and dispersion processes. No significant deterioration in water quality was observed, including the Eid al-Adha period. These results confirm the effective performance of the Kenitra WWTP in handling increased organic loads under controlled operational conditions, as recorded in 2021. The reduction of BOD_5 in the Sebou estuary is given as follows:

$$BOD_5\text{reduction} = \left(\frac{BOD_5\text{before treatment} - BOD_5\text{after treatment}}{BOD_5\text{before treatment}}\right) \times 100$$

The BOD_5 concentration in the Sebou River decreased from 9.8 $mg.L^{-1}$ before treatment to 0.9 $mg.L^{-1}$ after treatment, corresponding to an approximate reduction of 90%.

Simulation of WWTP Bypass During Eid al-Adha

Final simulations considered a discharge treated except that of the Eid al-Adha day (bypass in the WWTP), as shown in Fig. 12. The concentration of BOD_5 during Eid al-Adha is 990 $mg.L^{-1}$, which represents a 4591.9% increase from the average concentration observed during the monitoring period (50 $mg.L^{-1}$).

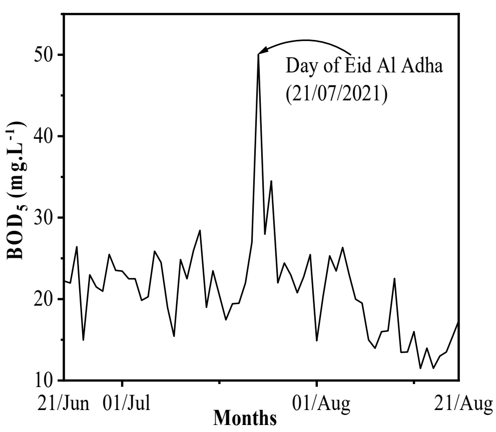

Fig. 10: BOD_5 concentration in water treated flow (lateral condition) (June 21st to August 21st, 2021).

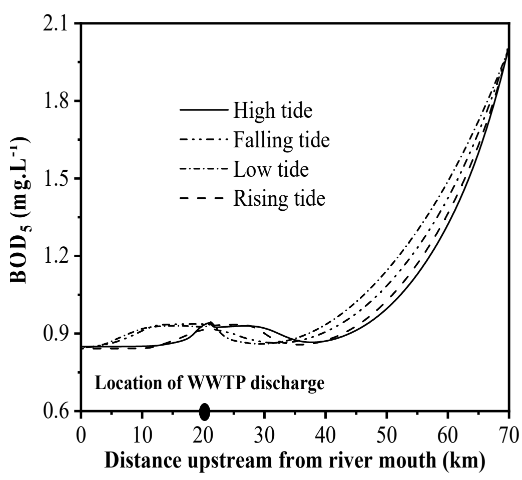

Fig. 11: Longitudinal evolution of BOD_5 along the Sebou estuary for treated urban waters on July 21st, 2021.

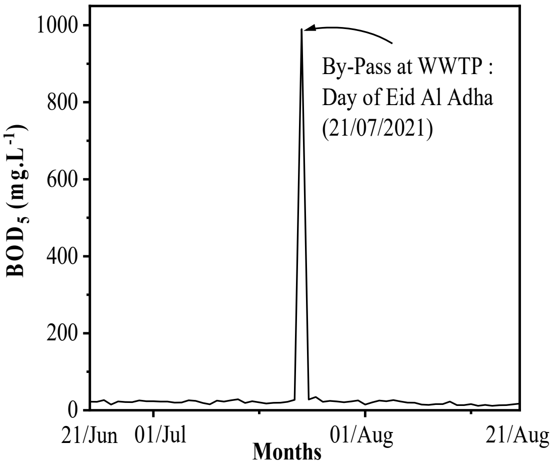

Fig. 12: BOD_5 concentration in the Bypass event at the WWTP during Eid al-Adha.

Fig. 13 shows the longitudinal evolution of BOD_5 concentrations from downstream to upstream under different residence times, following the end of the WWTP bypass event during Eid al-Adha, with a flow release of 43 $m^3.s^{-1}$. A marked deterioration in water quality was observed, particularly within the 0–35 km stretches from the estuary mouth, an area encompassing sensitive ecological zones adversely affected by decreased oxygen availability. BOD_5 concentrations rose to 4.3 $mg.L^{-1}$, reflecting a significant increase in organic pollution. Moreover, the residence time of this pollution within the estuary was approximately 7 days, reflecting the system's limited dilution and flushing capacity at this flow rate. The BOD_5 was reduced by approximately 56% during the WWTP bypass event on Eid al-Adha, compared to a 90% reduction under normal operating conditions.

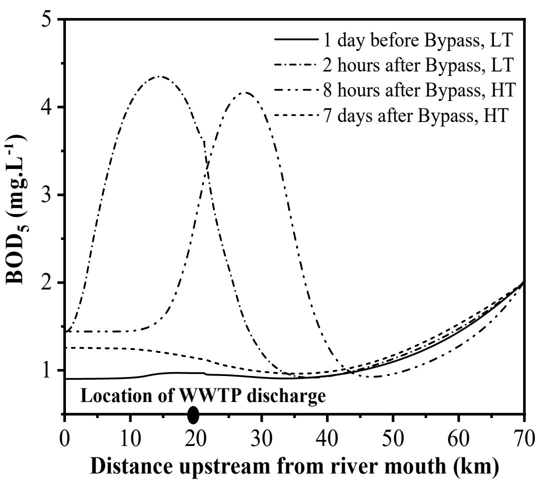

Fig. 13: BOD_5 along the estuary at different residence time after bypass event, for Q=43 $m^3.s^{-1}$, LT: low tide and HT: high tide.

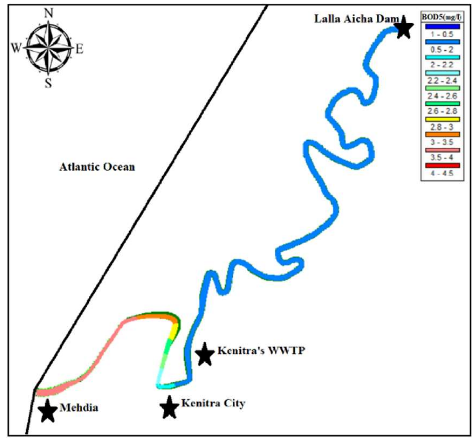

Fig. 14: BOD_5 distribution in the estuary at 2h after bypass event, for Q=300 $m^3.s^{-1}$, at low tide.

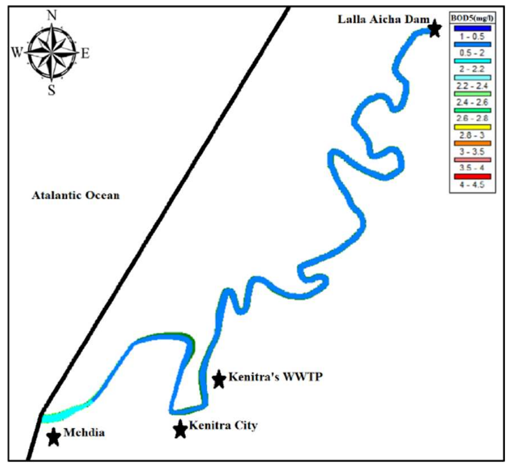

Fig. 15: BOD_5 distribution in the estuary 3 days after bypass event, for Q=300 $m^3.s^{-1}$, at low tide.

In this study, three simulations were carried out to assess the impact of freshwater flow rates released from the Lalla Aicha guard dam on the residence time of pollutants resulting from the WWTP bypass event in the Sebou estuary. These simulations considered two characteristic flow scenarios: a first with a free-flow condition at 300 $m^3.s^{-1}$ and a second simulating a closed dam at 0 $m^3.s^{-1}$. The analysis of BOD_5 discharges from the Kenitra WWTP under these different flow conditions offers valuable insights into the behavior and persistence of pollutants within the estuarine system.

For a free-flow condition at 300 $m^3.s^{-1}$, Figs. 14 and 15 show that after the discharge ended, BOD_5 released from WWTP was rapidly evacuated towards the ocean. The residence time was reduced to approximately 3 days, and a notable decrease in BOD_5 concentrations was observed. This is attributed to the enhanced flushing action, combined with natural attenuation processes such as dispersion and biodegradation.

Conversely, under conditions where no river flow is released (0 $m^3.s^{-1}$) from the Lalla Aïcha guard dam (upstream end), Figs. 16 and 17 show that the pollutant remains within the estuary even after 9 days, maintaining a BOD_5 concentration level of approximately 2 $mg.L^{-1}$. The limited dilution and circulation due to tidal dominance result in a residence time extending up to 10 days. These findings emphasize the critical role of freshwater input in controlling pollutant dispersion and improving estuarine water quality during pollution peaks.

In this low-flow context, marine tides emerge as influential regulators of BOD_5 discharges. The dispersion and movement of pollutants within the estuary are controlled by the tidal cycles. This observation highlights the significance of not only considering flow rates but also recognizing the intricate interdependencies between tidal dynamics and the fate of pollutants in the Sebou estuary water quality during peak pollution events such as Eid al-Adha.

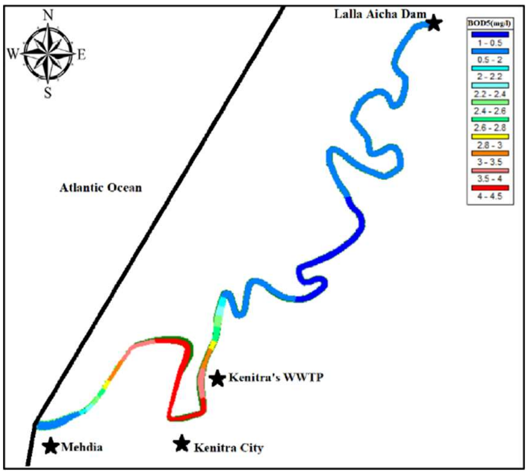

Fig. 16: BOD_5 distribution in the estuary 2h after bypass event, for Q=0 $m^3.s^{-1}$, at low tide.

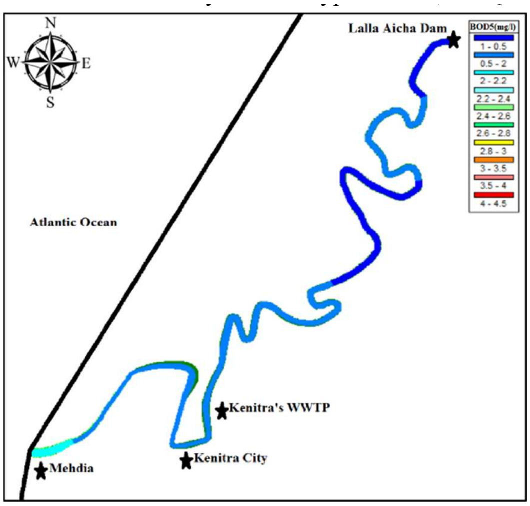

Fig. 17: BOD_5 distribution in the estuary 9 days after bypass event, for Q=0 $m^3.s^{-1}$, at low tide.

CONCLUSIONS

This study assessed the effect of bypass discharges from the Kenitra WWTP on Sebou estuary water quality during the pollution peak period associated with Eid al-Adha, using a calibrated and validated one-dimensional hydraulic model (HEC-RAS). The water quality module simulated BOD_5 variations along the estuary, based on hydraulic conditions. The findings revealed that, under normal operation, the WWTP achieves approximately 90% BOD_5 removal efficiency. However, during bypass events such as Eid al-Adha, this efficiency drops to around 56%, leading to BOD_5 concentrations of up to 4.3 $mg.L^{-1}$ in the estuary. These elevated levels can negatively affect aquatic ecosystems, particularly by reducing dissolved oxygen availability-critical for fish and invertebrates. This, in turn, poses risks to local fisheries and agricultural irrigation that rely on clean water sources. The simulation highlighted the influence of tides and river flows on the fate and dispersion of pollutants. At a freshwater flow of 300 $m^3.s^{-1}$ (freshwater dominance), complete decontamination of the WWTP bypass discharge occurs after an estimated residence time of 3 days, enabling faster evacuation of the discharge to the ocean. Under tidal dominance (0 $m^3.s^{-1}$ freshwater flow), pollutant retention increases, requiring about 10 days for full decontamination. These results highlight the necessity of addressing peak pollution events, such as those occurring during Eid al-Adha, in wastewater management strategies and WWTP design. To mitigate the impact of such events, several practical and quantitative measures can be considered. These include increasing treatment capacity, implementing pre-treatment during peak periods, launching public awareness campaigns to reduce organic waste, and increasing the flow release during Eid al-Adha to approximately 300 $m^3.s^{-1}$. This specific flow rate would help limit the residence time to 3 days, thereby significantly reducing the accumulation of organic pollutants. This study provides valuable insights and modeling tools to support informed decision-making for improved wastewater management and the protection of estuarine ecosystems.

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