URBAN EFFLUENT PROPAGATION IN INTERMITTENT RIVERS: KINEMATIC WAVE HYDRAULICS COUPLED WITH THE STREETER-PHELPS BOD-DO MODEL

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RESUMO – ETEs urbanas em municípios do semiárido lançam efluentes em rios intermitentes submetidos a condições sazonais contrastantes. Este estudo acopla a teoria da onda cinemática ao modelo DBO-OD de Streeter-Phelps e à fórmula de reaeração de O'Connor-Dobbins para simular, teoricamente, com parâmetros obtidos na literatura, a propagação superficial de efluentes de uma ETE na Bacia do Rio Paraíba do Meio (Alagoas, Brasil) em dois cenários: S1 (período seco, Q = 8 L/s apenas do efluente, DBO = 280 mg/L) e S2 (período chuvoso, Q = 508 L/s, DBO = 4,4 mg/L). A reduzida profundidade de escoamento em S1 (y_0 = 3,1 cm) gera coeficiente de reaeração kr = 294 d^{-1}, promovendo recuperação do oxigênio dissolvido acima do limite da Classe II da Resolução CONAMA nº 357/2005 em menos de 500 m, enquanto a DBO permanece em 276 mg/L a 1 km — dissociação entre DBO e OD não identificável por monitoramentos baseados apenas em OD. Associado à supressão estrutural do monitoramento em estiagens documentada por Fausto et al. (2026), o resultado sustenta a adoção da DBO como principal indicador regulatório em rios intermitentes. Um artigo complementar (Cavalcante et al., 2026) avalia a rota subsuperficial via modelo Green-Ampt/Streeter-Phelps aplicado ao solo.
Palavras-Chave – dissociação DBO-OD, rios intermitentes, Streeter-Phelps.

ABSTRACT– Urban WWTPs in semi-arid municipalities discharge effluents into intermittent rivers subjected to contrasting seasonal conditions. This study couples kinematic wave theory with the Streeter-Phelps BOD-DO model and the O'Connor-Dobbins reaeration equation to theoretically simulate, using parameters obtained from the literature, the surface propagation of effluents from a WWTP in the Paraíba do Meio River Basin (Alagoas, Brazil) under two scenarios: S1 (dry season, Q = 8 L/s consisting only of effluent, BOD = 280 mg/L) and S2 (wet season, Q = 508 L/s, BOD = 4.4 mg/L). The reduced flow depth in S1 (y_0 = 3.1 cm) produces a reaeration coefficient of kr = 294 d^{-1}, promoting dissolved oxygen recovery above the Class II limit established by CONAMA Resolution No. 357/2005 within less than 500 m, while BOD remains at 276 mg/L after 1 km — a dissociation between BOD and DO not detectable through monitoring based exclusively on DO. Combined with the structural suppression of drought-period monitoring documented by Fausto et al. (2026), these findings support the adoption of BOD as the main regulatory indicator for WWTP discharges into intermittent rivers. A companion paper (Cavalcante et al., 2026) evaluates the subsurface pathway using a coupled Green-Ampt/Streeter-Phelps soil model.
Keywords – BOD-DO decoupling; intermittent rivers; Streeter-Phelps.

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INTRODUCTION

The discharge of treated effluents from urban WWTPs into intermittent rivers is widespread in rapidly urbanising semi-arid north-eastern Brazil. CONAMA Resolutions No. 357/2005 and No. 430/2011 regulate this discharge assuming a surface receiving body capable of diluting and assimilating the organic load (BRASIL, 2005; BRASIL, 2011). In the Agreste of Alagoas, the receiving rivers are intermittent, experiencing extended zero-flow periods (DATRY; LARNED; TOCKNER, 2014; MALTCHIK, 2017). During drought the exposed streambed becomes the direct interface between effluent and underlying soil, creating a subsurface infiltration pathway invisible to current surface monitoring.

This paper is one of three companion papers submitted to the XVI ENAU / VI SRRU that together address the regulatory gap for WWTP discharges into intermittent rivers in Alagoas. Fausto et al. (2026) provides the empirical and regulatory foundation, documenting up to 93.6% suppression of scheduled monitoring samples during drought in the Alagoas Agreste. Fausto et al. (2026), submitted to this same conference, examines the complementary surface pathway, modelling how effluent propagates and dilutes in the channel under each seasonal scenario using kinematic wave theory and the Streeter-Phelps BOD-DO model. The present paper addresses the subsurface pathway, quantifying how the effluent infiltrates into the exposed dry streambed and what contamination risk it poses to the vadose zone and unconfined aquifer.

Although the subsurface consequences of such infiltration have rarely been quantified in the Brazilian regulatory literature, the broader topic has attracted international attention. Several authors have examined the broader question of effluent discharge into water-stressed or intermittent stream systems. Leigh et al. (2020) conducted a global review of 147 quantitative studies of effluent-fed streams and explicitly identified naturally intermittent and ephemeral systems as a critical research gap. Luthy et al. (2015) showed that in semiarid regions WWTP effluent increasingly constitutes the sole baseflow in urban streams. Serrano et al. (2022) investigated infiltration losses of treated WWTP effluent through ephemeral channels, confirming that contaminant transport through the streambed is poorly characterised. Chiu et al. (2017) catalogued wastewater discharge as one of the most impactful anthropogenic threats to intermittent rivers globally. Pennsylvania DEP (2023) recognised that discharges to intermittent streams present significant challenges to meeting surface water quality standards due to limited assimilative capacity.

This study couples the Green-Ampt model (GREEN; AMPT, 1911) with a vertical BOD-DO model adapted from Christensen (1991). The simulations use literature-derived parameters and are explicitly a scenario-based argument for regulatory reform. Section 5 identifies the field measurements required to advance from theory to practice.

2. STUDY AREA AND SOIL PARAMETERS

The study is parameterised for the receiving channel of a small WWTP in the Paraíba do Meio River Basin, Agreste of Alagoas. The Mar Vermelho WWTP discharge point (9°26'48.4"S; 36°23'27.6"W) and the Paulo Jacinto upstream reference (9°21'41.2"S; 36°21'59.8"W) provide the spatial context studied by Fausto et al. (2026). The dominant soil is a Chromic Luvisol with sandy clay loam texture (EMBRAPA, 2018). All parameters were taken from published literature; Table 1 lists them with sources.

Table 1 – Model parameters for the coupled Green-Ampt / vertical BOD-DO simulation.

Parameter	Symbol	Value	Unit
Saturated hydraulic conductivity	Ks	2.18	mm/h
Capillary suction head	ψ	218.5	mm
Total porosity	θs	0.398	–
Initial moisture (dry season)	θi	0.18	–
Moisture deficit	$\Delta\theta$	0.218	–
Long-term pore velocity (Ks/$\Delta\theta$)	v_pore	0.24	m/d
Effluent BOD – S1 (dry)	L_0	280	mg/L
Effluent BOD – S2 (wet, diluted)	L_0	28	mg/L
Effluent DO	DO_0	2.0	mg/L
DO saturation at 28°C	DO_sat	7.8	mg/L
Soil BOD decay rate (aerobic)	k_d	0.10	d^{-1}
O_2 re-supply by gas diffusion	k_a	0.05	d^{-1}

Sources: Rawls, Brakensiek and Miller (1983); Christensen (1991); Bouwer (2002); Chapelle (2001).

3. METHODOLOGY

3.1 Scenario Definition and Effluent Concentration Rationale

The effluent BOD adopted for S1 (C_0 = 280 mg/L) requires justification. CONAMA Resolution No. 430/2011 permits effluent discharge when BOD removal efficiency is at least 60% relative to the raw influent, with no absolute upper concentration limit for this compliance pathway. Von Sperling (2007) reports typical raw domestic sewage BOD in Brazil between 150 and 400 mg/L under normal water-use conditions. During extended droughts in semi-arid municipalities, per capita water consumption falls by 30–50% (TSUTIYA; BUENO, 2004), concentrating the organic load; raw sewage BOD of

400–700 mg/L has been reported for small north-eastern Brazilian towns during drought events (SILVA et al., 2019). A WWTP achieving the CONAMA 430 minimum 60% removal from concentrated dry-season raw sewage at 700 mg/L would discharge an effluent at approximately 280 mg/L – fully compliant in removal efficiency yet highly concentrated in absolute terms. SNIS (2022) data show that approximately 58% of Brazilian municipalities below 50,000 inhabitants have wastewater treatment classified as inadequate or partial, making elevated effluent BOD a realistic rather than exceptional condition. For S2, mixing with the 500 L/s river discharge yields C_0 = 4.4 mg/L, consistent with well-performing facultative pond effluents and already below the CONAMA 357/2005 Class II standard of 5 mg/L (VON SPERLING, 2007).

3.2 Kinematic Wave Hydraulics

The kinematic wave model (CHAUDHRY, 2008) retains continuity and Manning's uniform-flow relation. Normal depth solved iteratively; celerity c = (5/3)·V.

3.3 Streeter-Phelps BOD-DO Model and O'Connor-Dobbins Reaeration

Under steady-state advection (STREETER; PHELPS, 1925; VON SPERLING, 2007):

$$L(x) = L^0 \cdot \exp(-k_d \cdot x/V_d)\,; D(x) = [k_d L^0/(k_r - k_d)] \cdot [e^{-\mathrm{kd}}x - e^{-\mathrm{k8}}x] + D^0 \cdot e^{-\mathrm{k8}}x \quad (1–2)$$

O'Connor-Dobbins reaeration, applied here as a novel – and as yet field-unvalidated – application to effluent-only flows in intermittent channels:

$$k_r = 3.93 \cdot \frac{V^{0.5}}{H^{1.5}} [d^{-1}] \qquad (3)$$

4. RESULTS AND DISCUSSION

Figure 1 presents six panels: upper row (a-c) covers hydraulic outputs; lower row (d-f) covers Streeter-Phelps water-quality outputs. The subsurface contamination behaviour of the same effluent scenarios is analysed in the companion paper (FAUSTO et al., 2026).

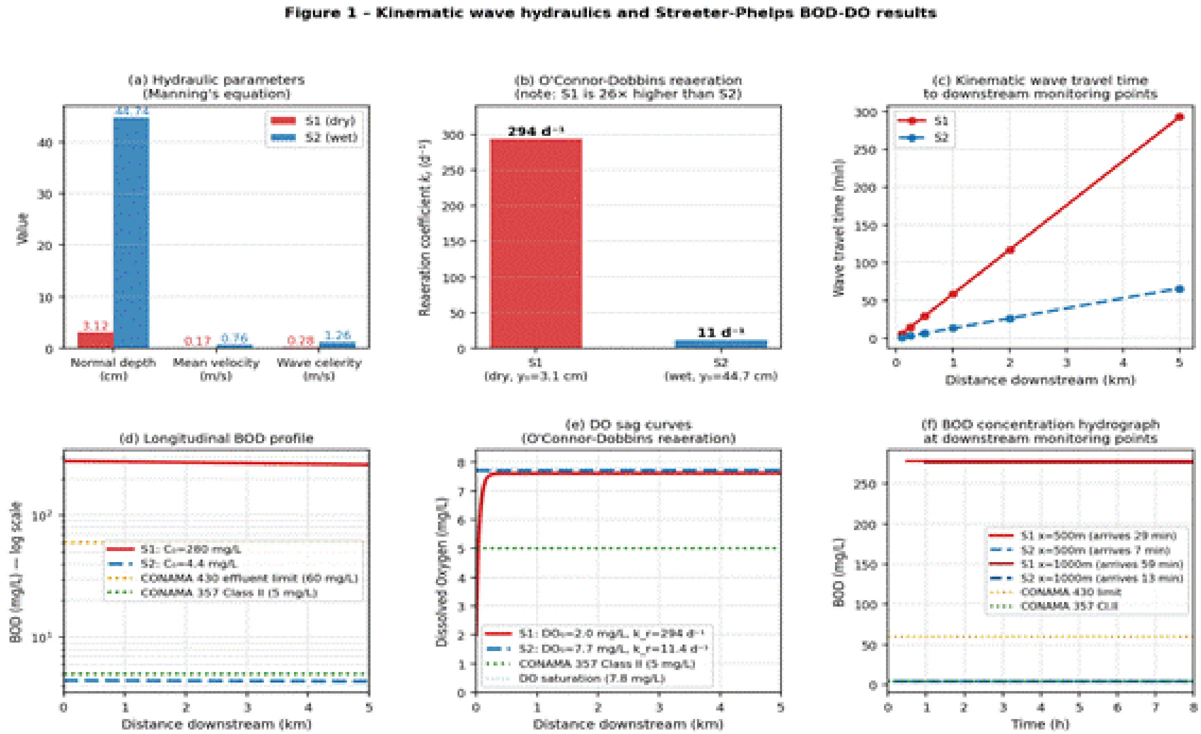

Figure 1 – Coupled Kinematic Wave / Streeter-Phelps results (theoretical, literature-parameterised). Upper row: (a) hydraulic parameters; (b) O'Connor-Dobbins reaeration coefficients (k_r = 294 d⁻¹ for S1 vs. 11.4 d⁻¹ for S2); (c) kinematic wave travel times. Lower row: (d) longitudinal BOD profile (log scale); (e) DO sag curves with the CONAMA 357/2005 Class II threshold; (f) BOD concentration hydrographs at x = 500 m and x = 1,000 m. See Section 5 for field validation requirements.

Panel (b) exposes the core mechanism, which is $k_r = 294\ d^{-1}$ for S1 is 26 times greater than $11.4\ d^{-1}$ for S2, a direct consequence of the $H^{1.5}$ denominator applied to a 3.1 cm normal depth.

Panel (e) shows the consequence, which is DO in S1 recovers above the CONAMA 357/2005 Class II limit within approximately 500 m, while panel (d) simultaneously shows BOD remaining near 280 mg/L throughout 5 km. Panel (f) confirms that this BOD violation is present at all monitored downstream distances from the moment of wave arrival.

The regulatory failure at the centre of this analysis is a documented structural problem. Fausto et al. (2026) showed that monitoring of WWTPs discharging into intermittent rivers of the Alagoas Agreste is suppressed by up to 93.6% of scheduled samples during drought, because the standard upstream-downstream comparison protocol requires flow availability at both reference points. The Streeter-Phelps results add a further dimension: even when monitoring is conducted during wet-season events, DO readings are acceptable throughout (panel e), giving no indication of the high

BOD conditions of S1. The O'Connor-Dobbins reaeration anomaly in very shallow flows thus creates a structural false-negative in DO-based monitoring, compounding the sampling-frequency problem documented by Fausto et al. (2026).

Together with the companion paper (FAUSTO et al., 2026), which shows that the same effluent simultaneously penetrates the soil to 86.7 cm under fully anaerobic conditions during S1, the present results build a complete contamination picture: the dry-season discharge contaminates both the surface channel (undetectable by DO monitoring) and the subsurface (unreachable by upstream-downstream monitoring). Neither pathway is addressed by current Brazilian regulation in the intermittent river context.

5. MODEL LIMITATIONS AND RESEARCH NEEDS

The results presented in this paper are entirely theoretical. The simulations were designed to expose a structural gap in the Brazilian legislative framework for effluent discharge licensing in intermittent rivers: the combination of kinematic wave hydraulics and the Streeter-Phelps BOD-DO model reveals that the hydrological conditions of the dry season simultaneously produce the worst water quality impact and the lowest reaeration-based DO signal, making the standard regulatory indicator (DO) misleading under precisely the conditions that matter most. This is a scenario-based regulatory argument, not a calibrated site-specific prediction.

The boundary conditions (i.e. channel geometry, bed slope, Manning roughness, effluent discharge, BOD and DO concentrations, and BOD decay rate) were estimated from published literature and regional remote sensing data (SRTM), not from direct measurements at the study sites. Converting this theoretical framework into a site-specific assessment requires investment in the following activities: (i) Channel bathymetric survey. The rectangular cross-section with $b = 1.5$ m and $S_0 = 0.005$ m/m were estimated; both should be measured in the field. An error of 50% in normal depth propagates to an error of approximately 180% in k_r via the $H^{1.5}$ dependence, the most sensitive parameter in the entire model chain. (ii) WWTP effluent flow and quality monitoring during drought. The effluent discharge $Qw = 8$ L/s and BOD = 280 mg/L require direct measurement during dry-season events. Regulatory reform should mandate continuous flow measurement at the WWTP outlet and regular effluent quality sampling throughout the year, independently of receiver flow conditions. (iii) In-stream BOD and DO measurements during low-flow events. The BOD-DO dissociation identified in S1 is a model prediction that requires field validation. Simultaneous BOD and DO measurements at multiple downstream points during effluent-only flow would allow direct comparison with the Streeter-Phelps predictions and calibration of k_d. (iv) Validation of O'Connor-Dobbins at extreme low depths. The formula of O'Connor and Dobbins (1958) was derived for turbulent open-channel flows in perennial rivers. Its application to a 3.1 cm flow depth is physically extrapolatory and represents the main theoretical limitation of this study. Tracer reaeration experiments at very low discharges would provide the empirical data needed to validate or correct the formula at such depths. (v) Manning roughness calibration. The roughness coefficient n = 0.04 was assumed for a natural earthen channel. A salt dilution gauging during a representative S1-type event would allow Manning's equation to be inverted for n.

The qualitative finding that the dry-season scenario produces a BOD-DO dissociation is robust because it follows from the $H^{1.5}$ dependence of the O'Connor-Dobbins formula: any realistic effluent-only depth in an Agreste channel will generate reaeration rates far above those of the wet season. The regulatory reform proposed here is grounded in physical reasoning that the model makes explicit, independently of precise calibration.

6. CONCLUSIONS

The theoretical simulations reveal a fundamental regulatory blind spot: in S1, $k_r = 294\ d^{-1}$ recovers DO above CONAMA 357/2005 Class II thresholds within 500 m while BOD simultaneously remains near 278 mg/L throughout 5 km. DO monitoring alone would signal compliance at the moment of greatest BOD violation. Combined with the subsurface contamination findings of the companion paper (CAVALCANTE et al., 2026) and the empirical monitoring suppression documented by Fausto et al. (2026), these results provide the physical and quantitative basis for legislative reform: requiring BOD as the primary regulatory indicator and mandatory dry-season WWTP-outlet monitoring, independently of receiver flow.

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