GROUNDWATER CONTAMINATION RISK FROM URBAN EFFLUENTS IN INTERMITTENT RIVERS: COUPLED GREEN-AMPT AND STREETER-PHELPS OXYGEN DEPLETION MODEL

Leon Carvalho Vieira Cavalcante [1]; Thayse Farias de Barros Fausto [1]; Yasmin Peixoto Carvalho [1]; Fábio Farias Pereira [2]; Marllus Gustavo Ferreira Passos das Neves[3] Tais Pereira Luz[1] & José Marcio de Medeiros Maia [1].

RESUMO – Pequenas ETEs urbanas em municípios do semiárido descarregam em rios intermitentes, criando dois cenários contrastantes: S1 (período seco, fluxo apenas de efluente, alta DBO e baixa carga hidráulica) e S2 (período chuvoso, efluente diluído e maior carga hidráulica). Este estudo apresenta uma estrutura teórica acoplada Green-Ampt / Streeter-Phelps vertical para quantificar o risco de contaminação subsuperficial em Luvissolos Crômicos do Agreste Alagoano. Os parâmetros foram obtidos da literatura; o estudo constitui um argumento baseado em cenários para reforma regulatória, não uma previsão calibrada. Os resultados incluem taxa e infiltração acumulada, profundidade da frente de molhamento, evolução do perfil de DBO, perfis verticais de OD e DBO com frentes anóxicas em 1,7 cm (S1) e 19,4 cm (S2), além da massa acumulada de DBO infiltrada (52,9 versus 6,4 g/m² em 48 h). O cenário seco maximiza simultaneamente a carga poluidora, minimiza a atenuação aeróbia e coincide com a supressão do monitoramento em estiagens documentada por Fausto et al. (2026). Um artigo complementar (CAVALCANTE et al., 2026) analisa o transporte superficial via modelo onda cinemática / Streeter-Phelps.
Palavras-Chave – rios intermitentes; modelo de Green-Ampt; depleção subsuperficial de oxigênio.

ABSTRACT – Small urban wastewater treatment plants (WWTPs) in semi-arid municipalities discharge into intermittent rivers, creating two contrasting scenarios: S1 (dry season, effluent-only flow, high BOD, low hydraulic head) and S2 (wet season, diluted effluent, higher hydraulic head). This study presents a coupled Green-Ampt / vertical Streeter-Phelps theoretical simulation framework to quantify subsurface contamination risk for the Chromic Luvisol soils of the Alagoas Agreste, Brazil. Parameters were drawn from published literature; the study is a scenario-based argument for regulatory reform, not a calibrated site prediction. Six result panels show: infiltration rate, cumulative infiltration, wetting front depth, BOD depth profile evolution, DO and BOD vertical profiles with anoxic fronts at 1.7 cm (S1) and 19.4 cm (S2), and cumulative BOD mass infiltrated (52.9 vs. 6.4 g/m² at 48 h). The dry-season scenario simultaneously maximises pollutant loading, minimises aerobic attenuation, and coincides with the monitoring suppression during drought documented by Fausto et al. (2026). A companion paper submitted to this same conference ([Student Name]; PEREIRA, 2026b) examines surface transport using a kinematic wave / Streeter-Phelps channel model and should be read alongside this work.

Keywords – intermittent rivers; Green-Ampt model; subsurface oxygen depletion.

1) Agência Reguladora de Serviços Públicos do Estado de Alagoas – ARSAL, Rua Engenheiro Roberto Gonçalves Menezes,149, Centro, Maceió – AL, CEP 57020680, (82) 3315-3100; leoncavalcante.arsal@gmail.com; thaysebarros.arsal@gmail.com; yasminpeixoto.arsal@gmail.com; saneamento.arsal@gmail.com
2) Laboratório de Pesquisa em Recursos Naturais – Campus A.C. Simões, Universidade Federal de Alagoas Av. Lourival Melo Mota, s/n - Tabuleiro do Martins, Maceió - AL, CEP: 57072-970. Email: fabio.pereira@ceca.ufal.br[1]
3) Centro de Tecnologia (CTEC)–Universidade Federal de Alagoas (UFAL) Campus A. C. Simões, Av. Lourival Melo Mota, s/n, Cidade Universitária, Maceió – AL, CEP: 57072-900; marllus.neves@ctec.ufal.br

1. 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. Cavalcante 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/Δθ)	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 Green-Ampt Model

The Green-Ampt model with ponding depth h_0 (TUCCI, 2004):

$$f(t) = K_s \cdot [1 + (\psi + h^0) \cdot \Delta\theta / F(t)]; K_s \cdot t = F - B \cdot \ln[1 + F/B], B = (\psi + h^0) \cdot \Delta\theta \qquad (1)$$

Solved by Newton-Raphson. Wetting front $z_f = F/\Delta\theta$. Long-time pore velocity $v_{pore} = Ks/\Delta\theta = 0.24$ m/d.

3.3 Vertical BOD-DO Model: Streeter-Phelps Analogy in the Unsaturated Zone

The classical Streeter-Phelps model (STREETER; PHELPS, 1925) was formulated for surface water bodies. Its extension to the subsurface is a structural analogy: the same first-order coupled BOD–DO kinetics were independently derived for the unsaturated zone by Christensen (1991). Bouwer (2002) applied equivalent principles in soil aquifer treatment systems, documenting oxygen depletion within the first centimetres of soil under high organic loading. Chapelle (2001) provided the geochemical foundation for the anoxic front concept. The present study bridges these frameworks: the Green-Ampt pore velocity drives a vertical BOD–DO balance (after Christensen, 1991) along the depth coordinate, with k_a corresponding to the gas-phase oxygen diffusion supply term. This specific coupling represents the primary methodological novelty of this work.

$$dL/dz = -(k_d/v_pore) \cdot L; dD/dz = (k_d/v_pore) \cdot L - (k_a/v_pore) \cdot D, D = DO_sat - DO \qquad (2\text{–}3)$$

Analytical solutions give L(z) and D(z). The anoxic front z_a is where $DO(z_a) = 0$. The oxygen re-supply rate $k_a = 0.05\ d^{-1}$ is two to four orders of magnitude smaller than stream reaeration rates (CHRISTENSEN, 1991; BOUWER, 2002).

4. RESULTS AND DISCUSSION

Figure 1 presents six panels in two rows: upper (a-c) shows Green-Ampt hydraulic results; lower (d-f) shows vertical Streeter-Phelps water-quality results. The surface transport behaviour of the same effluent scenarios in the channel is analysed in the companion paper (CAVALCANTE et al., 2026).

Figure 1 - Green-Ampt infiltration and vertical Streeter-Phelps oxygen depletion results

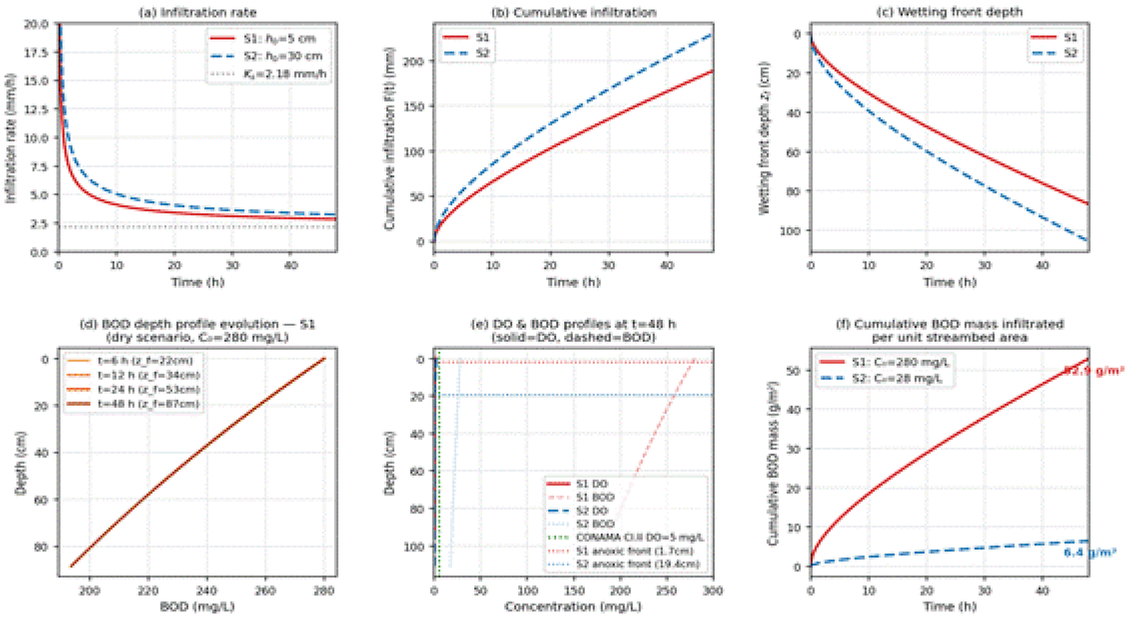

Figure 1 – Coupled Green-Ampt / vertical Streeter-Phelps results (theoretical, literature-parameterised). Upper row: (a) infiltration rate f(t); (b) cumulative infiltration F(t); (c) wetting front depth z_f(t). Lower row: (d) BOD depth profiles in S1 at t = 6, 12, 24 and 48 h; (e) DO (solid) and BOD (dashed) profiles for both scenarios at t = 48 h, with horizontal dotted lines marking the anoxic front (z_a = 1.7 cm in S1; 19.4 cm in S2); (f) cumulative BOD mass M(t) per unit streambed area. See Section 5 for field measurements required for site-specific calibration.

S2 achieves greater cumulative infiltration (230 mm at 48 h vs. 189 mm in S1) and a deeper wetting front (105.6 cm vs. 86.7 cm) due to its sixfold higher ponding head.

Panel (d) reveals the temporal evolution of the BOD depth profile in S1. At all time steps, BOD remains near 280 mg/L throughout the infiltrated profile, confirming that aerobic decay is negligible below the 1.7 cm anoxic front: the wetting front is not a purification front.

Panel (e) shows the critical quality result. In S1, DO reaches zero at 1.7 cm depth; in S2 the anoxic front is delayed to 19.4 cm. Panel (f) integrates both effects: 52.9 g/m² of BOD reaches the vadose zone in S1 over 48 h versus 6.4 g/m² in S2, a factor of 8.2. These are theoretical predictions based on literature parameter ranges; specific numerical values are sensitive to Ks, k_d, and k_a, whose site specific measurement is identified as a research priority in Section 5.

The regulatory failure to which these findings speak is a documented structural problem. Fausto et al. (2026) showed that regulatory monitoring of WWTPs discharging into intermittent rivers in the

Alagoas Agreste is suppressed by up to 93.6% of scheduled samples during drought periods, because the upstream-downstream comparison protocol requires river flow at both reference points. The absence of flow that disables monitoring is precisely the condition under which, according to the present model, the greatest subsurface contamination occurs: anoxic conditions at 1.7 cm depth, 8.2 times greater BOD mass loading to the vadose zone (52.9 vs. 6.4 g/m² over 48 h), and near-complete absence of aerobic attenuation.

From an urban water management perspective, this contamination pathway is entirely unaddressed by the surface-water focus of current Brazilian sanitation regulation. The companion paper (CAVALCANTE et al., 2026) shows that the surface pathway presents a different but equally significant regulatory blind spot: when the channel carries only effluent, rapid atmospheric reaeration restores DO to acceptable levels within 500 m while BOD simultaneously remains near 280 mg/L, a BOD-DO dissociation invisible to standard DO-based monitoring.

5. MODEL LIMITATIONS AND RESEARCH NEEDS

The results presented in this paper are entirely theoretical. The simulations were constructed specifically to expose a structural gap in the current legislative framework for effluent discharge licensing in intermittent rivers, namely, that the regulatory system presupposes a hydrological condition that does not exist during the period of greatest subsurface contamination risk. The modelling exercise should be understood as a scenario-based argument in support of regulatory reform, not as a calibrated prediction of conditions at any specific site.

The boundary conditions (i.e. effluent BOD concentration, ponding depth, soil hydraulic parameters, and oxygen kinetic rates) were derived from published literature ranges representative of the regional soil class and WWTP type, not from measurements at the study sites. Transforming this theoretical framework into a site-specific risk assessment requires investment in the following field and laboratory activities: (i) Soil hydraulic characterisation. The Green-Ampt parameters (Ks, ψ, θs, θi) should be measured in situ using double-ring infiltrometers and tension disk permeameters at multiple locations along the streambed of the receiving channels. Spatial variability of Ks in alluvial Luvisols of the Agreste can span one to two orders of magnitude and is the dominant source of uncertainty in the wetting front depth predictions. (ii) Effluent quality monitoring during drought. The 280 mg/L BOD adopted for S1 must be validated by direct sampling of the WWTP effluent during dry-season events. This requires monitoring protocols that are triggered by the absence of receiver flow and that operate at the WWTP outlet independently of conditions in the receiving channel. (iii) Subsurface oxygen and BOD profiles. The oxygen re-supply rate $k_a = 0.05\ d^{-1}$ and aerobic BOD decay rate k_d =

0.10 d^{-1} were adopted from Christensen (1991) and Bouwer (2002) for sandy clay loam soils. Site-specific determination requires laboratory soil column experiments with the local Luvisol, measuring dissolved oxygen and BOD at multiple depths under controlled infiltration of representative effluent. The anoxic front depth is highly sensitive to these two parameters. (iv) Groundwater depth and vulnerability. The relevance of the anaerobic infiltration pathway for aquifer contamination depends critically on the depth to the water table beneath the streambed. Hydrogeological surveys including shallow piezometers along the alluvial plain are needed to assess whether the computed wetting fronts can reach the unconfined aquifer under representative dry-season conditions. (v) Model validation. The Green-Ampt model should be validated against time-lapse infiltration measurements for the specific soil and effluent combination. The vertical Streeter-Phelps oxygen model should be validated against depth-resolved pore-water oxygen and BOD measurements in soil column experiments before the anoxic front depth is used as a regulatory criterion.

Until these measurements are available, the simulations establish the order of magnitude and direction of the effect, not its precise quantitative value. The core qualitative finding, that the dry-season scenario simultaneously maximises pollutant loading, minimises aerobic attenuation, and eliminates monitoring capacity, is robust to parameter uncertainty because it follows directly from the structure of the governing equations. The call for legislative reform is therefore grounded in physical reasoning that the models make explicit, even if the specific numerical predictions require field calibration.

6. CONCLUSIONS

This theoretical simulation demonstrates that the dry-season discharge scenario (S1) simultaneously maximises BOD mass loading to the vadose zone (52.9 g/m² in 48 h vs. 6.4 g/m² in S2), establishes anoxic conditions from 1.7 cm depth, and eliminates aerobic BOD attenuation throughout 98% of the 86.7 cm wetting front, while also coinciding with the monitoring suppression during drought documented by Fausto et al. (2026). Together with the surface pathway analysis of the companion paper (CAVALCANTE et al., 2026), these results provide quantitative and physical grounding for legislative reform, requiring dry-season effluent characterisation at the WWTP outlet and addressing both the subsurface and surface contamination pathways as regulated impacts.

REFERENCES

BOUWER, H. Artificial recharge of groundwater: hydrogeology and engineering. Hydrogeology Journal, v. 10, n. 1, p. 121–142, 2002.

BRASIL. CONAMA Resolution No. 357, 17 March 2005. Brasília, DF, 2005.

BRASIL. CONAMA Resolution No. 430, 13 May 2011. Brasília, DF, 2011.

CAVALCANTE et al. Urban effluent propagation in intermittent rivers: kinematic wave hydraulics coupled with the Streeter-Phelps BOD-DO model. In: XVI Encontro Nacional de Águas Urbanas e VI Simpósio de Revitalização de Rios Urbanos (XVI ENAU / VI SRRU), 2026, São Carlos, SP. Submetido.

CHAPELLE, F. H. Ground-Water Microbiology and Geochemistry. 2nd ed. New York: Wiley, 2001.

CHIU, M. C. et al. Anthropogenic threats to intermittent rivers and ephemeral streams. In: DATRY et al. (Ed.). Intermittent Rivers and Ephemeral Streams. London: Academic Press, 2017. p. 433–454.

CHRISTENSEN, S. A model for oxygen transport and consumption in the unsaturated zone. Water Resources Research, v. 27, n. 9, p. 2357–2368, 1991.

DATRY, T.; LARNED, S. T.; TOCKNER, K. Intermittent rivers: a challenge for freshwater ecology. BioScience, v. 64, n. 3, p. 229–235, 2014.

EMBRAPA. Brazilian Soil Classification System. 5th ed. Brasília: Embrapa, 2018.

FAUSTO, et al. Monitoramento de efluentes em rios intermitentes: desafios regulatórios do saneamento em Alagoas. In: XVI Encontro Nacional de Águas Urbanas e VI Simpósio de Revitalização de Rios Urbanos (XVI ENAU / VI SRRU), 2026, São Carlos, SP. Submetido.

GREEN, W. H.; AMPT, G. A. Studies on soil physics, Part I. Journal of Agricultural Science, v. 4, n. 1, p. 1–24, 1911.

LEIGH, C. et al. Release of treated effluent into streams: a global review of ecological impacts. Freshwater Biology, v. 65, n. 10, p. 1900–1915, 2020.

LUTHY, R. G. et al. Wastewater-effluent-dominated streams as ecosystem-management tools in a drier climate. Frontiers in Ecology and the Environment, v. 13, n. 10, p. 565–573, 2015.

MALTCHIK, L. Intermittent rivers of Brazil. In: DATRY et al. (Ed.). Intermittent Rivers and Ephemeral Streams. London: Elsevier, 2017. p. 63–74.

PENNSYLVANIA DEP. Policy for Evaluating Wastewater Discharges to Intermittent and Ephemeral Streams. Document 386-2000-013. Harrisburg, PA, 2023.

PEREIRA, F. F. et al. A hydrological routing scheme for ED2+R tested in the Tapajós River basin. Hydrology and Earth System Sciences, v. 21, p. 4629–4648, 2017.

RAWLS, W. J.; BRAKENSIEK, D. L.; MILLER, N. Green-Ampt infiltration parameters from soil data. Journal of Hydraulic Engineering, v. 109, n. 1, p. 62–70, 1983.

SANTOS, E. O.; COSTA, N. B.; MEDEIROS, P. R. P. Paraíba do Meio River Basin water parameters. In: XII SYMPOSIUM POST-GRADUATION EARTH SYSTEM SCIENCE, 2024.

SERRANO, L. G. et al. Assessing transmission losses through ephemeral streams. Water, v. 14, n. 22, art. 3758, 2022.

SILVA, D. D. et al. Sewage characteristics in water-scarce regions of north-eastern Brazil during drought. Engenharia Agrícola, v. 39, n. 4, p. 512–520, 2019.

SNIS. National Sanitation Information System. Brasília: Ministry of Cities, 2022.

STREETER, H. W.; PHELPS, E. B. A Study of the Pollution and Natural Purification of the Ohio River. U.S. Public Health Service, Bulletin No. 146, 1925.

TSUTIYA, M. T.; BUENO, R. C. R. Water supply in health emergencies. In: TSUTIYA, M. T. (Ed.). Water Supply. São Paulo: EPUSP, 2004.

TUCCI, C. E. M. (Ed.). Hydrology: science and application. 4th ed. Porto Alegre: UFRGS/ABRH, 2004.

VON SPERLING, M. Wastewater Characteristics, Treatment and Disposal. London: IWA Publishing, 2007.