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Toward an Amazonian Digital Twin: Integrating Urbanism, Hydrology, and Indigenous Peoples' Knowledge

Rumo ao Gêmeo Digital Amazônico: integrando urbanismo, hidrologia e conhecimento dos povos originários

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Resumo

A Amazônia enfrenta uma crise climática grave, com inundações, incêndios e secas que afetam principalmente as comunidades indígenas e ribeirinhas. Este artigo apresenta o Gêmeo Digital Amazônico (GDA) como uma estrutura conceitual para a gestão integrada do ambiente urbano regional. A partir de uma síntese teórica e da análise de três casos internacionais, o estudo identifica limitações conceituais, técnicas e de governança nos modelos atuais e propõe uma arquitetura de três camadas interdependentes: física-natural, institucional e sociocultural. A contribuição é dupla: integrar a dinâmica urbana aos ciclos hidrológicos como base analítica; e posicionar a etnomodelagem hidrológica, que formaliza o conhecimento dos povos originários sobre os ciclos do rio e da floresta, como variável central do GDA. A agenda de pesquisa proposta organiza-se em quatro eixos: modelagem integrada em cidades-piloto; soberania de dados indígenas; arquiteturas resilientes à baixa conectividade; e fundamentos metodológicos da etnomodelagem hidrológica.

Palavras-chave: Governança digital. Hidrologia urbana. Tecnologias digitais territoriais.

Abstract

The Amazon faces a severe climate crisis, with floods, wildfires, and droughts affecting primarily indigenous and riverside communities. This article presents the Amazonian Digital Twin (ADT) as a conceptual framework for the integrated management of the regional urban environment. Drawing on a theoretical synthesis and the analysis of three international cases, the study identifies conceptual, technical, and governance limitations in current models and proposes a three-layer interdependent architecture: physical-natural, institutional, and sociocultural. The contribution is twofold: integrating urban dynamics with hydrological cycles as an analytical foundation; and positioning hydrological ethnomodeling, which formalizes indigenous peoples' knowledge of river and forest cycles, as a central variable of the ADT. The proposed research agenda is organized around four axes: integrated modeling in pilot cities; indigenous data sovereignty; architectures resilient to low connectivity; and methodological foundations of hydrological ethnomodeling.

Keywords: Digital governance. Urban hydrology. Territorial digital technologies.

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INTRODUCTION

The Brazilian Amazon faces an urgent climate crisis, with flooding events increasing fivefold, fires tenfold, and droughts tripling between 2000 and 2022, affecting around 1.8 million people annually, primarily indigenous communities in smaller municipalities [1].

The vast spatial and temporal scales of changes in natural systems, the built environment, and communities present significant challenges for managers and policymakers. Digital technologies like Digital Twins (DTs) are well-suited to represent, simulate, and monitor these changes at the scales and speeds required by Amazonian managers. Successful urban DT implementations, such as Virtual Singapore (2020) and Sentilo in Barcelona (2021), have shown effectiveness in reducing congestion by 12-18% and saving energy by 7-12% [2].

Despite advancements, most existing models do not combine urbanism, hydrology, and human rights into a unified framework. This lack of integration causes urban planning to overlook hydrological risks, excludes indigenous knowledge from decision-making, and leaves managers unprepared for interconnected crises. This article introduces the Amazonian Digital Twin (ADT), a conceptual framework and research plan aimed at fostering integrated territorial governance in the Amazon. To the authors' knowledge, no previous framework has treated Amazonian indigenous hydrological knowledge as a core modeling system rather than merely as auxiliary qualitative data, thereby enabling its formal integration into a digital twin architecture.

This article explores two research questions: (RQ1) What conceptual and architectural requirements must an ADT meet to unify urban dynamics, hydrology, and indigenous knowledge within a territorial governance framework? (RQ2) What technical, governance, and epistemological challenges must be addressed before implementing an ADT in the Amazonian context? These questions are revisited in the Discussion and Conclusion sections, where insights from the theoretical synthesis and comparative case analysis are discussed in relation to each question.

This article makes two main contributions. First, it introduces a conceptual framework for the ADT that defines three interconnected layers (physical-natural, institutional, and sociocultural) and positions hydrological ethnomodelling as a core component of the system rather than an add-on. Second, it identifies challenges in concepts, technology, and governance, and outlines a four-pronged research agenda that offers an empirically testable plan for future development and validation of the ADT.

The article is structured as follows. Section 2 details the research method, including the theoretical sampling strategy and the structured comparative protocol for three cases. Section 3 examines digital twins as sociotechnical systems and emphasizes the need to integrate urbanism and hydrology within the Amazonian context. Section 4 reviews the current state of urban-environmental integration in literature, highlighting disciplinary and infrastructural gaps that underpin ADT. Section 5 introduces the ADT framework and its three-layer architecture. Section 6 draws lessons from three international cases (Virtual Singapore, Barcelona's Sentilo, and the Smart Yangtze

River project). Section 7 analyzes the findings with respect to two research questions and identifies conceptual, technical, and governance gaps. Section 8 outlines the research agenda, and Section 9 concludes with key contributions, limitations, and future research directions.

RESEARCH METHOD

This article combines analyses of three case studies and exploratory research to propose an ADT conceptual framework. The cases were chosen through theoretical sampling [3], not for statistical representativeness, because each highlights a different, yet complementary, aspect of the framework: 1) Virtual Singapore [4] showcases the integration of urban and natural data across various scales; 2) Barcelona's Sentilo [6] demonstrates open infrastructure and institutional interoperability; and 3) the Smart Yangtze River project [5] offers proof of the deployment of a river basin digital twin at a continental level.

The analysis of each case followed a structured comparative protocol adapted from Yin [3] in four steps: (a) defining the project context and objectives; (b) identifying layer integration mechanisms; (c) mapping technical, institutional, and governance challenges; and (d) extracting lessons applicable to the Amazonian context. This protocol ensures analytical consistency across cases and enables systematic comparison despite differences in scale, geography, and institutional context, making the lessons transferable to the Amazonian setting. The following section establishes the theoretical foundations of the ADT framework.

THEORETICAL BACKGROUND

DIGITAL TWINS AS SOCIOTECHNICAL SYSTEMS

A DT could operate as a sociotechnical system, continuously reconciling three elements: digital models of assets, real-time data from physical assets, and inputs from the various actors involved [7]. Organizational culture, work processes, and human readiness are as critical to this reconciliation as sensor networks. This reconciliation generates simulated scenarios that inform decisions; that is, people do not decide directly about assets, but about model outputs, which require clarity about human roles in the process.

In this regard, it is important to distinguish two frequently confused concepts: human-in-the-loop and participatory citizenship. Human-in-the-loop refers to the role of humans in model control and validation loops, ensuring that algorithms operate within acceptable parameters and that their outputs are interpreted by specialists before triggering action [8]. Participatory management, or participatory citizenship, is a distinct matter: the inclusion of social actors, such as communities, indigenous peoples, and citizens, in governance processes and decision-making on policies and territorial interventions. In the ADT context, both dimensions are necessary but

operate at distinct levels and must not be conflated: the former is a technical condition of model reliability; the latter, a political condition of system legitimacy.

Recent advances in urban DT research [6; 9] emphasize the shift from technocratic, top-down models to participatory DT. In these systems, communities co-design and inform planning, which enhances legitimacy, contextual accuracy, and social robustness in urban decision-making. This transition is especially important in the ADT context. Here, indigenous and riverside communities can become co-producers of spatial knowledge and planning scenarios. Building on this premise and the [6; 9] discussion, we observe that indigenous knowledge can be formalized as structured inputs for modeling. This shifts their role from passive data sources to active epistemological frameworks that inform simulations and reshape urban-environmental planning.

URBANISM–HYDROLOGY INTEGRATION: AN ANALYTICAL NECESSITY

The modern distinction between urbanism and hydrology is a construct that masks deep interdependence. Historically, Amazonian cities were planned with strong consideration of river systems, featuring stilt-house housing structures, activity calendars aligned with flood-drought cycles, and economies based on river access. Modern urbanization, with its typical continental infrastructure, created the illusion of separation between the city and the river.

However, the climate vulnerability of Amazonian cities cannot be understood without integrated modeling of urban dynamics and regional hydrological cycles. Urban land-use policies (paving, artificial drainage, floodplain occupation) influence infiltration, runoff, and water availability, generating effects that isolated urban models fail to capture. The ADT must recognize this integration as a fundamental analytical necessity.

URBAN-ENVIRONMENTAL INTEGRATION

URBAN DIGITAL TWIN IMPLEMENTATIONS

Urban DT implementations have grown significantly but remain concentrated on the operational optimization of isolated subsystems such as transport, energy, and sanitation [9; 10]. Systematic reviews highlight advances in interoperability standards and federated data architecture but also indicate recurring limitations: the absence of an environmental dimension, even in cities vulnerable to climate change; top-down approaches that marginalize genuine community participation; and legal and social gaps that are frequently neglected [9; 10]. A review of 88 articles concludes that there is a large gap between stated system goals and actual contributions, precisely because sociotechnical complexities such as organizational culture, governance structures, and community dynamics are treated as secondary to technical implementation [9]. The ADT must be designed to avoid these same failures.

DISCONNECTED ENVIRONMENTAL MONITORING SYSTEMS

Environmental monitoring systems and hydrological modeling have evolved independently of urban DTs, further complicating integration. Incorporating hydrological models into urban planning frameworks requires interdisciplinary collaboration that rarely occurs in practice, with persistent gaps between the scales of hydrological processes and the resolutions of applied models [10]. Conventional hydrological models do not incorporate urban dynamics in an integrated manner, and urban plans often ignore the hydrological impacts of land-use decisions [10]. In the Amazon, where urban growth and river dynamics are inseparable, this disconnection is not a technical inconvenience but a structural barrier to effective territorial governance.

THE INTEGRATION GAP

The fragmentation extends beyond the disciplinary or institutional dimensions, reaching the infrastructural level. In the Brazilian Amazon, few digital platforms can continuously and practically integrate urban, environmental, and indigenous territorial data. Rather than connecting existing systems, the ADT proposes an integrated architecture that currently presents gaps across all layers [11; 13]. As the primary contribution of this article, it advances a conceptual infrastructure for a problem that has yet to find a comprehensive digital solution.

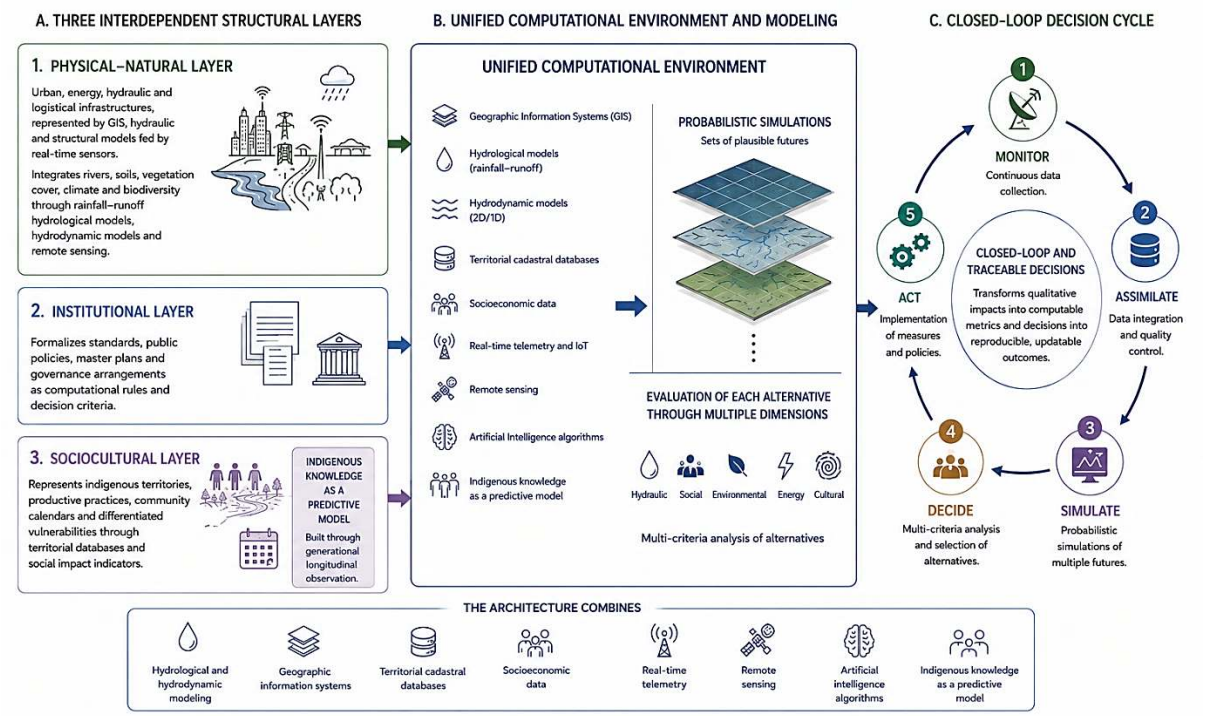
THE AMAZONIAN DIGITAL TWIN: FRAMEWORK AND ARCHITECTURE

An ADT is an integrated territorial digital infrastructure that articulates, within a unified computational environment, three interdependent structural layers: (i) the physical-natural layer, composed of urban, energy, hydraulic and logistical infrastructures, represented by GIS, hydraulic and structural models fed by real-time sensors, which integrates rivers, soils, vegetation cover, climate and biodiversity through rainfall-runoff hydrological models, hydrodynamic models and remote sensing; (ii) the institutional layer, which formalizes standards, public policies, master plans and governance arrangements as computational rules and decision criteria; and (iii) the sociocultural layer, which represents indigenous territories, productive practices, community calendars and differentiated vulnerabilities through territorial databases and social impact indicators.

The sociocultural layer carries the most distinctive theoretical proposition of this framework. The traditional knowledge of indigenous peoples about river and forest cycles, including flood and drought calendars, natural indicators of extreme events, floodplain management practices, and historical land occupation logics, is treated not as auxiliary qualitative data but as a high-temporal- and spatial-resolution predictive model built through generational longitudinal observation. This is a hypothesis to be verified empirically in the proposed research agenda, but one that reorients the epistemological foundation of the ADT: indigenous knowledge is not an input to be collected, but a modeling system to be formally integrated.

Figure 1 illustrates the systemic organization of the ADT. The integration of these three layers enables the analysis of systemic impacts and the prospective evaluation of decisions that affect communities, ecosystems, and regional economic chains, characterizing the ADT as a dynamic platform for territorial governance in the Amazon.

Figure 1: Conceptual architecture of the Amazonian Digital Twin as an integrated territorial digital infrastructure



Source: Authors

This architecture combines hydrological and hydrodynamic modeling, geographic information systems, territorial cadastral databases, socioeconomic data, real-time telemetry, remote sensing, and artificial intelligence algorithms. Rather than running a single probable scenario, the ADT operates with sets of plausible futures through probabilistic simulations, evaluating each alternative not only through the hydraulic lens but also its social, environmental, energy, and cultural consequences. The structural differentiator lies in closing the decision cycle: monitor, assimilate, simulate, decide, and act, with full traceability, transforming qualitative impacts into computable metrics and decisions into reproducible, updatable outcomes. The three cases examined below were chosen specifically because they highlight, from various perspectives, how this cycle has been partially implemented across different contexts and what adjustments remain to be made in the Amazonian setting.

LESSONS FROM INTERNATIONAL CASES

VIRTUAL SINGAPORE: MULTI-SCALE DATA INTEGRATION

The literature on Virtual Singapore demonstrates how urban data at various scales, from IoT sensors to regional climate modeling, can be integrated into a single platform

[4]. The key lesson for the ADT is that federated architectures can combine diverse data sources without requiring centralization, preserving the local sovereignty that Amazonian indigenous and riverside communities require.

Barcelona: Open Infrastructure and Institutional Interoperability

The literature on Sentilo, Barcelona's open-source platform, demonstrates that architecture based on open standards enables interoperability between heterogeneous systems and reduces dependence on proprietary vendors [6]. By allowing public institutions, universities, and territorial organizations to connect their systems without centralization, Sentilo shows that openness is an essential technical condition for sustainable DT integration. The Digital Urban Europe organizations' efforts to connect their systems without centralization, etc. reinforce this by demonstrating that architectures based on open standards, such as ISO 37120:2021 and CityGML, facilitate multi-scale data integration and reduce long-term maintenance costs [2]. The key lesson for the ADT is that institutional resilience depends less on technological sophistication and more on the openness and modularity of its architecture.

Yangtze River: River Basin Digital Twin

The Smart Yangtze River project [5], led by China's Ministry of Water Resources and funded at approximately US$82 million, is the most ambitious river basin management initiative currently in operation. With more than 52,000 reservoirs and 2,700 monitoring stations, its core is a 3D digital twin that combines climate, flow, ecology, sediment, topography, and energy demand data for real-time modeling. The challenges encountered, including data dispersed across agencies in incompatible formats and institutional resistance to information sharing [6], are directly analogous to those the ADT will face in the Amazon. For the Amazon, effective basin management additionally requires integrating: (a) the extreme seasonal variability of river systems; (b) regional precipitation patterns; (c) the hydrological effects of deforestation and urbanization; and (d) the data sovereignty of riverside and indigenous communities, preventing data openness from reinforcing existing power asymmetries.

CURRENT CHALLENGES

The synthesis of international cases and the theoretical background reveals three interdependent challenges that structure the ADT's research agenda: conceptual, technical, and governance.

Conceptual Challenges: Disciplinary Fragmentation and Absence of Integrated Models

Urban DT research generally does not engage with environmental or hydrological literature, and indigenous governance specialists typically do not operate in technical platforms. This disciplinary divide has a direct practical cost [11]: urban DTs built without hydrological variables systematically underestimate flood risk in riverside

cities, while indigenous governance frameworks developed outside technical platforms remain invisible to the models that most affect those communities.

The main conceptual gap is the absence of frameworks that treat Amazonian sociodiversity, including productive calendars, traditional territories, and knowledge systems, as essential model variables rather than mere externalities. In this regard, hydrological ethnomodelling, the computational formalization of indigenous peoples' traditional knowledge about river and forest cycles, represents the most critical gap to address and a more feasible approach than depending on communities' direct access to digital platforms.

Technical Challenges: Architecture, Interoperability, and Connectivity

In the Amazonian environment, standardization challenges are compounded by low connectivity in riverside cities and indigenous territories. A key technical priority is therefore to develop edge computing architectures suited for low-connectivity areas, enabling local operation and asynchronous synchronization with central platforms. Interoperability protocols connecting the four ADT layers with legacy systems for hydrological monitoring, land registry, and urban management are equally essential [4; 5]. BIM-GIS integration offers a promising strategy for linking building-scale to river-basin-scale data, but requires adaptations for riverside cities where infrastructure is largely informal and cadastral records are incomplete.

Governance Challenges: Data Sovereignty and Substantive Participation

The Barcelona and Yangtze examples show that the long-term sustainability of DT depends more on the quality of governance structures than on advanced technology [5; 6]. For the ADT, the main problem is the lack of practical mechanisms to apply Free, Prior, and Informed Consent (FPIC) to the digital transformation [12; 13]. The collection of traditional knowledge that feeds the ADT must follow rigorous ethical protocols as a condition of legitimacy, prior to and external to the system architecture. This requires: (a) FPIC protocols adapted to the Amazonian legal and cultural context; (b) benefit-sharing models with knowledge-holding communities; (c) transparency about how traditional knowledge is formalized and incorporated into the model.

RESEARCH AGENDA

The identified challenges shape a research agenda comprising four interconnected strands. The first strand involves the development and testing of integrated models of the three ADT layers in Amazonian pilot cities such as Manaus, Belém, Santarém, and Parintins, chosen for their contrasting profiles of connectivity, institutional capacity, and indigenous presence.

The second strand is the development of indigenous data sovereignty protocols, following the CARE guidelines (Benefit, Authority to Control, Responsibility, Ethics) and adapting them to the Brazilian legal context [13].

The third strand proposes and tests technical architectures resilient to low connectivity, with emphasis on edge computing, asynchronous synchronization, and

low-data-consumption interfaces suited to the infrastructure constraints of riverside and indigenous territories.

The fourth strand develops the methodological foundations of hydrological ethnomodelling, establishing protocols to formalize indigenous knowledge of river and forest cycles as structured predictive variables within the ADT, and empirically testing their performance against conventional hydrological models in selected Amazonian contexts. The following section discusses the findings of the theoretical and comparative analysis, with reference to the two research questions that frame this study.

DISCUSSION

This study offers insights into the requirements and practicality of creating an integrated digital twin for Amazonian territorial governance. Regarding RQ1, an analysis of global examples and the theoretical framework shows that an effective ADT must meet four key architectural criteria: live data integration across physical, natural, institutional, and sociocultural levels; interoperable, federated infrastructure that maintains local data sovereignty; reliable operation even with limited connectivity; and formal mechanisms to include indigenous knowledge as a core structural element rather than just supplementary input. The cases examined do not satisfy all four conditions simultaneously. This indicates that developing an ADT cannot rely on repurposing existing models but demands innovative architectural and epistemological design.

Regarding RQ2, the study highlights three interconnected gaps that must be addressed before the ADT can become operational. The conceptual gap involves the lack of frameworks that consider Amazonian sociodiversity, such as productive calendars, traditional territories, and knowledge systems, as core model variables, rather than external factors. The technical gap concerns the lack of edge computing architectures suitable for low-connectivity settings and interoperability protocols that link urban, environmental, and territorial data across multiple scales. The governance gap revolves around the lack of practical mechanisms to implement Free, Prior, and Informed Consent (FPIC) in data collection, risking the reinforcement of existing power imbalances rather than their redistribution. While each gap is well-documented separately in the literature [9; 10; 11], this framework's main contribution is recognizing their structural interdependence: a technologically advanced ADT without FPIC protocols will face political failure; conversely, a system with strong governance but lacking low-connectivity infrastructure will fail operationally.

Hydrological ethnomodelling is a key component of the framework, proposing that indigenous knowledge of river and forest cycles constitutes a detailed predictive system developed over generations of observation. Currently, this remains a hypothesis rather than an established fact, though supporting evidence comes from ethnobiology, human geography, and climate adaptation research. To formally incorporate it into simulation models, the steps outlined in Research Strand 4 are necessary. This transparency, distinguishing confirmed facts from hypotheses,

enhances the framework's robustness. Such an approach suits a conceptual paper that outlines a research agenda rather than presents empirical results.

CONCLUSION

This article presents the ADT as a conceptual step toward integrating urban and environmental aspects in the Amazon. A comparative review of three international examples shows that digital twins are technically feasible in complex environments but require tailored adjustments for the Amazonian context, including river dynamics, protecting indigenous data sovereignty, and creating infrastructure suitable for low connectivity. The article's contribution is twofold: it introduces a three-layer architectural model for the ADT and highlights hydrological ethnomodelling as its most unique and innovative feature, transforming indigenous knowledge from a passive data source into an active epistemological framework that guides simulations and influences urban-environmental planning.

ADTs offer potential for Amazonian urbanism if they are designed with careful consideration of governance, epistemological fairness, and acknowledgment of non-Western knowledge systems. Instead of simply introducing technology to communities, hydrological ethnomodelling reverses the typical approach of digital participation by integrating local knowledge into the technology itself, allowing communities to co-create the models rather than just being data sources.

This study has three notable limitations. First, the framework is primarily conceptual and has not been empirically tested; the four research strands outlined are intended to guide the transition from hypothesis to evidence. Second, the choice of three international case studies, selected for their complementary coverage of different framework dimensions, is illustrative rather than exhaustive and should not be taken to support broad generalizations. Third, the Amazon is treated as relatively uniform in the analysis, despite considerable differences across municipalities, states, and countries in connectivity, institutional capacity, and sociocultural factors. Future research should consider this internal diversity when selecting pilot locations and designing protocols. Recognizing these limitations is not a weakness of the framework but an integral part of the research proposed in the four strands.

DECLARATION

In preparing this manuscript, the first author used the following generative AI tools: Grammarly (web version) for spelling, grammar, and style correction; and ChatGPT-4o (OpenAI) for the generation of Figure 1, used as a conceptual visualisation of the Amazonian Digital Twin architecture. All AI-generated output was critically reviewed and verified by the authors. The authors take full responsibility for the entire intellectual content of this work, including its conceptualisation, methodology, analysis, findings, and conclusions. This use of AI tools is acknowledged in accordance with Portaria 2664/2026.

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