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Research Article

Cyber-Physical Architecture for Urban Drainage Digital Twins: A Methodological Handbook Integrating AutoCAD Civil 3D and SewerGEMS

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Abstract

Dynamic management of urban drainage networks necessitates the integration of cyber-physical systems to overcome the limitations of static design approaches. This study presents a universal technical handbook that combines the topological integrity of AutoCAD Civil 3D with the full dynamic modeling capacity of the SewerGEMS platform. The methodology systematizes topological data integration in a step-by-step manner, incorporating the numerical configuration where Saint-Venant equations are solved via a four-point implicit finite difference scheme and the Newton-Raphson iteration method. The study defines the integration protocol of Extended Period Simulation (EPS) and SCADA-based continuous multipliers, necessary for the system to evolve into a living digital twin (living DT) form, as a technical procedure. The sensitivity of the Kutter formulation in detecting sedimentation risks, which resolves the non-linear interaction between roughness and energy gradient especially in low-slope lines, is emphasized. In the hydrodynamic control phase, occupancy rates exceeding the 70-80% threshold and flow velocities falling below 0.50-0.60 m/s are identified as primary operational risk indicators regarding corrosion, gas accumulation, and capacity loss. This guide establishes a proactive decision support mechanism that prioritizes rehabilitation strategies, such as cured-in-place pipe (CIPP) and egg-shaped pipe optimization, through what-if scenarios. This integrated approach offers a resilient and universal engineering standard for sustainable urban infrastructure management.

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Cyber-Physical Architecture, Digital Twin, Saint-Venant Equations, AutoCAD Civil 3D, Hydraulic Modelling, Urban Infrastructure Management

Kentsel Drenaj Şebekeleri İçin Siber-Fiziksel Dijital İkiz Mimarisi: AutoCAD Civil 3D ve SewerGEMS Tabanlı Teknik Bir Kılavuz

Özet

Kentsel drenaj şebekelerinin dinamik yönetimi, statik tasarım yaklaşımlarının kısıtlarını aşmak adına siber-fiziksel sistemlerin entegrasyonunu gerektirmektedir. Bu çalışma, AutoCAD Civil 3D'nin topolojik bütünlüğü ile SewerGEMS platformunun tam dinamik modelleme kapasitesini birleştiren evrensel bir teknik kılavuz sunmaktadır. Metodoloji; topolojik veri entegrasyonu, Saint-Venant denklemlerinin dört-nokta örtük sonlu farklar şeması ve Newton-Raphson iterasyon yöntemiyle çözüldüğü sayısal konfigürasyonu adım adım sistematize etmektedir. Çalışma, sistemin yaşayan bir dijital ikiz formuna evrilmesi için gerekli olan Genişletilmiş Zaman Simülasyonu (EPS) ve SCADA tabanlı sürekli çarpanların entegrasyon protokolünü teknik bir prosedür olarak tanımlamaktadır. Özellikle düşük eğimli hatlarda pürüzlülük ve enerji eğimi arasındaki lineer olmayan etkileşimi çözen Kutter formülasyonunun, sedimantasyon risklerini saptamadaki hassasiyeti vurgulanmıştır. Hidrodinamik denetim aşamasında, doluluk oranlarının %70-80 eşiğini aşması ve akış hızlarının 0,50-0,60 m/s altına düşmesi; korozyon, gaz birikimi ve kapasite kaybı açısından temel operasyonel risk göstergeleri olarak belirlenmiştir. Sunulan bu rehber, yerinde kaplama (CIPP) ve yumurta kesitli boru optimizasyonu gibi rehabilitasyon stratejilerini olası senaryolarla önceliklendiren proaktif bir karar destek mekanizması tesis etmektedir. Bu bütünleşik yaklaşım, sürdürülebilir kentsel altyapı yönetimi için dirençli ve evrensel bir mühendislik standardı sunmaktadır.

Anahtar Kelimeler
Siber-Fiziksel Mimari, Dijital İkiz, Saint-Venant Denklemleri, AutoCAD Civil 3D, Hidrolik Modelleme, Kentsel Altyapı Yönetimi

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INTRODUCTION

Anthropogenic pressures on urban infrastructure systems have reached a critical threshold due to rapid demographic changes and the scarcity of water resources [1,2]. Impervious surfaces expanding with uncontrolled urbanization directly threaten the hydraulic capacity and resilience of drainage networks against extreme meteorological events, making dynamic management strategies a technical necessity [3–5].

Traditional Manning equation-based deterministic and static calculation methods used for urban drainage network design fail to simulate second-by-second flow fluctuations and downstream backwater effects while attempting to predict system behavior through average values. The inability of static models to resolve instantaneous capacity exceedances in pipelines and the cumulative pressure of infiltration waters on the energy gradient line (EGL) misleads engineers and causes the safe design range to be exceeded under actual operating conditions. This leads to serious design errors [6–8]. To overcome these technical bottlenecks, the cyber-physical system architecture designed within the Industry 4.0 framework establishes seamless bidirectional data exchange between physical processes and cyber layers, shifting infrastructure management away from the reactive intervention cycle. Beyond a simple geometric copy, this structure, which continuously feeds back changes in the physical world to its cyber representation throughout the system life cycle, functions as a proactive living digital twin (living DT) and an integrated methodology that enhances behavioral insight into infrastructure components [8–12].

Hydrodynamic simulations based on dynamic modeling and Saint-Venant equations have long been recognized as a core methodology in academic literature and large-scale master planning [3,13]. Yet, despite such theoretical competence, static and deterministic approaches like the Manning equation continue to dominate the daily design routines of local authorities and water utilities [12,14]. This work intends to bridge the technical divide caused by the lack of high-resolution hydraulic solutions in everyday engineering practices and advocates for establishing dynamic modeling as a standard operating procedure for local governments.

While the literature separately documents the topological data editing capabilities of AutoCAD Civil 3D and the Saint-Venant-based numerical solver precision of SewerGEMS, there is a noted absence of a systematic technical handbook for integrating these systems into a cyber-physical architecture [6,8,15,16]. This study represents the first technical guide to convert the Civil 3D and SewerGEMS workflow into a step-by-step methodology via the ModelBuilder protocol, proposing this hybrid structure as a universal engineering standard in the form of a Living Digital Twin.

This study establishes a technical methodological handbook for engineers and designers that combines the topological integrity of the AutoCAD Civil 3D platform with the full dynamic modeling capacity of the SewerGEMS software. The presented cyber-physical architecture aims to enhance the capacity to prevent design errors by systematizing the technical configuration of Saint-Venant-based simulations and the installation stages of a living digital twin.

MATERIAL AND METHOD

Sustainable management of urban infrastructure systems requires the proactive management of dynamic hydraulic risks that static design approaches fail to predict. This section systematizes a universal and high-precision workflow for establishing dynamic network model architecture through the integration of AutoCAD Civil 3D and SewerGEMS platforms. The presented methodology includes engineering standards applicable at any urban catchment or network scale. The proposed cyber-physical architecture is structured based on the methodological sequence shown in Figure 1.

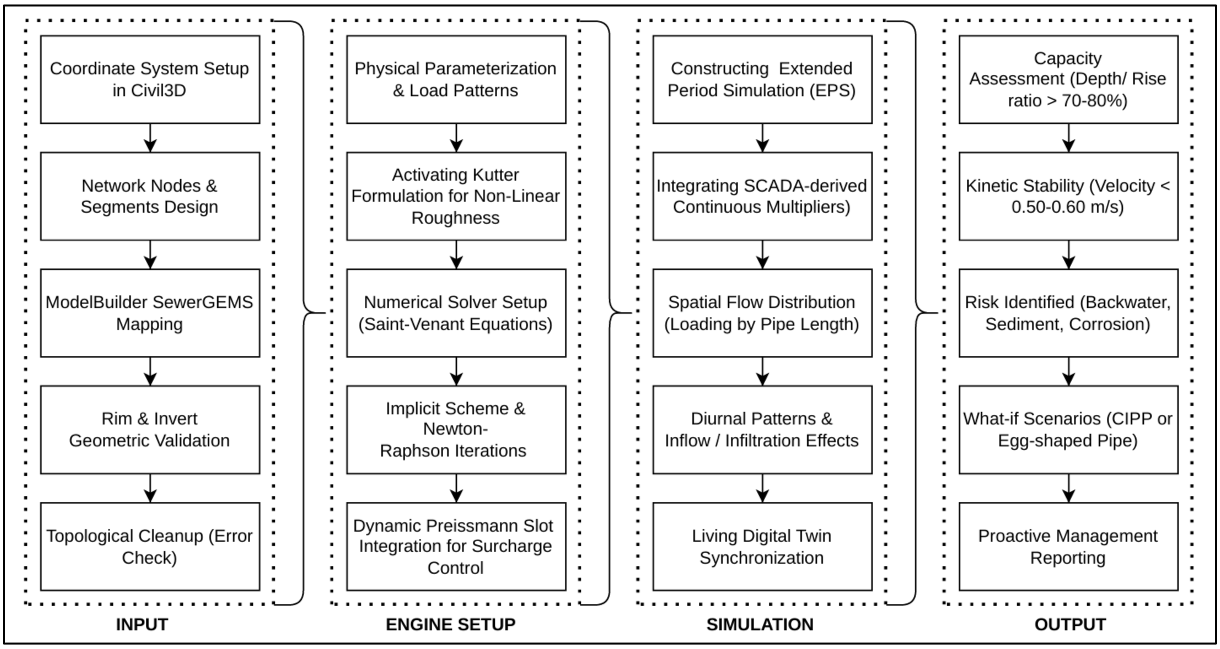

Figure 1. Implementation flowchart of the cyber-physical digital twin architecture.

Topological Data Integration and ModelBuilder Protocol

In the process of establishing urban infrastructure networks as an integrated digital ecosystem, high-resolution city models form the fundamental data layer of the digital twin ecosystem. Synchronization of the SewerGEMS ecosystem with the topological integrity provided by the AutoCAD Civil 3D platform enables mapping structural data from CAD attribute tables to hydraulic parameters with millimetric precision through the ModelBuilder protocol. During this integration process, to maximize the representation capability of the physical entity within the digital environment, the network structure, nodes, and segments derived from polylines prepared in the ITRF 96 coordinate system are transferred to the digital environment within a hierarchical integrity [7,14,16].

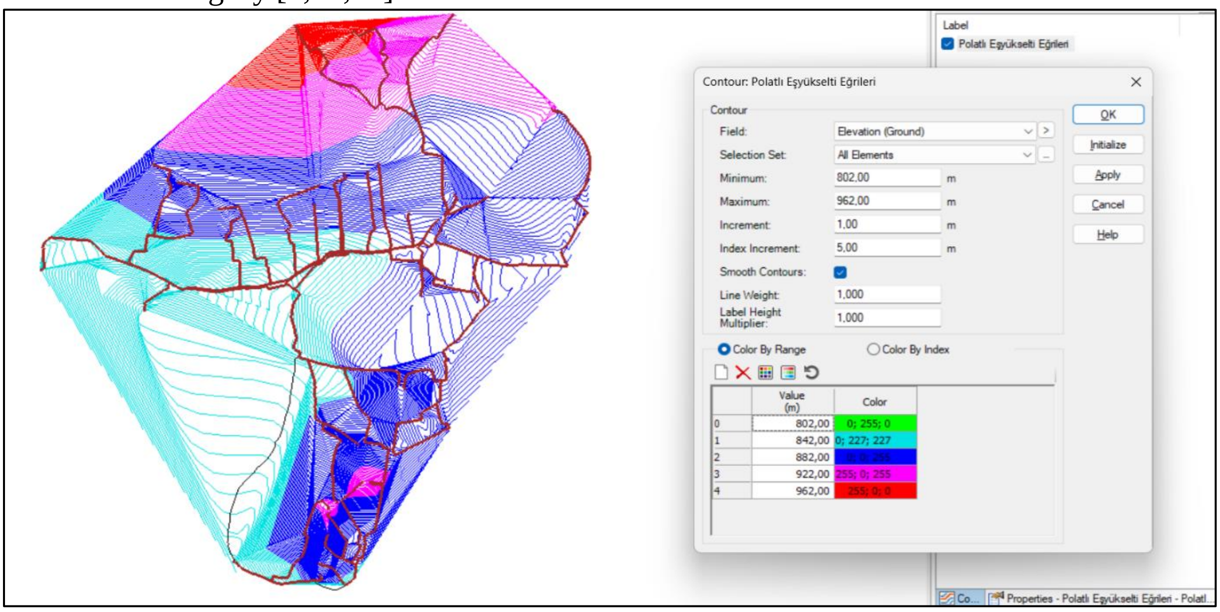

Figure 2. Cyber-physical application site and contour map of the Polatlı urban infrastructure network on the SewerGEMS platform

The proposed model was applied to the urban wastewater network in the Polatlı district of Ankara. This study evaluates the potential of a dynamic model based on universal Saint-Venant equations to resolve local-scale hydrodynamic irregularities in the sewerage network of a rapidly industrializing and growing district. In this application site serving a population of approximately 128,318, the cyber-physical architecture integrating SewerGEMS and AutoCAD Civil 3D software was employed; the map illustrating the network topology and physical distribution is presented in Figure 2.

Following the data transfer via ModelBuilder, the node (manhole) data that form the hydraulic foundation of the system must be rigorously inspected. At this stage, precise positional coordinates (X, Y) and the rim elevations that determine surface levels for each node should be verified individually or collectively through the Property Grid interface. Specifically, defining the invert elevations that determine hydraulic flow characteristics is a methodological requirement for establishing the geometric boundary conditions needed for Saint-Venant momentum components. Maintaining invert elevation accuracy proactively prevents deviations in the energy gradient calculations of the integrated model, guaranteeing the alignment between the physical system and its digital copy [14–16].

The technical validation protocol, the final stage in establishing cyber-physical architecture; must be executed systematically through the software's Validation and Network Review tools to ensure the hydrodynamic consistency of the system. Topographic inconsistencies, hydraulic disconnections, and particularly reverse slope errors leading to numerical instabilities in solving Saint-Venant momentum components identified during this process must be corrected for each segment in accordance with physical reality. Subjecting the network hierarchy to these topographic continuity tests eliminates technical bottlenecks that could disrupt real-time data flow during the simulation phase, ensuring that the digital twin model represents the physical entity with a minimum margin of error [12,14–16].

Identification of Physical Parameters and Kutter Formulation

In the cyber-physical representation of urban drainage networks, the precise definition of physical components and their accurate processing into the database are essential prerequisites for the accuracy of hydrodynamic behavior within the computational domain. While establishing the hierarchical structure of the model; pipe diameters that gradually expand from lateral lines toward main interceptors should be defined through the Property Grid interface, preserving the topological hierarchy of the system. Integrating these physical parameters with spatial validation allows the hydraulic capacity and operational reserve potential of the network to be resolved on a second-by-second basis under actual operating conditions [14,16].

In hydraulic resistance analyses, the selection of pipe material (concrete, HDPE, or PVC) must be included as a user-defined input into the simulation engine via the material-specific Manning roughness coefficient (n). Unlike traditional static approaches, the Kutter Formulation, which dynamically calculates the non-linear interaction between the roughness coefficient and the energy gradient (S), offers a high-resolution methodological standard for detecting sedimentation risks in low-velocity zones, particularly in sections with low-sloped topography. The software's calculation engine processes manually entered Manning values through the Kutter equation, transferring the inversely proportional relationship between roughness and slope to the cyber-physical plane to simulate flow velocities [16–18]. In the hydrodynamic simulation of free-surface flows, the velocity equation (Equation 1) and the Chézy coefficient function (Equation 2) are configured using empirical constants k_1=23.0, k_2=0.00155 and k_3=1.0:

$$V = C\sqrt{RS} \qquad \text{(Eq. 1)}$$

Within the Kutter approach, the Chézy roughness coefficient (C) is determined through the following function by relating it to Manning’s n coefficient and the energy gradient (S) [16]:

$$C = \frac{k_1 + \frac{k_2}{S} + \frac{k_3}{n}}{1 + \frac{n}{\sqrt{R}}\cdot\left(k_1 + \frac{k_2}{S}\right)} \quad \text{(Eq. 2)}$$

In these equations, V represents the flow velocity (m/s); R the hydraulic radius (m); S the energy gradient or pipe bed slope (m/m), and n the Manning roughness coefficient.

Technical precision in physical parameter entry ensures the scientific monitoring of the self-cleaning velocity criterion within the network. High-resolution entry of pipe diameters, material types, and line lengths via the Property Grid makes it possible to monitor whether millimetric changes in the roughness coefficient push the flow velocity below the threshold values of 0.50 m/s to 0.60 m/s [3,13]. This cyber-physical control mechanism transforms infrastructure management from reactive cleaning interventions into a data-driven proactive maintenance model by enabling the prediction of sedimentation risk and the resulting sulfuric acid (H_2SO_4) corrosion [8,17,19].

Numerical Solver Configuration: Newton-Raphson and Implicit Scheme

Saint-Venant equations, based on continuity representing mass conservation and momentum based on energy conservation, are used to simulate the hydrodynamic behavior of unsteady free-surface flow regimes in complex urban drainage networks. These equations, forming the computational core of cyber-physical architecture, allow the in-network flow to be resolved with second-based precision through the dynamic wave routing protocol. Hydrodynamic flows within the network are solved with second-based precision via continuity (Equation 3) and momentum (Equation 4) equations, which reflect the principles of mass and energy conservation, respectively [15,16].

$$\frac{\partial Q}{\partial x} + \frac{\partial (A + A_0)}{\partial t} - q = 0 \quad \text{(Eq. 3)}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial (\beta Q^2/A)}{\partial x} + gA\left(\frac{\partial y}{\partial x} - S_0 + S_f + S_e\right) + L = 0 \quad \text{(Eq. 4)}$$

In the equations forming the numerical solver algorithm; Q represents the flow rate (l/s or m^3/s); A the active flow cross-sectional area (m^2); y the flow depth (m); t the simulation time (s); and x the longitudinal distance along the channel (m). While A_0 denotes the additional cross-sectional area defined within the scope of the Preissmann slot during the transition to surcharged flow conditions; lateral flows are defined by q (m^3/s/m) and the cumulative momentum effect of these flows by L. The physical dynamics of the system are formulated using the parameters gravitational acceleration (g=9.81 m/s^2), momentum correction (Boussinesq) coefficient β, channel bed slope (S_0, m/m), friction-induced energy gradient (S_f, m/m), and local head loss gradient (S_e, m/m).

While methods such as Finite Element or Finite Volume offer high spatial resolution, the four-point implicit finite difference method is often preferred for 1D urban drainage models due to its superior numerical stability and computational efficiency in gravity-driven sewer networks. In the implicit solver configuration, a weighted four-point implicit scheme is applied to manage the complex hydraulic interactions found in gravity-driven sewerage systems. This scheme provides a universal engineering standard due to its flexibility in handling unequal distance steps and its capacity to easily integrate internal boundary conditions such as pumps, manholes, and weirs. Solving non-linear dynamic equations at each calculation interval results in a complex matrix system where flow (Q) and water head (h) values at each node remain unknown [15,16,20].

In the numerical solution of the matrix system in question, the Newton-Raphson iteration method establishes hydrodynamic stability with high computational efficiency by optimizing complex network matrices within user-defined tolerance thresholds. This algorithm plays a critical role in determining air-water interface positions during pipe filling processes, ensuring rapid convergence of the system to second-based variables [21]. However, spurious oscillations occurring during transition phases—where flow shifts from a free-surface regime to a surcharged state by contacting the pipe crown—represent a fundamental engineering challenge that compromises simulation accuracy and numerical stability. For the proactive management of these numerical instabilities, using hybrid numerical flux solvers that integrate centered schemes to smooth flow near the pipe crown provides precise results even at high wave velocities, unlike Manning-based static approaches [22]. The Dynamic Preissmann Slot (DPS) approach, designed to overcome the fixed slot width constraints of the traditional Preissmann slot model, defines the slot as a dynamic transient storage unit via the cross-sectional area rather than a static geometric element. This dynamic network architecture, which damps celerity shocks via a Preissmann Number parameter, systematizes downstream backwater effects under a high-resolution management mechanism by preserving the hydrodynamic boundary conditions required for Saint-Venant momentum components[23].

Dynamic Loading: Continuous Multipliers and Extended Period Simulation (EPS)

The evolution of a cyber-physical urban infrastructure model from a static simulation into a living digital twin (living DT) form depends on the meticulous configuration of the Extended Period Simulation (EPS) protocol, which reflects real-time system behavior instead of deterministic peak factors. The dynamic loading process should be built on a 168-hour (one-week) cyclical logic [8]. This duration accounts for both weekday and weekend diurnal flow fluctuations, ensuring that the living digital twin captures the full range of cyclical anthropogenic patterns. Within this methodological workflow, raw flow data obtained from SCADA or PLC systems are first cleaned of outliers and then converted into continuous multipliers by being proportioned to the average flow during the normalization stage [24]. These high-resolution coefficients are integrated into the system via the Pattern module of the SewerGEMS software, reflecting both daily fluctuations in urban consumption and the cumulative pressure of uncontrolled infiltration and inflow (I/I) waters onto the digital environment with second-based precision [25]. Regarding the spatial distribution of flow across the network, the use of the Loading by Pipe Length technique offers a strategic methodological rationale in urban catchments where access to household-based billing or subscriber records is restricted. This technique distributes the flow proportionally to the physical spread of the network and segment lengths, enabling the integrated model to detect hydrodynamic stress thresholds at levels closest to reality [14,16].

The 168-hour simulation cycle configured in accordance with international engineering principles demonstrates the operational limits of the system for both weekdays and weekends, as well as pipe occupancy rates (depth/rise) during morning and evening peak loading periods [24]. Unlike static design criteria, digital twin models fed by continuous multipliers enable proactive management of biokinetic risks at the network-facility interface by making visible the critical moments when the actual operating capacity of the system exceeds design limits [25]. This dynamic loading framework constitutes the most strategic data layer in a cyber-physical architecture gaining functionality as a living digital twin (living DT) [8].

RESULT AND DISCUSSION

Model outputs obtained via a cyber-physical digital twin in urban infrastructure management demonstrate that the network is no longer a static design object but a dynamic mechanism responding instantaneously to environmental and anthropogenic variables. How data generated through the integration of SewerGEMS and Civil 3D should be interpreted from an engineering perspective, and the technical benefits this digital architecture provides across the system, are addressed following a methodological guide logic.

Detection of Hydraulic Bottlenecks and Operational Risk Analysis

The primary technical indicator in the dynamic performance assessment of urban drainage networks is the occupancy rate (depth/rise) parameter, which characterizes the ratio of flow depth to pipe diameter. Engineers designing cyber-physical digital twin architecture should identify segments where this ratio reaches 100% through the hydraulic data tables (FlexTables) of the SewerGEMS platform as full flow conditions, in which the system completely exhausts its hydraulic reserve. This indicates that the pipeline has exceeded its designed attenuation capacity and that no hydraulic safety margin remains in the system during peak flow fluctuations. This enables the proactive deciphering of design errors [14,16].

Within the axis of operational risk analysis, an occupancy rate reaching 100% should be interpreted as the onset of a biochemical corrosion cycle threatening network integrity and hydraulic capacity deficiency. According to wastewater engineering standards, maintaining the occupancy rate within the 70-80% band is a technical measure intended to preserve ventilation capacity and prevent septicity. Exceeding this threshold value causes the loss of the headspace at the pipe crown, the accumulation of hydrogen sulfide (H_2S) gas under anaerobic conditions, and structural fatigue resulting from sulfuric acid (H_2SO_4) corrosion. Unlike traditional static methods, cyber-physical models resolve these critical bottlenecks with second-based precision, enabling operational units to intervene directly at risky points and preserve the operational resilience of the system [3,8,15,17].

Investigation of Backwater Effects via Profiles

Negative headloss values identified by the dynamic calculation engine of the digital network architecture serve as the primary numerical indicator of backwater, resulting from downstream water levels exceeding those at the upstream [13]. In the graphical representation of hydrodynamic behavior, the horizontal trend of the Hydraulic Grade Line (HGL) and Energy Grade Line (EGL) slopes confirm that the pipe has lost its gravity flow characteristic and reached the boundary of the surcharged regime. This hydrodynamic pressure directly reduces flow velocities, proactively threatening the instantaneous capacity of the network [26,27].

Considering dynamic data obtained from profile views, improvement scenarios such as strategic diameter increases or pipe slope revisions can be tested within the digital environment through what-if analyses. Consequently, dynamic monitoring of backwater effects via profiles is a methodological necessity for managing downstream-induced hydrodynamic bottlenecks using a data-driven approach [25].

Evaluation of In-Pipe Flow Velocities and Sedimentation Problems

Dynamic simulations constructed via the Kutter formulation identify sedimentation risks with higher hydrodynamic resolution compared to static Manning models, particularly in catchments with variable topography and critical low-slope line segments [16,18]. Velocity data falling below the threshold values of 0.50 m/s to 0.60 m/s defined in the methodological workflow represent a chronic risk of solids accumulation at the pipeline bed and operational cost increases due to effective cross-section narrowing. These depositions occurring in low-flow regimes proactively threaten the structural integrity and mechanical life of concrete pipe walls by triggering sulfuric acid (H_2SO_4) corrosion because of the anaerobic decomposition of the organic load [3,13,19]

High-precision velocity maps provided by the cyber-physical model function as a strategic decision support parameter for identifying sedimentation vulnerability throughout the network in the digital environment and for deploying maintenance teams directly to high-risk locations [14,28]. These cyber-physical simulations maintain the biokinetic stability of urban infrastructure by shifting management from reactive cleaning interventions toward a data-driven proactive maintenance model [8,29].

Biokinetic Stability and Decision Support Strategies

Monitoring dynamic interactions between urban infrastructure networks and wastewater treatment plants (WWTPs) through a cyber-physical architecture preserves operational resilience and biokinetic stability [29,30]. Dilution of raw wastewater characterization by uncontrolled infiltration and inflow (I/I) risks discharge standards by lowering substrate concentration and nitrification rates in bioreactors [13,29]. Concurrent tracking of these biokinetic risks alongside network hydraulics establishes a proactive decision-support metric that analyzes the impact of flow peaks identified via the cyber-physical model on Hydraulic Retention Times (HRT) [6,30]. Within the framework of the decision-support mechanism, segments where occupancy rates reach 100% or flow velocities fall below threshold values are mapped as high-risk zones for gas accumulation, corrosion, and sedimentation [3,13,17].

Through what-if scenarios, engineers can prioritize strategic rehabilitation interventions—such as Cured-in-Place Pipe (CIPP) or egg-shaped pipe optimization—targeting the segments that most significantly threaten biokinetic stability [8,17,19,25,31]. This integrated approach ensures operational integrity at the network-facility interface while minimizing reactive intervention costs.

CONCLUSION

Urban infrastructure management necessitates a transition from static calculations to dynamic cyber-physical architecture based on Saint-Venant equations. This methodology, established through the integration of Civil 3D and SewerGEMS, demonstrates technical superiority in preventing design errors and deciphering downstream-induced backwater effects with second-based precision. Unlike traditional models, this approach transforms reactive intervention processes into a proactive management model by revealing the hydraulic reserve and operational limits of the network under actual operating conditions with high resolution.

To enhance operational resilience, Cured-in-Place Pipe (CIPP) technologies that ensure sealing and egg-shaped pipe geometries that provide velocity optimization in segments with low detected velocities should be adopted as strategic interventions. Establishing Dynamic Modeling Units within Water and Sewerage Administrations will facilitate managing infrastructure inventories via continuously updated digital twins and institutionalize a proactive decision-support mechanism aligned with the United Nations Sustainable Development Goals. This integrated approach serves as a universal engineering guide to maintain urban drainage systems in a resilient and sustainable state against future growth projections.

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REFERENCES

[1] Saikia SD, Ryan P, Nuyts S, Nolan P, Clifford E. Impacts of projected future changes in precipitation on wastewater treatment plant influent volumes connected by combined sewer collection systems. Clim Serv. 2024 Aug;35:100511. doi:10.1016/j.cliser.2024.100511

[2] Sun S, Zheng X, Liu X, Wang Z, Liang L. Global pattern and drivers of water scarcity research: a combined bibliometric and geographic detector study. Environ Monit Assess. 2022 Aug 23;194(8):523. doi:10.1007/s10661-022-10142-4

[3] Butler D, Digman C, Makropoulos C, Davies JW. Urban Drainage. 5th ed. Boca Raton: CRC Press; 2024. doi:10.1201/9781003408635

[4] Alshami A, Ali E, Elsayed M, Eltoukhy AEE, Zayed T. IoT innovations in sustainable water and wastewater management and water quality monitoring: A comprehensive review of advancements, implications, and future directions. IEEE Access. 2024;12:58427–53. doi:10.1109/ACCESS.2024.3392573

[5] Jones ER, Bierkens MFP, Wanders N, Sutanudjaja EH, van Beek LPH, van Vliet MTH. Current wastewater treatment targets are insufficient to protect surface water quality. Commun Earth Environ. 2022 Oct 6;3(1):221. doi:10.1038/s43247-022-00554-y

[6] Sardar MA, Amir E, Rehman MA, Malik KF, Khalid MA. Integration of Digital Twin Technology for Water Resource Management of Smart Cities and Communities: A Narrative Review. International Journal of Advanced Natural Sciences and Engineering Researches. 2025;9(2):75–85. doi:10.5281/zenodo.14823713

[7] Xu H, Omitaomu F, Sabri S, Zlatanova S, Li X, Song Y. Leveraging generative AI for urban digital twins: a scoping review on the autonomous generation of urban data, scenarios, designs, and 3D city models for smart city advancement. Urban Informatics. 2024 Oct 14;3(1):29. doi:10.1007/s44212-024-00060-w

[8] Pedersen AN, Borup M, Brink-Kjær A, Christiansen LE, Mikkelsen PS. Living and Prototyping Digital Twins for Urban Water Systems: Towards Multi-Purpose Value Creation Using Models and Sensors. Water (Basel). 2021 Feb 25;13(5):592. doi:10.3390/w13050592

[9] Callcut M, Cerceau Agliozzo JP, Varga L, McMillan L. Digital Twins in Civil Infrastructure Systems. Sustainability. 2021 Oct 19;13(20):11549. doi:10.3390/su132011549

[10] Dobaj J, Riel A, Macher G, Egretzberger M. Towards DevOps for Cyber-Physical Systems (CPSs): Resilient Self-Adaptive Software for Sustainable Human-Centric Smart CPS Facilitated by Digital Twins. Machines. 2023 Oct 19;11(10):973. doi:10.3390/machines11100973

[11] Fuller A, Fan Z, Day C, Barlow C. Digital Twin: Enabling Technologies, Challenges and Open Research. IEEE Access. 2020;8:108952–71. doi:10.1109/ACCESS.2020.2998358

[12] Hartmann S, Valles R, Schmitt A, Al-Zuriqat T, Dragos K, Gölzhäuser P, Jung JT, Villinger G, Varela Rojas D, Bergmann M, Pullmann T, Heimer D, Stahl C, Stollewerk A, Hilgers M, Jansen E, Schoenebeck B, Buchholz O, Papadakis I, Merkle DR, Jäkel JI, Mackenbach S, Klemt-Albert K, Reiterer A, Smarsly K. Digital-Twin-Based Management of Sewer Systems: Research Strategy for the KaSyTwin Project. Water (Basel). 2025 Jan 22;17(3):299. doi:10.3390/w17030299

[13] Metcalf & Eddy Inc, Tchobanoglous G, Stensel HD, Tsuchihashi R, Burton FL. Wastewater Engineering: Treatment and Resource Recovery [Internet]. 5th ed. New York, NY: McGraw-Hill Education; 2014. Available from: https://books.google.com.tr/books?id=6KVKMAEACAAJ

[14] Bhagat RM, Pande PB, Raut JM, Dhengare SW, Borse AS, Jasutkar DB. Optimizing urban infrastructure: Design and analysis of sewer networks with SewerGEMS. International Journal of Engineering Trends and Technology. 2024;72(10):225–34. doi:10.14445/22315381/IJETT-V72I10P122

[15] Rossman LA. Storm water management model user's manual, version 5.0. Vol. 276. Cincinnati, OH, USA: National Risk Management Research Laboratory, Office of Research and Development, US Environmental Protection Agency; 2010 Jul.

[16] Bentley Systems Inc,. SewerGEMS Help Documentation, Version 23.0. Exton, PA: Bentley Systems, Inc.; 2023.

[17] Acar E. Yumurta ve Dairesel Enkesit Geometrisine Sahip Atıksu Boru Modeli İçerisindeki Akışın Hidrodinamik Açıdan Karşılaştırmalı Sayısal Analizi. Artvin Çoruh Üniversitesi Mühendislik ve Fen Bilimleri Dergisi. 2024;2(2):80–9.

[18] Walski TM., Barnard TE., Harold Eric, Merritt LB., Walker Noah, Whitman BE. Wastewater collection system modeling and design. Bentley Institute Press; 2007. 606 p.

[19] Kaushal V, Najafi M, Serajiantehrani R. Environmental Impacts of Conventional Open-Cut Pipeline Installation and Trenchless Technology Methods: State-of-the-Art Review. J Pipeline Syst Eng Pract. 2020 May;11(2). doi:10.1061/(ASCE)PS.1949-1204.0000459

[20] Crossley AJ. Accurate and efficient numerical solutions for the Saint Venant equations of open channel flow [Doctoral dissertation]. [Nottingham]: University of Nottingham; 1999.

[21] Fuertes-Miquel VS. Transient Flows: Mathematical Models, Laboratory Tests, Protection Elements and Systems. Water (Basel). 2025 May 12;17(10):1454. doi:10.3390/w17101454

[22] An H, Lee S, Noh SJ, Kim Y, Noh J. Hybrid Numerical Scheme of Preissmann Slot Model for Transient Mixed Flows. Water (Basel). 2018 Jul 6;10(7):899. doi:10.3390/w10070899

[23] Sharior S, Hodges BR, Vasconcelos JG. Generalized, Dynamic, and Transient-Storage Form of the Preissmann Slot. Journal of Hydraulic Engineering. 2023 Nov;149(11). doi:10.1061/JHEND8.HYENG-13609

[24] Rousso BZ, Gong J. Smart sewers in practice: a systematic review of instrumentation, applications and pathways to adoption for sustainable urban systems. J Environ Manage. 2026 Mar;401:128922. doi:10.1016/j.jenvman.2026.128922

[25] Karpf C, Krebs P. Modelling of groundwater infiltration into sewer systems. Urban Water J. 2013 Aug;10(4):221–9. doi:10.1080/1573062X.2012.724077

[26] Ashley R, Bertrand-Krajewski J, Hvitved-Jacobsen T, Verbanck M. Solids in Sewers: Characteristics, Effects and Control of Sewer Solids and Associated Pollutants. Water Intelligence Online. 2004 Dec 30;4(0):9781780402727–9781780402727. doi:10.2166/9781780402727

[27] Xie J, Qiang W, Lin Y, Huang Y, Xu KQ, Zheng D, Chen S, Pei Y, Fan G. Enhancing Urban Drainage Resilience Through Holistic Stormwater Regulation: A Review. Water (Basel). 2025 May 20;17(10):1536. doi:10.3390/w17101536

[28] Mester T, Szabó G, Kiss E, Balla D. Towards Environmental Sustainability: Wastewater Management and Sewer Networks for Protecting Groundwater in Rural Settlements. Urban Science. 2025 Mar 12;9(3):80. doi:10.3390/urbansci9030080

[29] Torfs E, Nicolaï N, Daneshgar S, Copp JB, Haimi H, Ikumi D, Johnson B, Plosz BB, Snowling S, Townley LR, Valverde-Pérez B, Vanrolleghem PA, Vezzaro L, Nopens I. The transition of WRRF models to digital twin applications. Water Science and Technology. 2022 May 15;85(10):2840–53. doi:10.2166/wst.2022.107

[30] Daneshgar S, Polesel F, Borzooei S, Sørensen HR, Peeters R, Weijers S, Nopens I, Torfs E. A full-scale operational digital twin for a water resource recovery facility—A case study of Eindhoven Water Resource Recovery Facility. Water Environment Research. 2024 Mar 25;96(3). doi:10.1002/wer.11016

[31] Ortigara A, Kay M, Uhlenbrook S. A Review of the SDG 6 Synthesis Report 2018 from an Education, Training, and Research Perspective. Water (Basel). 2018 Sep 28;10(10):1353. doi:10.3390/w10101353