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System dynamics for integrated domestic wastewater management: A review of stock–flow models, policy scenarios, and river water quality

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Abstract: Domestic wastewater management is a long-term systems problem shaped by population growth, water use, sanitation coverage, treatment capacity, infrastructure deterioration, institutional performance, finance, pollutant generation, and receiving-water conditions. This review synthesizes the use of System Dynamics (SD) for integrated domestic wastewater planning, with emphasis on causal-loop structures, stock–flow models, policy scenarios, pollutant-load estimation, and river-water-quality responses. A structured narrative search covering 2010 to June 2026 was used to identify peer-reviewed studies that applied explicit SD concepts to wastewater, sanitation, water pollution, or coupled water-quality management. The literature shows that most models represent population, wastewater generation, treatment capacity, and pollution control, but fewer integrate on-site sanitation, faecal-sludge pathways, microbiological pollutants, river hydrology, climate stress, finance, and institutional behavior in one model. Scenario analysis is widely used, particularly business-as-usual, capacity expansion, service-coverage improvement, treatment-efficiency enhancement, and combined-policy scenarios. The evidence indicates that isolated infrastructure expansion often underperforms when household connections, operation and maintenance, financing, or treatment efficiency remain constrained. More robust models combine service coverage and capacity dynamics with pollutant mass balance, receiving-water dilution, validation tests, and sensitivity or uncertainty analysis. Coastal and data-limited cities require additional representation of shallow groundwater, infiltration and inflow, flooding, tidal backwater, sea-level rise, and the dominance of on-site sanitation. The review proposes an integrated framework linking socio-demographic, service, infrastructure, treatment, pollutant, river-quality, financial, institutional, and climate subsystems. Future development should priorities spatial SD, participatory modelling, global sensitivity analysis, adaptive policy pathways, real-time monitoring, and hybridization with GIS, hydrological models, optimization, and machine learning.

Keywords: system dynamics; domestic wastewater; stock–flow model; policy scenarios; river water quality; urban sanitation

1. Introduction

Domestic wastewater management remains a major challenge for urban environmental protection, public health, and sustainable water-resource management. Population growth, urban expansion, and increasing household water consumption continue to increase wastewater generation, whereas the development of sewer networks, treatment facilities, faecal-sludge services, and institutional capacity often lags behind demand. Consequently, untreated or inadequately treated wastewater containing organic matter, suspended solids, nutrients, ammonia, detergents, and pathogenic microorganisms is

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frequently discharged into soil, drainage systems, rivers, lakes, and coastal waters (Harahap et al., 2021; Jones et al., 2021; The United Nations Human Settlements Programme (UN-Habitat) and the World Health Organization (WHO), 2024). In 2022, an estimated 42% of household wastewater was not safely treated before discharge, equivalent to approximately 113 billion m³ released with inadequate or no treatment (The United Nations Human Settlements Programme (UN-Habitat) and the World Health Organization (WHO), 2024). Addressing this challenge therefore requires a comprehensive sanitation approach that covers the entire service chain, from containment and collection to transport, treatment, reuse, and final disposal (Medland et al., 2016).

The problem is especially complex in small, medium-sized, and coastal cities, where wastewater management often relies on on-site sanitation systems. Shallow groundwater, permeable soils, flooding, tidal influence, saline intrusion, limited sewer coverage, and constrained municipal budgets further increase the risk of environmental contamination (Cahoon & Hanke, 2019; Flood & Cahoon, 2011; Fung & Babcock, 2020; Hummel et al., 2018). Infrastructure planning traditionally relies on population projections, per-capita wastewater generation, and static treatment-capacity calculations. Although these approaches are useful for engineering design, they cannot adequately capture feedback mechanisms, accumulation effects, non-linear interactions, behavioural responses, and implementation delays (Kelly et al., 2013; Sterman, 1994; Sterman & Series, 2003). As a result, expanding treatment capacity alone may produce only limited environmental improvement when household connection rates remain low, whereas rapid increases in sewer connections may instead increase bypasses and untreated discharges if treatment capacity and operational performance fail to keep pace (Demirel et al., 2022; Jeong & Adamowski, 2016; Kayal et al., 2026; Lemaire et al., 2021; Liu et al., 2015; Rehan et al., 2011).

SD provides a suitable framework for analysing complex wastewater-management systems through causal-loop diagrams, stock–flow structures, feedback mechanisms, auxiliary variables, and time delays (Sterman, 1994; Sterman & Series, 2003). Previous studies have applied this approach to wastewater infrastructure finance, treatment-capacity planning, sanitation behaviour, wastewater estimation, and water-quality management (Demirel et al., 2022; Jeong & Adamowski, 2016; Li et al., 2021; Liu et al., 2015; Rehan et al., 2011). Nevertheless, the existing literature remains fragmented, as most models focus on only one or two components of wastewater systems rather than representing the entire service chain. Comprehensive stock–flow models that simultaneously integrate domestic wastewater generation, sanitation-service coverage, treatment capacity, untreated discharge, pollutant loading, and river-water-quality responses remain scarce (Kayal et al., 2026; Liu et al., 2015; Tian et al., 2020; X. Zhang et al., 2025).

This review has four objectives. First, it identifies the principal subsystems, variables, and feedback structures used in SD models of wastewater and water pollution. Second, it compares model architectures, validation procedures, sensitivity tests, and policy scenarios. Third, it examines how service coverage and treatment capacity are connected to pollutant loads and receiving-water quality. Fourth, it proposes a consolidated modelling framework for coastal and data-limited cities. The review reduces the previously fragmented discussion into 12 integrated sections and focuses on practical model development and policy interpretation.

2. Material and methods

2.1 Literature search

This study employed a structured narrative review to synthesise previous research on the application of SD in domestic wastewater management. The review followed the reporting transparency recommended by PRISMA 2020 to ensure a transparent process of literature identification, screening, eligibility assessment, and study selection (Page et al., 2021). A quantitative meta-analysis was not performed because the reviewed studies differed substantially in their system boundaries, temporal scales, model structures, policy assumptions, and performance indicators, making statistical synthesis inappropriate. The literature search covered publications from January 2010 to June 2026, while seminal studies published before 2010 were retained to provide the theoretical foundation for SD modelling and model validation. Figure 1 summarises the literature selection process.

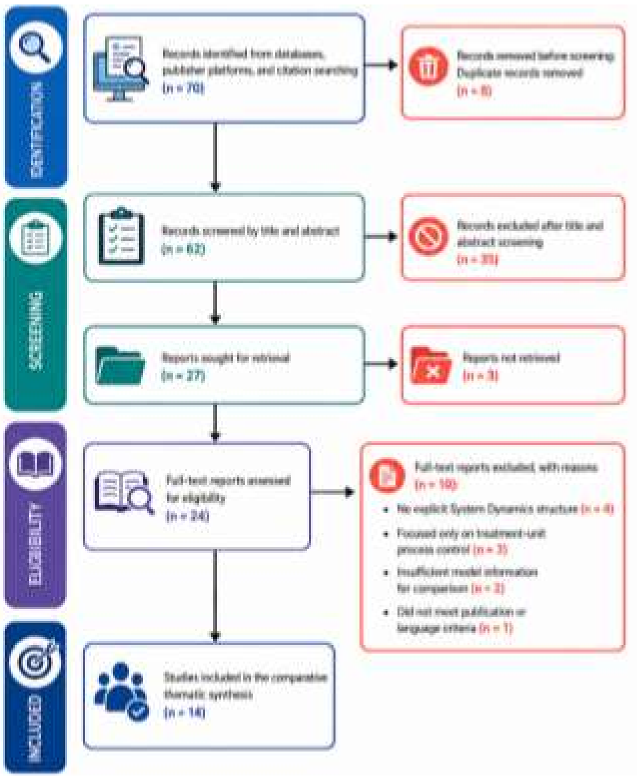

Figure 1. PRISMA 2020 flow diagram of the literature selection process for the structured narrative review on SD applications in domestic wastewater management

The literature search employed Boolean search strings comprising three groups of keywords: (i) “system dynamics”, “causal loop”, or “stock–flow”; (ii) “domestic wastewater”, “municipal wastewater”, “sanitation”, “faecal sludge”, “wastewater treatment”, or “wastewater infrastructure”; and (iii) “pollutant load”, “river water quality”, “water pollution”, “service coverage”, “treatment capacity”, or “policy scenario”. Searches were conducted in Scopus, ScienceDirect, SpringerLink, Wiley Online Library, Taylor & Francis Online, and Google Scholar. Reference lists of relevant review papers and primary studies were also examined through backward citation searching to identify additional relevant publications. The initial search yielded 70 records, which were subsequently screened following the PRISMA 2020 workflow (Figure 1).

2.2 Eligibility criteria and data extraction

tudies were selected according to predefined inclusion and exclusion criteria, and each eligible study was systematically coded for comparative analysis. Detailed eligibility criteria, data extraction items, and synthesis procedures are summarised in Table 1. Because of the substantial heterogeneity in model structures, system boundaries, temporal scales, policy assumptions, and performance indicators, the findings were synthesised using a comparative thematic approach rather than quantitative meta-analysis.

Table 1. Literature search strategy and eligibility criteria

Component	Specification
Review type	Structured narrative review guided by PRISMA 2020 transparency principles (Page et al., 2021).
Publication period	January 2010 to June 2026, with foundational methodology retained where required.
Core concepts	SD, causal-loop diagram, stock–flow model, wastewater, sanitation, treatment capacity, pollution load, river quality.
Inclusion	Peer-reviewed English study; explicit SD structure; system-level management, policy, infrastructure, sanitation, or water-quality focus.
Exclusion	Unit-process control only; no explicit SD formulation; non-peer-reviewed commentary; inadequate model description.
Data extraction	Location, objective, subsystems, stocks, flows, horizon, scenarios, validation, sensitivity, outcomes, and limitations.
Synthesis method	Comparative thematic synthesis of model structures, policy levers, validation practices, and research gaps.

3. Results and discussion

3.1 Integrated domestic wastewater management as a dynamic system

An integrated domestic wastewater system begins with households and other domestic water users. Water consumption produces blackwater and greywater, which are conveyed through sewered systems, decentralised or communal systems, septic tanks, pit-based systems, open drains, or direct discharge pathways. Management performance depends on containment integrity, sewer connections, collection reliability, desludging frequency, transport, treatment availability, effluent quality, sludge handling, reuse, and safe disposal (Li et al., 2021; Medland et al., 2016). Failures at any stage transfer pollutants to groundwater, drainage networks, rivers, lakes, or coastal waters, thereby increasing environmental degradation and public health risks (Mbae et al., 2024).

The dynamic behaviour of the system arises because its principal variables change at different rates (Sterman, 1994; Sterman & Series, 2003). Population growth and water consumption generally increase continuously, whereas treatment capacity expands only after planning, budgeting, procurement, financing, and construction processes. At the same time, sanitation infrastructure gradually deteriorates, household willingness to connect is influenced by tariffs, service reliability, regulatory enforcement, and perceived benefits, and river water quality responds to pollutant accumulation, hydrological variability, dilution, natural decay, sediment interaction, and episodic storm or tidal events (Demirel et al., 2022; Li et al., 2021; Liu et al., 2015; Rehan et al., 2011). Consequently, wastewater loads frequently increase more rapidly than sanitation infrastructure and environmental systems are able to respond, creating persistent service deficits and environmental pressures (Demirel et al., 2022; Kayal et al., 2026; Liu et al., 2015; Rehan et al., 2011). Figure 2 illustrates the principal conceptual domains synthesised from previous SD studies of integrated domestic wastewater management. These domains provide the conceptual foundation for defining system boundaries and representing the major interactions within the wastewater system.

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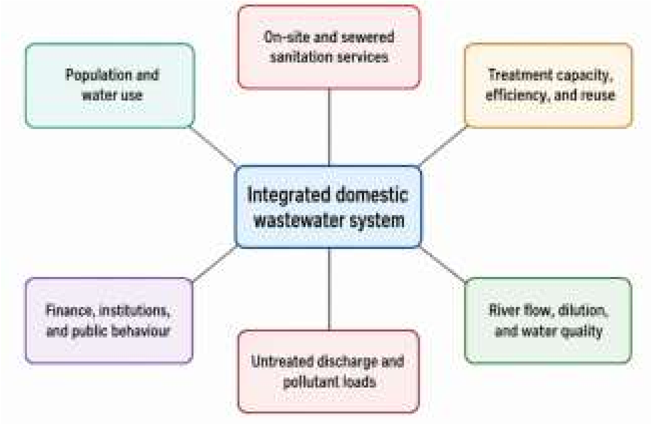

Figure 2. Components and feedback domains of an integrated domestic wastewater management system

Figure 2 highlights that the wastewater system should be viewed as an interconnected network rather than a collection of independent components. Population and water use drive wastewater generation, sanitation services and treatment capacity determine the proportion of wastewater that is safely managed, pollutant loads influence receiving-water quality, and finance, institutions, and public behaviour regulate the long-term effectiveness of infrastructure development and service delivery. The interactions among these domains form the feedback structure that governs overall system performance (Demirel et al., 2022; Li et al., 2021; Liu et al., 2015; Rehan et al., 2011; Tian et al., 2020).

The conceptual domains shown in Figure 2 can be decomposed into eight interacting subsystems for SD modelling. These subsystems comprise socio-demographic growth, domestic water use and wastewater generation, sanitation service coverage, collection and conveyance, treatment capacity and efficiency, pollutant generation and removal, receiving-water quantity and quality, and finance, institutions, and public behaviour. Depending on the policy objective, additional modules may represent wastewater reuse, energy recovery, greenhouse-gas emissions, sludge management, public health, or groundwater contamination. Model boundaries should therefore be determined primarily by the policy question rather than by data availability alone, since excluding a dominant constraint may reproduce historical trends while leading to misleading policy recommendations. Table 2 summarises the principal subsystems, their representative state variables, dominant feedback mechanisms, and policy levers identified from the reviewed literature.

Table 2. Principal subsystems of the integrated domestic wastewater management system and their dynamic roles

Subsystem	Typical state variables	Main feedback or delay	Representative policy lever
Population and water use	Population, household water demand, per-capita use	Growth increases wastewater and infrastructure demand	Demand management; water-use efficiency
Sanitation service	Connected households, functional on-site systems, desludging coverage	Service quality affects willingness to connect and pay	Connection support; scheduled desludging

Subsystem	Typical state variables	Main feedback or delay	Representative policy lever
Collection infrastructure	Sewer length, functional network, infiltration and inflow	Deterioration raises leakage, blockages, and bypass risk	Rehabilitation; expansion; inflow control
Treatment system	Installed capacity, effective capacity, removal efficiency	Overloading reduces performance and compliance	Capacity addition; process upgrading
Pollutant load	BOD, COD, TSS, nutrients, ammonia, faecal indicators	Untreated volume and residual effluent determine load	Source control; disinfection; reuse
Receiving water	River discharge, background concentration, assimilative capacity	Low flow and tidal backwater reduce dilution	Environmental flow; discharge timing
Finance and institutions	Revenue, budget, debt, staffing, enforcement	Service performance affects revenue and political support	Tariff reform; capital finance; governance
Public behavior	Connection willingness, maintenance practices, illegal discharge	Awareness and trust affect service uptake	Education; incentives; enforcement

Rather than operating independently, the subsystems presented in Table 2 interact through multiple feedback relationships. Population growth increases wastewater generation and service demand, while sanitation infrastructure and treatment capacity respond more gradually because of financial, institutional, and technical constraints. Likewise, pollutant loads directly affect receiving-water quality, whereas governance and public behaviour influence infrastructure utilisation, operational performance, and long-term sustainability. These interactions demonstrate that improvements in one subsystem often depend on changes occurring elsewhere in the system, supporting the need for integrated policy interventions instead of isolated infrastructure investments (Demirel et al., 2022; Kayal et al., 2026; Li et al., 2021; Liu et al., 2015; Tian et al., 2020; Wang et al., 2021).

Three types of delay are particularly important in integrated domestic wastewater systems (Sterman, 1994; Sterman & Series, 2003). The first is the infrastructure delay between recognising service deficits and providing operational treatment capacity (Demirel et al., 2022; Rehan et al., 2011; Rehan, Knight, et al., 2014). The second is the connection delay between constructing sanitation facilities and their actual utilisation by households (Li et al., 2021; Rehan et al., 2011). The third is the environmental delay between reducing pollutant loads and achieving measurable improvements in receiving-water quality (Lemaire et al., 2021; Liu et al., 2015; Tian et al., 2020; Wang et al., 2021). Collectively, these delays explain why policy interventions often appear ineffective in the short term despite generating substantial improvements in long-term system performance (Lemaire et al., 2021; Liu et al., 2015; Sterman, 1994).

Overall, the reviewed studies indicate that integrated wastewater management cannot be represented adequately using isolated engineering components. Instead, interactions among demographic growth, sanitation services, treatment capacity, pollutant transport, and institutional performance determine long-term system behaviour. These interactions provide the conceptual foundation for understanding how SD represents feedback structures, stocks, flows, and policy interventions, which are discussed in the following section.

3.2 System dynamics foundations and applications

SD conceptualises management problems as feedback-controlled systems whose behaviour emerges from the interactions among system components rather than from isolated events (Sterman, 1994; Sterman & Series, 2003). Causal-loop diagrams describe causal relationships and feedback mechanisms, whereas stock–flow diagrams translate these conceptual relationships into quantitative simulation models through stocks, flows, and auxiliary variables. Reinforcing feedback loops amplify change, balancing feedback loops promote system stability, and time delays frequently generate oscillation, overshoot, persistent deficits, and policy resistance (Sterman, 1994; Sterman & Series, 2003).

In integrated wastewater management, the principal stocks commonly include population, connected households, functional sanitation infrastructure, installed treatment capacity, accumulated pollutant mass, and financial resources. Corresponding flows represent population growth, new service connections, infrastructure construction and deterioration, wastewater generation, treated and untreated discharges, pollutant transport, natural decay, and pollutant export. Auxiliary variables generally describe service coverage, treatment efficiency, per-capita wastewater generation, tariff structures, investment rules, river discharge, and policy triggers (Demirel et al., 2022; Jeong & Adamowski, 2016; Kayal et al., 2026; Li et al., 2021; Liu et al., 2015; Rehan et al., 2011; Tian et al., 2020). Together, these variables enable SD models to represent the accumulation processes, feedback relationships, and temporal dynamics that characterise domestic wastewater systems.

Previous applications of SD in wastewater management can be grouped into six major functions, namely:

1. Forecasting wastewater generation, considering demographic growth, economic development, tariff policies, and water-use scenarios (Y. Zhang et al., 2016).
2. Planning sanitation infrastructure, including infrastructure expansion, rehabilitation, investment strategies, and long-term financial sustainability (Demirel et al., 2022; Rehan et al., 2011; Rehan, Knight, et al., 2014; Rehan, Unger, et al., 2014).
3. Analysing sanitation adoption and stakeholder behaviour, particularly household participation, rural toilet retrofitting, and faecal sludge management (Li et al., 2021).
4. Assessing pollutant generation and pollution control, by linking socioeconomic development, land use, and human activities with wastewater generation and pollutant emissions (Liu et al., 2015; Wu et al., 2025; X. Zhang et al., 2025).
5. Coupling hydrological and water-quality processes, through the integration of water quantity, pollutant transport, and receiving-water quality dynamics (Jeong & Adamowski, 2016; Lemaire et al., 2021; Tian et al., 2020; Wang et al., 2021).
6. Evaluating integrated policy interventions, including technical, economic, behavioural, governance, and regulatory compliance strategies for improving wastewater management performance (Kayal et al., 2026).

Table 3 summarises representative SD applications relevant to integrated domestic wastewater management. The selected studies illustrate the evolution of modelling objectives, system boundaries, validation approaches, and policy applications reported in the literature.

Table 3. Representative applications of SD in integrated wastewater management

Study	Context	Primary focus	Scenario or horizon	Testing	Key contribution
(Rehan et al., 2011)	Canada; water and wastewater utility	Financial sustainability and asset management	Long-term fee, investment, and replacement policies	Structure and behavior comparison	Connected physical condition, finance, and service performance.
(Rehan, Knight, et al., 2014)	Urban wastewater collection	Causal structure for deteriorating sewer assets	Rehabilitation and financing alternatives	Conceptual and structural tests	Clarified feedback among condition, costs, revenue, and service.
(Rehan, Unger, et al., 2014)	Ontario, Canada	Implemented wastewater infrastructure model	Debt and capital-work strategies	Case-data parameterization	Showed borrowing can reduce life-cycle cost while improving service.
(Liu et al., 2015)	Dianchi Lake watershed, China	Socioeconomic, pollutant-load, and lake-quality coupling	BAU plus spatial, capacity, and agricultural scenarios	Historical and water-quality comparison	Found treatment-capacity construction highly effective for COD, TN, and TP.
(Y. Zhang et al., 2016)	Wuhan, China	Municipal wastewater quantity estimation	Nine socioeconomic and tariff scenarios to 2030	Historical trend comparison	Demonstrated changing importance of water-use intensity and economic growth.
(Jeong & Adamowski, 2016)	South Korean watershed	Socio-hydrology and agricultural wastewater reuse	Urbanization and flow-regulation scenarios	Structural and behavioral tests	Integrated social, policy, hydrological, and reuse dynamics.
(Tian et al., 2020)	Tianjin, China	Coupled water quantity and quality	Water-supply and environmental scenarios	Calibration and independent-year verification	Linked water demand, supply, economy, population, and water quality.
(Li et al., 2021)	Eastern China	Rural toilet retrofitting and faucal-sludge system	Stakeholder and implementation strategies	Structure and behavior evaluation	Represented households, government, suppliers, O&M, and sludge users.

Study	Context	Primary focus	Scenario or horizon	Testing	Key contribution
(Lemaire et al., 2021)	Peri-urban stream, Denmark	Data-driven water quantity and quality modules	Source and pathway configurations	Performance indicators including NSE	Demonstrated modular coupling of urban and natural processes.
(Wang et al., 2021)	Jiaxing, China	Industry structure and river-network quality	Five industrial-adjustment scenarios, 2021–2035	Model validation and sensitivity	Identified sector-specific effects on COD, TN, NH_3-N, and TP.
(Demirel et al., 2022)	Antalya, Türkiye	Treatment-facility location and network timing	Population-demand scenarios, 2015–2040	Case-based testing	Used SD to determine where and when new facilities are required.
(X. Zhang et al., 2025)	Liuyang County, China	Water availability and wastewater-treatment necessity	Baseline and integrated governance scenarios	Framework and scenario consistency	Coupled pollutant discharge with environmental carrying capacity.
(Wu et al., 2025)	Xiaoxingkai Lake basin, China	Population, agriculture, and pollution load	Five development scenarios, 2020–2030	Historical fitting and sensitivity	Modelled TN, TP, COD, and NH_3-N loads under alternative pathways.
(Kayal et al., 2026)	Jordan	Technical, economic, behavioral, and compliance framework	Treatment-performance and policy scenarios	Calibration and policy testing	Provides a transferable integrated framework for wastewater treatment decisions.

Table 3 demonstrates a clear progression in the development of SD applications for wastewater management. Earlier studies primarily concentrated on infrastructure asset management, financial sustainability, and long-term investment planning, particularly for sewer networks and wastewater utilities (Rehan et al., 2011; Rehan, Knight, et al., 2014; Rehan, Unger, et al., 2014). Subsequent studies expanded model boundaries by incorporating socioeconomic drivers, wastewater generation, pollutant transport, and receiving-water quality, thereby improving the representation of interactions between human activities and environmental processes (Jeong & Adamowski, 2016; Liu et al., 2015; Tian et al., 2020; Wang et al., 2021). More recent research has further integrated governance, stakeholder behaviour, environmental carrying capacity, and policy compliance into SD models, reflecting a shift from sector-specific analyses toward comprehensive decision-support frameworks for sustainable wastewater management (Demirel et al., 2022; Kayal et al., 2026; Li et al., 2021; Wu et al., 2025; X. Zhang et al., 2025).

The reviewed studies also reveal a gradual improvement in model validation practices. Early applications commonly relied on structural verification and historical behaviour comparison, whereas more recent studies increasingly incorporate calibration, sensitivity analysis, independent-data verification, and scenario consistency testing to improve model credibility and policy relevance (Demirel et al., 2022; Lemaire et al., 2021; Tian et al., 2020; Wang et al., 2021; Wu et al., 2025). Despite these advances, relatively few studies simultaneously integrate wastewater generation, sanitation-service coverage, treatment capacity, pollutant loading, receiving-water quality, institutional governance, and behavioural responses within a single modelling framework. This gap highlights the need for more comprehensive SD models capable of evaluating interactions across the entire domestic wastewater management system (Kayal et al., 2026; Li et al., 2021; Liu et al., 2015; Tian et al., 2020; X. Zhang et al., 2025). Two general lessons emerge from the reviewed literature. First, model usefulness depends more on the credibility of the underlying problem structure than on model size or complexity (Barlas, 1996; Oliva, 2003; Qudrat-Ullah & Seong, 2010; Sterman, 1994; Sterman & Series, 2003). Large models supported by weak causal structures often obscure important leverage points and reduce model transparency. Second, simulation results should be interpreted as conditional futures rather than deterministic predictions (Haasnoot et al., 2013; Kwakkel et al., 2016). Their principal value lies in revealing feedback effects, policy trade-offs, implementation delays, system thresholds, and combinations of interventions that remain effective under a range of plausible future conditions.

3.3 Causal-loop and stock–flow model structures

Generic SD models of domestic wastewater management are commonly represented using two complementary structures: causal-loop diagrams (CLDs), which describe feedback relationships qualitatively, and stock–flow diagrams (SFDs), which translate those relationships into quantitative simulation models (Sterman, 1994; Sterman & Series, 2003). Although individual studies differ in scope and policy objectives, the reviewed literature consistently identifies interactions among population growth, wastewater generation, sanitation services, treatment capacity, pollutant discharge, environmental quality, and institutional responses as the dominant drivers of long-term system behaviour (Liu et al., 2015; Rehan et al., 2011; Rehan, Knight, et al., 2014; Rehan, Unger, et al., 2014). Figure 3 synthesises the principal feedback mechanisms reported across previous SD studies of domestic wastewater management. The reinforcing demand-growth loop (R1) describes how population growth continuously increases wastewater generation, leading to higher demand for sanitation services and treatment capacity. When infrastructure expansion fails to keep pace with increasing demand, service deficits accumulate and untreated discharge increases (Kayal et al., 2026; Liu et al., 2015; Rehan et al., 2011; Y. Zhang et al., 2016).

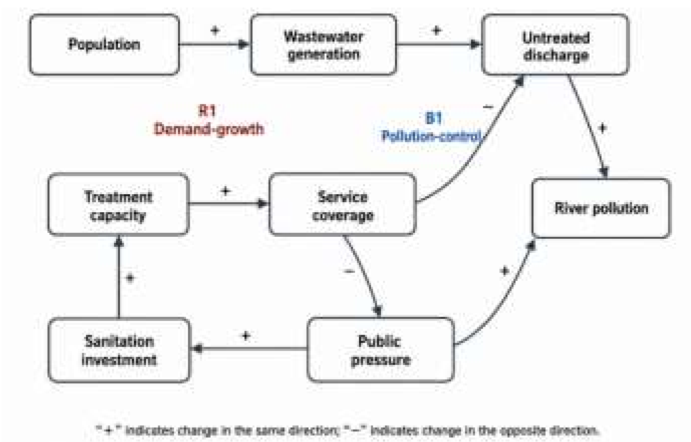

Figure 3. Generic causal-loop structure for integrated domestic wastewater management

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Conversely, the balancing pollution-control loop (B1) represents the management response to environmental deterioration. Increasing untreated discharge elevates river pollution, which stimulates public pressure, regulatory intervention, and sanitation investment. These responses expand treatment capacity and service coverage, ultimately reducing untreated discharge. However, this balancing mechanism weakens when monitoring systems are ineffective, political responses are delayed, tariffs are insufficient to sustain operation and maintenance, or newly constructed facilities remain underutilised (Kayal et al., 2026; Liu et al., 2015; Rehan et al., 2011).

Beyond these two dominant loops, previous studies consistently identify additional reinforcing mechanisms associated with infrastructure deterioration and service adoption. Infrastructure ageing increases failures, infiltration, inflow, leakage, blockages, and operational costs. Rising maintenance costs subsequently reduce available investment for preventive rehabilitation, thereby accelerating further deterioration and creating a long-term infrastructure trap (Rehan et al., 2011; Rehan, Knight, et al., 2014; Rehan, Unger, et al., 2014). Similarly, service adoption generates either virtuous or vicious cycles. Reliable services and visible environmental improvements increase public trust, household willingness to connect, and utility revenue, whereas poor service quality discourages user participation, weakens financial sustainability, and further constrains maintenance and infrastructure development (Kayal et al., 2026; Li et al., 2021).

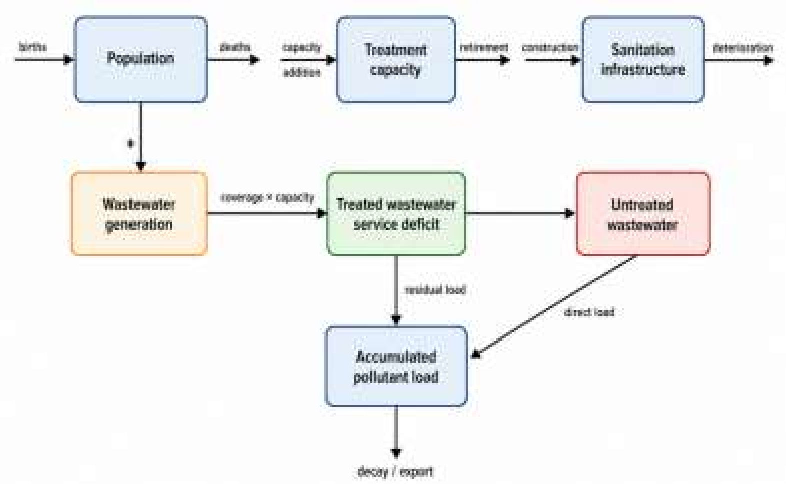

Figure 4. Generic stock–flow architecture linking wastewater generation, service, capacity, and pollutant accumulation

While the causal-loop diagram explains the underlying feedback structure, the stock–flow architecture provides the quantitative basis for simulation. Figure 4 illustrates how population acts as the primary driver of wastewater generation, while treatment capacity determines the proportion of wastewater that can be safely managed. The remaining untreated wastewater contributes directly to pollutant accumulation, thereby linking infrastructure performance with environmental outcomes. Unlike causal-loop diagrams, stock–flow models explicitly represent accumulation processes, enabling simulation of infrastructure deficits, pollutant loading, and long-term policy impacts under alternative development scenarios (Kayal et al., 2026; Liu et al., 2015; Rehan et al., 2011; Sterman, 1994).

An important modelling consideration is the distinction between installed capacity and effective capacity. Installed capacity represents the physical design capability of treatment facilities, whereas effective capacity reflects actual operational performance after accounting for equipment downtime, process limitations, infiltration and inflow, operator performance, and hydraulic overloading (Cahoon & Hanke, 2019; Fung & Babcock, 2020; Rehan et al., 2011). Likewise, nominal sanitation coverage should be distinguished from safely managed sanitation coverage, since the existence of toilets or septic tanks does not necessarily guarantee safe containment, desludging, treatment, or final disposal (Li et al., 2021; Mbae et al., 2024; Medland et al., 2016).

The minimum SD model for integrated domestic wastewater management may include four principal stocks: population, connected or safely served households, effective treatment capacity, and accumulated pollutant load. More comprehensive models additionally represent sewer condition, on-site containment condition, treatment-plant condition, sludge accumulation, financial balance, and river pollutant mass. Model complexity, however, should only increase when additional stocks improve the interpretation of policy responses or substantially influence overall system behaviour rather than merely increasing model size (Barlas, 1989; Oliva, 2003; Sterman, 1994).

Table 4. Generic stocks, flows, and core equations

Element	Definition	Generic formulation	Unit	Modelling note
Population stock	Residents generating domestic wastewater	$P(t+\Delta t)=P(t)+(\text{births}-\text{deaths}+\text{migration})\Delta t$	persons	Use census trends or cohort projections where available.
Wastewater generation	Domestic flow entering the sanitation chain	$Q_{ww}=P \times q_w \times f_{ww}$	m³/day	qw is water use; fww is the return-to-sewer factor.
Effective treatment capacity	Operational flow that can be reliably treated	$C_{eff}=C_{installed} \times \text{availability} \times \text{performance factor}$	m³/day	Separates design capacity from real operating capacity.
Treated wastewater	Flow receiving required treatment	$Q_t=\min(Q_{ww} \times \text{service fraction}, C_{eff})$	m³/day	May be divided by centralised, communal, and on-site routes.
Untreated wastewater	Unserved, bypassed, leaked, or improperly disposed flow	$Q_u=\max(0,Q_{ww}-Q_t)+Q_{bypass}+Q_{illegal}$	m³/day	Should include unsafe on-site and faecal-sludge pathways.

Element	Definition	Generic formulation	Unit	Modelling note
Treatment capacity stock	Accumulated functional capacity	dC/dt=capacity addition−retirement−loss	m^3/day per year	Addition follows planning and construction delays.
Pollutant load	Mass discharged after treatment and bypass	Li=QuCi,u+QtCi,e	kg/day	Apply consistent conversion factors for flow and concentration.
River pollutant mass	Mass stored in a river reach or water body	dMi/dt=input−output−decay−settling	kg/day	Required when accumulation or residence time matters.

Table 4 summarises the minimum stocks, flows, and mathematical relationships required for constructing an integrated SD model of domestic wastewater management. The proposed equations are intentionally generic so that they can be adapted to different geographical settings, data availability, and policy objectives. Their primary purpose is to preserve the dominant feedback mechanisms governing wastewater generation, service delivery, treatment performance, and environmental quality rather than to prescribe a fixed modelling framework. A notable feature of the proposed formulation is the explicit separation between physical infrastructure and operational performance. Distinguishing installed treatment capacity from effective treatment capacity enables models to represent situations in which treatment plants exist but operate below design capacity because of operational constraints. Similarly, separating wastewater generation, treated wastewater, untreated wastewater, and pollutant accumulation allows policy interventions to be evaluated across the entire sanitation service chain instead of focusing solely on treatment facilities. These distinctions improve the realism of policy simulations and better represent the complex interactions among infrastructure, environmental processes, institutional performance, and human behaviour (Cahoon & Hanke, 2019; Fung & Babcock, 2020; Li et al., 2021; Medland et al., 2016).

Collectively, the causal-loop structure, stock–flow architecture, and generic equations provide a transferable conceptual foundation for developing integrated SD models of domestic wastewater management. Rather than prescribing a universal model structure, this framework should be adapted to the specific policy questions, institutional settings, and available data of each study while maintaining the dominant feedback mechanisms that control long-term system behaviour.

3.4 Model variables, data, verification, validation, and uncertainty

The reliability of a SD model depends not only on its conceptual structure but also on the quality of model variables, data sources, verification procedures, validation methods, and uncertainty analysis. These components collectively determine whether the model provides a credible basis for understanding system behaviour and evaluating alternative policy interventions (Barlas, 1989; Oliva, 2003; Sterman, 1994; Sterman & Series, 2003). Model inputs should be selected according to the defined system boundary. In integrated domestic wastewater management, the principal variables generally comprise socio-demographic characteristics, water use, sanitation services, treatment performance, and environmental conditions (Demirel et al., 2022; Lemaire et al., 2021; Li et al., 2021; Rehan et al., 2011; Tian et al., 2020). Model variables should be selected according to the objectives and system boundaries of the SD model. The reviewed studies consistently classify these variables into five broad categories: socio-demographic, water-use, sanitation, treatment, and environmental variables

Socio-demographic variables typically include population, growth rate, household size, urbanisation, and migration. Water-use variables comprise service population, per-capita consumption, non-revenue water (where relevant), and the wastewater return factor. Sanitation variables describe sewer connections, on-site systems, containment quality, desludging frequency, faecal sludge management, communal sanitation, illegal discharge, and service uptake. Treatment variables include installed and effective treatment capacity, inflow, operational downtime, removal efficiency, effluent quality, sludge production, energy consumption, and operating costs, whereas environmental variables generally include river discharge, tidal conditions, rainfall, temperature, and observed pollutant concentrations (Chen et al., 2011; Demirel et al., 2022; Kayal et al., 2026; Li et al., 2021; Liu et al., 2015; Medland et al., 2016; Rehan et al., 2011; Tian et al., 2020; Wang et al., 2021; Y. Zhang et al., 2016).

When comprehensive datasets are unavailable, SD models commonly rely on coefficients obtained from engineering standards, design manuals, household surveys, analogous cities, or expert judgement. Rather than treating these values as fixed inputs, the reviewed studies recommend documenting their sources explicitly and assigning appropriate uncertainty ranges to distinguish observed data from estimated parameters, calibration values, and policy assumptions (Barlas, 1989; Oliva, 2003; Qudrat-Ullah & Seong, 2010; Sarrazin et al., 2016). Parameter adjustment should remain consistent with physical processes and institutional conditions rather than being used solely to improve statistical agreement with historical observations.

Model verification evaluates whether the model has been implemented correctly, whereas validation assesses whether the model is sufficiently accurate for its intended policy purpose (Barlas, 1989; Oliva, 2003; Qudrat-Ullah & Seong, 2010). Verification commonly includes equation review, dimensional consistency, stock–flow conservation, initial-condition assessment, numerical stability, and extreme-condition testing. Validation extends beyond statistical goodness-of-fit by considering structural validity, behavioural reproduction, boundary adequacy, expert judgement, and sensitivity to key assumptions (Barlas, 1989; Oliva, 2003; Sterman, 1994). Historical model performance may be evaluated using indicators such as Mean Absolute Percentage Error (MAPE), Root Mean Square Error (RMSE), coefficient of determination (R^2), Nash–Sutcliffe Efficiency (NSE), Theil statistics, or graphical comparison, depending on the variable being assessed and the intended decision context (Barlas, 1989; Oliva, 2003).

Sensitivity analysis complements validation by identifying the assumptions that most strongly influence model behaviour. Simple one-at-a-time analyses provide an initial assessment of parameter influence, whereas Monte Carlo simulation, global sensitivity analysis, and scenario discovery are more appropriate when multiple uncertain parameters interact simultaneously (Pianosi et al., 2016; Sarrazin et al., 2016). For integrated wastewater models, uncertainty analysis should at minimum evaluate demographic growth, water consumption, wastewater return factors, sanitation uptake, infrastructure construction delays, deterioration rates, treatment efficiency, river discharge, and pollutant concentrations. Table 5 summarises the principal verification, validation, sensitivity, and uncertainty analyses recommended for SD models of integrated domestic wastewater management. The proposed tests represent complementary procedures that collectively improve model credibility rather than independent validation criteria.

Table 5 demonstrates that no single test is sufficient to establish model credibility. Structural verification ensures that the model correctly represents causal relationships and conservation principles, whereas validation focuses on whether the simulated behaviour is appropriate for the intended policy application. Sensitivity and uncertainty analyses further evaluate the robustness of model conclusions under plausible variations in data and assumptions. Collectively, these procedures reduce the risk of overconfidence in simulation results and provide stronger evidence for policy evaluation than reliance on statistical fit alone (Barlas, 1989; Oliva, 2003; Pianosi et al., 2016; Qudrat-Ullah & Seong, 2010; Sarrazin et al., 2016).

Table 5. Recommended verification, validation, sensitivity, and uncertainty tests

Test group	Test	Purpose	Practical acceptance evidence
Structural verification	Equation and boundary review	Confirm causal logic and included mechanisms	Agreement with theory, field knowledge, and stakeholder understanding.
Dimensional consistency	Unit check for every equation	Prevent hidden conversion errors	No unit mismatch; explicit conversion for flow × concentration.
Mass balance	Inflows, outflows, and accumulation	Protect conservation of wastewater and pollutants	Residual mass-balance error is negligible or explained.
Extreme conditions	Zero population, zero capacity, maximum efficiency, drought	Test logical behaviour outside normal range	Outputs remain physically meaningful and bounded.
Historical behavior	Compare simulated and observed time series	Assess trend, timing, and magnitude	Acceptable graphical fit and stated error statistics.
Behavior-pattern test	Compare growth, decline, oscillation, and turning points	Assess dynamic mode rather than exact values	Model reproduces dominant behavior relevant to policy.
One-at-a-time sensitivity	Change parameters by ±10% and ±20%	Identify influential assumptions	Ranked effect on service, untreated volume, load, and quality.
Monte Carlo analysis	Sample joint parameter distributions	Quantify outcome ranges and threshold risk	Confidence intervals and probability of target achievement.
Global sensitivity	Variance-based or screening methods	Identify interactions and nonlinear influence	Contribution of each parameter and interaction to output variance.
Policy robustness	Test policies across multiple futures	Avoid strategies that succeed in only one forecast	Performance remains acceptable under demographic, climate, and cost uncertainty.

The reviewed literature also indicates that validation should be interpreted within the context of the modelling objective. A model that accurately reproduces demographic trends may still inadequately represent pollutant dynamics or institutional behaviour. Consequently, each major subsystem should be evaluated using evidence that is directly relevant to its intended function. Where environmental monitoring data remain limited, SD models should primarily be regarded as exploratory decision-support tools that compare the relative performance of alternative policies rather than predict precise future environmental conditions (Barlas, 1989; Oliva, 2003; Pianosi et al., 2016; Sarrazin et al., 2016).

Overall, robust SD modelling requires an appropriate balance between conceptual soundness, data quality, verification, validation, and uncertainty analysis. These elements ensure that simulation outcomes are scientifically credible and sufficiently reliable for policy evaluation. Building upon these methodological foundations, the following section synthesises the principal policy interventions and leverage points identified across previous SD applications in integrated domestic wastewater management.

3.5 Policy scenarios, treatment capacity, and service coverage

Scenario analysis transforms a SD model from a descriptive representation of system behaviour into a decision-support tool for evaluating alternative policy interventions. Rather than predicting a single future, SD explores how different assumptions regarding population growth, infrastructure development, financial capacity, environmental conditions, and institutional performance influence long-term wastewater management outcomes (Haasnoot et al., 2013; Kwakkel et al., 2016; Sterman, 1994; Sterman & Series, 2003). Previous studies consistently demonstrate that policy evaluation should consider not only treatment infrastructure but also service coverage, operational efficiency, governance, and behavioural responses because these components interact through multiple feedback mechanisms (Demirel et al., 2022; Kayal et al., 2026; Liu et al., 2015; Rehan et al., 2011; Tian et al., 2020).

The reviewed literature identifies six broad categories of policy scenarios commonly implemented in SD models:

1. Business-as-usual (BAU), which extends current demographic, infrastructure, financial, and operational trends without introducing additional policy interventions.
2. Capacity-expansion scenarios, which evaluate investments in new treatment facilities or decentralised sanitation systems.
3. Coverage-expansion scenarios, which increase sewer connections, communal sanitation services, or scheduled faecal sludge collection.
4. Efficiency-improvement scenarios, which improve treatment performance, reduce operational downtime, minimise infiltration and inflow, and enhance asset management.
5. Reuse and source-control scenarios, which reduce wastewater generation or pollutant loads through water conservation, wastewater reuse, and pollution prevention.
6. Combined or adaptive policy scenarios, which integrate multiple interventions simultaneously or activate policy responses once predefined service or environmental thresholds are exceeded (Demirel et al., 2022; Haasnoot et al., 2013; Kayal et al., 2026; Kwakkel et al., 2016; Rehan et al., 2011).

Figure 5 illustrates how alternative policy scenarios are translated into SD simulations and subsequently evaluated using multiple performance indicators. Rather than testing individual interventions in isolation, the framework emphasises the interactions between demographic change, wastewater generation, treatment capacity, service coverage, operational efficiency, and implementation delays.

The resulting policy outcomes include improvements in service ratio, reductions in untreated wastewater volume and pollutant loads, enhancement of river water quality, and changes in economic performance and regulatory compliance. This integrated evaluation enables decision makers to compare not only the effectiveness of individual policies but also the potential synergies among combined interventions (Demirel et al., 2022; Kayal et al., 2026; Rehan et al., 2011).

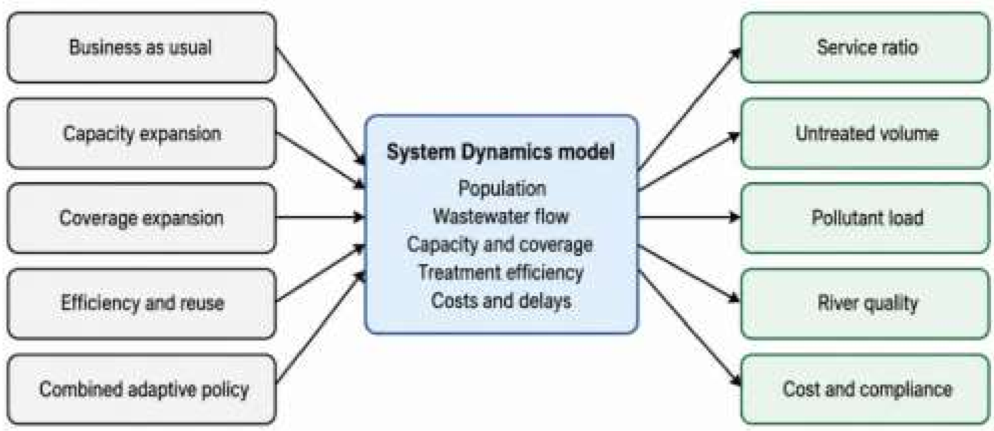

Figure 5. Policy-scenario framework and principal decision outcomes

A consistent finding across the reviewed studies is that treatment capacity and service coverage should be modelled as separate but interdependent components. Expanding treatment capacity without increasing service coverage frequently results in underutilised infrastructure, whereas expanding service coverage without corresponding treatment capacity creates hydraulic overloading, bypass events, declining treatment efficiency, and regulatory non-compliance (Demirel et al., 2022; Li et al., 2021; Rehan et al., 2011). Accordingly, SD models should evaluate both service ratio and capacity gap. The service ratio represents the proportion of generated wastewater that is safely collected and treated, whereas the capacity gap measures the difference between treatment demand and effective treatment capacity. Evaluating these indicators together provides a more realistic assessment of system performance because installed infrastructure alone does not necessarily indicate effective wastewater treatment (Kayal et al., 2026; Lemaire et al., 2021; Tian et al., 2020).

The reviewed literature consistently indicates that integrated policy packages outperform isolated interventions. Infrastructure expansion becomes substantially more effective when accompanied by improvements in service coverage, operation and maintenance, financial sustainability, treatment efficiency, and source control. Likewise, in areas dominated by on-site sanitation, improved containment, scheduled desludging, reliable sludge transport, adequate treatment facilities, and regulatory enforcement should be implemented simultaneously to achieve meaningful environmental improvements (Demirel et al., 2022; Kayal et al., 2026; Li et al., 2021; Mbae et al., 2024; Medland et al., 2016). Policy sequencing is equally important. Low-cost operational improvements and rehabilitation generally provide immediate benefits, medium-term investments strengthen service capacity, whereas long-term strategies integrate infrastructure expansion with urban planning, climate adaptation, and water reuse. SD models therefore enable planners to evaluate not only which interventions should be implemented but also when they should be introduced to avoid irreversible service deficits or environmental degradation (Cahoon & Hanke, 2019; Demirel et al., 2022; Flood & Cahoon, 2011; Haasnoot et al., 2013; Kwakkel et al., 2016). Table 6 summarises representative policy scenarios, their principal assumptions, and the corresponding diagnostic indicators commonly used in SD studies of integrated domestic wastewater management.

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Table 6. Recommended policy scenarios and parameter changes

Scenario	Illustrative assumptions	Expected diagnostic value	Primary outputs
Business as usual	Current population trend, committed capacity, existing efficiency, current budget	Reference trajectory and timing of service deficit	Coverage, untreated volume, load, compliance
Pessimistic	Higher growth, slower projects, lower river flow, faster deterioration	Stress-test exposure to unfavourable conditions	Peak deficit, overload duration, river-quality risk
Capacity expansion	Additional plant or decentralised treatment capacity	Test whether capacity is the binding constraint	Capacity utilisation, untreated volume, cost
Coverage expansion	More sewer connections, communal service, or scheduled desludging	Test demand uptake and collection constraints	Safely served population, delivered flow, bypass
Efficiency and rehabilitation	Higher removal efficiency, less downtime, reduced infiltration and inflow	Assess operational and asset-management leverage	Effluent load, effective capacity, O&M cost
Reuse and source control	Treated-water reuse, water conservation, pollutant-source reduction	Reduce discharge and freshwater pressure	Discharge volume, nutrient load, reuse benefit
Combined policy	Capacity, coverage, efficiency, finance, and institutions improved together	Identify synergy and avoid shifting constraints	Target achievement, cost, robustness
Adaptive policy	Intervention triggered by service, load, or quality threshold	Evaluate timing and flexible pathways	Trigger year, avoided deficit, long-term resilience

Table 6 demonstrates that different policy scenarios evaluate different aspects of system performance. Business-as-usual scenarios establish the reference trajectory against which policy effectiveness is assessed, whereas single-intervention scenarios identify the principal system constraints, such as insufficient treatment capacity, limited service coverage, or declining operational performance. Combined and adaptive scenarios extend this analysis by evaluating policy interactions, implementation timing, and long-term system resilience under uncertain future conditions (Demirel et al., 2022; Haasnoot et al., 2013; Kayal et al., 2026; Kwakkel et al., 2016).

A common pattern emerging from the reviewed literature is that policies focusing exclusively on infrastructure expansion rarely achieve optimal environmental outcomes. Instead, the greatest improvements are consistently observed when capacity expansion is integrated with service extension, operational optimisation, financial reform, behavioural change, and environmental protection measures. This finding highlights that the effectiveness of wastewater management depends on coordinated interventions across multiple subsystems rather than on isolated engineering solutions (Demirel et al., 2022; Kayal et al., 2026; Li et al., 2021; Rehan et al., 2011).

Overall, scenario analysis represents the principal strength of SD modelling because it enables comparison of alternative policy pathways under dynamic and uncertain conditions. By integrating technical, environmental, institutional, financial, and behavioural dimensions within a single modelling framework, SD provides a robust basis for identifying policy combinations that remain effective over the long term. These insights form the foundation for the final synthesis presented in the following section, which discusses future research directions and emerging opportunities for advancing integrated domestic wastewater management.

3.6 Pollutant-load and river-water-quality modelling

Pollutant-load modelling provides the critical link between sanitation-system performance and environmental outcomes within SD models. While previous sections describe wastewater generation, sanitation services, and treatment processes, pollutant-load modelling translates these processes into measurable impacts on receiving-water quality. Integrating wastewater generation, treatment performance, pollutant discharge, and river processes enables SD models to evaluate the environmental consequences of alternative wastewater-management policies rather than infrastructure performance alone (Lemaire et al., 2021; Liu et al., 2015; Tian et al., 2020; Wang et al., 2021).

The reviewed literature generally represents pollutant loads using a mass-balance approach that combines untreated wastewater with the residual pollutant load remaining after treatment. Untreated loads are estimated from untreated wastewater volume and pollutant concentration, whereas treated loads depend on treated flow, influent concentration, and treatment efficiency. Additional pollutant contributions may originate from bypass discharge, illegal disposal, or storm-related overflows (Lemaire et al., 2021; Liu et al., 2015; Tian et al., 2020; Wang et al., 2021). Based on the mass-balance formulations reported in previous SD studies, the pollutant load of constituent *i* is commonly represented by Equation (1).

$$L_i = Q_u C_{i,u} + Q_t C_{i,e} = Q_u C_{i,u} + Q_t C_{(i,in)}(1-\eta_i) \tag{1}$$

where:

L_i = pollutant load of constituent *i* (kg/day)
Q_u = untreated wastewater flow (m^3/day)
Q_t = treated wastewater flow (m^3/day)
$C_{i,u}$ = pollutant concentration in untreated wastewater (mg/L)
$C_{i,in}$ = influent pollutant concentration (mg/L)
$C_{i,e}$ = effluent pollutant concentration (mg/L)
ηi = pollutant removal efficiency (–)

Equation (1) demonstrates that the total pollutant load discharged to the receiving environment consists of two principal components: untreated wastewater and the residual pollutant load remaining after treatment. Consequently, pollutant reductions may be achieved by increasing sanitation coverage, expanding treatment capacity, improving treatment efficiency, or implementing these interventions simultaneously. This relationship explains why integrated wastewater-management policies consistently outperform isolated infrastructure investments in SD simulations (Kayal et al., 2026; Liu et al., 2015; Wang et al., 2021).

Commonly modelled pollutants include biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), ammonia (NH_3-N), and faecal-indicator bacteria. Organic matter and nutrient parameters dominate existing SD applications because they directly reflect treatment performance and eutrophication potential. In contrast, microbiological indicators remain comparatively underrepresented despite their importance for assessing sanitation-related public-health risks (De Brauwere et al., 2014; Lemaire et al., 2021; Liu et al., 2015; Tian et al., 2020; Wang et al., 2021).

To evaluate the environmental impacts of wastewater discharge on receiving waters, many SD studies employ a simplified mass-balance approach that assumes complete mixing between river flow and wastewater inflows. Under this assumption, the downstream concentration of pollutant *i* can be estimated using Equation (2). This formulation integrates upstream background water quality with treated and untreated wastewater discharges, providing a practical representation of river-water quality for long-term strategic assessments and policy evaluation in well-mixed river reaches (Chen et al., 2011; Lemaire et al., 2021).

$$C_{i,d} = \frac{Q_r C_{i,bg} + Q_u C_{i,u} + Q_t C_{i,e}}{Q_r + Q_u + Q_t} \tag{2}$$

where:

Q_r = river flow (m^3/day)
$C_{i,bg}$ = upstream background concentration (mg/L)
$C_{i,d}$ = downstream pollutant concentration (mg/L)

Equation (2) estimates downstream pollutant concentration by balancing pollutant mass entering the river with the combined river and wastewater flows. The equation highlights that downstream water quality depends not only on wastewater-treatment performance but also on river discharge and background water quality. Consequently, improvements in pollutant concentration may result either from genuine reductions in pollutant loads or from increased dilution during periods of higher river flow. These mechanisms should therefore be interpreted together when evaluating SD simulation results (Chen et al., 2011; Chidiac et al., 2023; Kachroud et al., 2019).

Although the complete-mixing formulation is appropriate for screening-level analyses, it becomes inadequate when tidal reversals, stratification, sediment interaction, pollutant decay, or complex river networks strongly influence water quality. Under such conditions, SD models are better employed to generate wastewater generation and pollutant-loading scenarios that subsequently provide boundary conditions for hydrodynamic or process-based water-quality models (Chen et al., 2011; Lemaire et al., 2021).

Environmental performance may be evaluated using pollutant concentrations, pollutant mass, dissolved-oxygen deficit, standards compliance, or composite indicators such as the Pollution Index (PI), Water Quality Index (WQI), and River Quality Index (RQI) (Chidiac et al., 2023; Kachroud et al., 2019; Sutadian et al., 2016; Uddin et al., 2021). Although composite indices facilitate communication with decision makers, they may conceal the pollutant primarily responsible for environmental degradation. Accordingly, SD studies should report both the composite index and its constituent parameters while distinguishing genuine water-quality improvements resulting from pollutant-load reduction from apparent improvements caused solely by increased river flow and dilution (Chidiac et al., 2023; Kachroud et al., 2019; Sutadian et al., 2016; Uddin et al., 2021).

The reviewed literature consistently demonstrates that the greatest strength of SD lies in integrating demographic growth, economic development, wastewater generation, treatment performance, pollutant transport, and receiving-water quality within a unified modelling framework. Although capacity expansion and treatment-efficiency improvements generally reduce pollutant loads substantially, the relative effectiveness of alternative interventions depends on dominant pollution sources, pollutant characteristics, river hydrology, and implementation delays (Kayal et al., 2026; Lemaire et al., 2021; Liu et al., 2015; Tian et al., 2020; Wang et al., 2021).

Table 7 demonstrates that pollutant selection should be driven primarily by modelling objectives rather than by the number of parameters included. Conventional indicators such as BOD, COD, TSS, TN, TP, and ammonia remain the core variables because they directly describe organic pollution, nutrient enrichment, and treatment performance. However, microbiological indicators receive comparatively limited attention despite their importance for evaluating public-health risks associated with untreated domestic wastewater. This imbalance suggests that future SD applications should incorporate microbial water-quality indicators alongside conventional physicochemical parameters, particularly in regions where sanitation-related diseases remain a major concern (De Brauwere et al., 2014; Lemaire et al., 2021; Liu et al., 2015).

Table 7. Pollutant parameters and recommended modelling treatment

Parameter	Main domestic source	Typical model representation	Key process or uncertainty	Useful outcome
BOD	Biodegradable organic matter	Flow × concentration; first-order decay in river	Temperature, reaeration, decay rate	Organic load and oxygen demand
COD	Organic and oxidisable matter	Flow × concentration; conservative or partial decay	Industrial contribution and fractionation	Total chemical load
TSS	Solids and particulate matter	Flow × concentration; settling and resuspension	Storm flow and sediment interaction	Suspended-solid load
Ammonia	Urine and nitrogen transformation	Influent load × removal; nitrification in river	Temperature, oxygen, pH	Toxicity and nutrient pressure
TN and TP	Domestic waste, detergents, food residues	Source-specific load and treatment removal	Agricultural overlap and retention	Eutrophication pressure
Faecal indicators	Human excreta and unsafe sludge disposal	Concentration or log concentration with decay	Sunlight, temperature, settling, regrowth	Public-health and recreational risk
Composite index	Weighted set of parameters	Standardised sub-indices and weights	Choice of weights and masking effects	Overall status and policy communication

The reviewed studies also indicate that increasing model complexity does not necessarily improve decision support. Simplified pollutant-load formulations are generally sufficient for long-term strategic planning, whereas more detailed representations become necessary when assessing regulatory compliance, ecological responses, or public-health protection. Consequently, pollutant selection should remain consistent with the intended policy question and supported by reliable monitoring data (Chen et al., 2011; Kachroud et al., 2019; Lemaire et al., 2021). Overall, pollutant-load and river-water-quality modelling extend SD beyond infrastructure planning by explicitly linking wastewater-management performance with environmental and public-health outcomes. By integrating pollutant generation, treatment efficiency, river processes, and water-quality indicators within a unified modelling framework, SD provides a scientifically robust basis for evaluating the environmental effectiveness of alternative wastewater-management policies. These findings complete the methodological synthesis presented in this review and provide a foundation for the concluding section, which summarises the principal research gaps and future directions for integrated domestic wastewater modelling.

3.7 System Dynamics for coastal and data-limited cities

Coastal cities present additional challenges for domestic wastewater management because hydrological, climatic, and environmental processes interact directly with sanitation infrastructure. Consequently, SD models developed for inland cities cannot be transferred directly to coastal settings without expanding the system boundary to include groundwater dynamics, tidal influence, flooding, and long-term climate-related changes. Incorporating these processes enables SD models to capture the complex interactions between wastewater infrastructure and coastal environmental conditions, thereby providing more realistic support for strategic planning (Cahoon & Hanke, 2019; Flood & Cahoon, 2011; Fung & Babcock, 2020; Hummel et al., 2018; Mbae et al., 2024).

The reviewed studies consistently identify groundwater, tidal processes, and climate change as the principal factors distinguishing coastal wastewater systems from inland systems. Shallow groundwater may intersect septic tanks, drains, and sewer networks, increasing leakage and groundwater contamination. High groundwater levels and intense rainfall increase infiltration and inflow, reducing the effective hydraulic capacity of sewer systems and treatment facilities while increasing the likelihood of overflow events. Likewise, tidal backwater can reduce drainage efficiency, elevate water levels, reverse local flow directions, and decrease river dilution capacity during critical periods. Long-term drivers such as sea-level rise and land subsidence further amplify these pressures, whereas salinity intrusion may influence treatment efficiency, infrastructure durability, and wastewater reuse opportunities (Cahoon & Hanke, 2019; Chen et al., 2011; Flood & Cahoon, 2011; Fung & Babcock, 2020; Hummel et al., 2018).

The literature also demonstrates that on-site sanitation remains the dominant wastewater management system in many small and medium-sized coastal cities. Consequently, SD models should extend beyond toilet coverage and explicitly represent the complete faecal-sludge management chain, including containment quality, leakage, scheduled and unscheduled desludging, transport logistics, treatment capacity, illegal disposal, and groundwater exposure (Li et al., 2021; Mbae et al., 2024; Medland et al., 2016; G. L. Putri et al., 2025). Rather than relying solely on sanitation coverage as a performance indicator, the reviewed studies recommend evaluating the proportion of generated wastewater and excreta that remains safely managed throughout the entire sanitation service chain. This systems perspective provides a more comprehensive measure of sanitation performance because failures occurring during collection, transport, treatment, or disposal may substantially reduce environmental protection despite high toilet access (Li et al., 2021; Mbae et al., 2024; Medland et al., 2016).

Climate uncertainty should be incorporated through scenarios representing both long-term environmental change and short-term extreme events. Long-term drivers typically include sea-level rise, land subsidence, demographic growth, and changing rainfall patterns, whereas event-based disturbances comprise extreme rainfall, flooding, high tides, power outages, and pumping failures (Cahoon & Hanke, 2019; Flood & Cahoon, 2011; Fung & Babcock, 2020; Haasnoot et al., 2013; Kwakkel et al., 2016). The reviewed studies further indicate that the temporal resolution of SD models should correspond to the dominant planning objectives. Monthly or annual time steps are generally appropriate for strategic investment planning, capacity expansion, and long-term policy evaluation. In contrast, short-duration hydraulic processes, including stormwater dynamics and tidal fluctuations, are more appropriately represented using linked hydrodynamic or drainage models rather than being incorporated directly into strategic SD simulations (Chen et al., 2011; Kelly et al., 2013; Sterman & Series, 2003).

Limited data availability remains a common challenge for wastewater modelling in developing regions. The reviewed literature consistently recommends modular model development, whereby an initial SD model represents only the essential relationships among population, wastewater generation, sanitation coverage, treatment capacity, and pollutant loads. Additional processes, including spatial heterogeneity, groundwater interactions, tidal influence, financial mechanisms, and institutional behaviour, can subsequently be incorporated as more reliable data become available (Demirel et al., 2022; Sarrazin et al., 2016; Sterman & Series, 2003). Multiple information sources may be integrated to overcome data limitations, including household surveys, sanitation-flow diagrams, treatment-facility records, river-water-quality monitoring, remote sensing, and structured expert elicitation (Lemaire et al., 2021; Li et al., 2021; Mbae et al., 2024; Medland et al., 2016). Rather than representing uncertain variables as fixed values, SD models should characterise them as plausible ranges and evaluate their influence through uncertainty and sensitivity analyses (Pianosi et al., 2016; Sarrazin et al., 2016).

The reviewed framework is particularly relevant to Indonesian coastal cities, where rapid urbanisation, limited sewerage coverage, widespread on-site sanitation, shallow groundwater, tidal influence, and recurrent flooding interact to influence domestic wastewater management. Kota Pariaman represents one example of this broader class of coastal cities because it combines increasing domestic wastewater generation with limited centralised infrastructure and environmentally sensitive receiving waters (E. E. Putri et al., 2021). Although local applications should remain grounded in measured wastewater flows, treatment performance, environmental monitoring, and institutional conditions, the conceptual SD structures synthesised throughout this review provide a transferable framework for supporting wastewater planning across coastal cities facing similar environmental and socioeconomic constraints.

Overall, the reviewed literature demonstrates that extending SD models to coastal and data-limited cities requires broadening conventional wastewater-management frameworks to incorporate environmental processes, climate-related uncertainties, and institutional constraints. Rather than increasing model complexity indiscriminately, successful applications prioritise the inclusion of variables that directly influence strategic planning and policy evaluation while remaining consistent with available data. This synthesis highlights the importance of integrating physical, environmental, and socio-institutional components within a unified modelling framework, thereby providing a robust basis for supporting sustainable domestic wastewater management in diverse coastal settings.

3.8 Comparative synthesis and limitations of existing models

The reviewed literature demonstrates that SD has evolved from a tool for infrastructure planning into an integrated decision-support framework capable of representing the interactions among wastewater generation, treatment infrastructure, financial resources, environmental quality, institutional behaviour, and policy implementation. Unlike conventional static planning approaches, SD explicitly incorporates feedback mechanisms, accumulation processes, and implementation delays, enabling the long-term evaluation of wastewater-management policies under changing socioeconomic and environmental conditions. Consequently, SD has become increasingly valuable for supporting strategic planning where infrastructure investments, service expansion, and environmental improvements occur over extended time horizons (Demirel et al., 2022; Kelly et al., 2013; Lemaire et al., 2021; Wang et al., 2021).

Despite this common modelling philosophy, the reviewed studies reveal five principal application domains. Infrastructure-oriented models primarily evaluate asset deterioration, investment strategies, operational costs, and service reliability. Wastewater-quantity models focus on wastewater generation and treatment-capacity planning. Governance-oriented models emphasise institutional arrangements, stakeholder interactions, and behavioural responses. Watershed and water-quality models investigate pollutant transport and environmental impacts, whereas integrated treatment-policy models combine technical, environmental, financial, and governance processes within a unified framework. These application domains illustrate the flexibility of SD but also demonstrate that model structure is generally determined by the specific policy questions addressed rather than by a standard modelling architecture (Demirel et al., 2022; Kayal et al., 2026; Lemaire et al., 2021; Rehan et al., 2011).

A recurring observation throughout the reviewed literature is that increasing model complexity does not necessarily improve decision support. Instead, the usefulness of an SD model depends on whether its system boundary adequately represents the dominant feedback processes influencing policy outcomes. Many studies intentionally simplify environmental processes, infrastructure performance, institutional behaviour, or economic interactions to maintain transparency and data availability. While such simplifications improve model applicability, they may also reduce the ability of the model to evaluate emerging challenges such as climate change, groundwater contamination, microbiological pollution, and adaptive infrastructure management (Cahoon & Hanke, 2019; Kelly et al., 2013; Lemaire et al., 2021).

Model validation also remains one of the principal methodological challenges. Most reviewed studies validate population dynamics, wastewater generation, or total system flow, whereas relatively few evaluate treatment efficiency, pollutant loads, river-water quality, financial performance, or behavioural responses simultaneously. Consequently, acceptable agreement for one subsystem does not necessarily imply that other interacting subsystems are represented with comparable accuracy. Future SD applications should therefore adopt multi-variable validation strategies that evaluate each major subsystem independently while preserving overall system consistency (Demirel et al., 2022; Sterman & Series, 2003; Wang et al., 2021).

Similarly, uncertainty analysis remains comparatively underdeveloped. One-at-a-time sensitivity analysis continues to dominate SD applications despite the increasing availability of global sensitivity analysis, Monte Carlo simulation, robust decision-making frameworks, and adaptive policy pathways. Considering that future wastewater management will be influenced simultaneously by demographic growth, climate variability, infrastructure deterioration, and institutional uncertainty, future SD studies should evaluate policy robustness under multiple interacting uncertainties rather than relying solely on deterministic scenario comparisons (Haasnoot et al., 2013; Kwakkel et al., 2016; Pianosi et al., 2016).

Another limitation concerns spatial representation. Many reviewed models aggregate wastewater generation, treatment performance, and river-water quality at the city scale. Although such

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aggregation is appropriate for strategic policy analysis, it may conceal pollution hotspots, unequal sanitation services, environmentally sensitive tributaries, and localised public-health risks. Hybrid modelling approaches that couple SD with Geographic Information Systems (GIS), hydrodynamic models, or distributed water-quality models therefore provide an effective strategy for combining strategic policy analysis with spatially explicit environmental assessment (Chen et al., 2011; Chidiac et al., 2023; Lemaire et al., 2021).

The literature further indicates that future SD applications should move beyond representing wastewater infrastructure solely through treatment capacity. More comprehensive models should incorporate infrastructure condition, operational reliability, maintenance scheduling, sludge management, groundwater interaction, climate variability, institutional performance, and adaptive investment policies. Such integration would improve the capability of SD to evaluate not only infrastructure expansion but also long-term system resilience under uncertain environmental and socioeconomic conditions (Cahoon & Hanke, 2019; Kayal et al., 2026; Rehan et al., 2011). Table 8 summarises the principal methodological limitations identified across the reviewed studies together with recommended improvements and their expected contributions to future SD applications. Rather than evaluating individual publications, the table synthesises common methodological patterns that repeatedly emerged throughout the literature and identifies priorities for advancing integrated domestic wastewater modelling.

Table 8. Comparative limitations and recommended improvements

Observed limitation	Why it matters	Recommended improvement	Expected benefit
Population and flow dominate validation	Other subsystems may remain untested	Validate capacity, service, load, cost, and water quality separately	Greater confidence in policy interpretation
Installed capacity treated as effective capacity	Downtime and overloading are hidden	Use availability, condition, and performance factors	Realistic treatment and bypass estimates
Sanitation coverage treated as toilet access	Unsafe containment and sludge disposal are missed	Model the full sanitation service chain	Accurate safely managed coverage
Constant pollutant concentrations	Seasonal and behavioural variation is ignored	Use ranges, seasonal functions, or measured distributions	More credible load uncertainty
Single average river reach	Hotspots and tidal effects are masked	Link SD with spatial or hydrodynamic models	Improved location-specific decisions
Limited microbiological modelling	Public-health risk is underestimated	Include faecal indicators and disinfection scenarios	Health-relevant policy outcomes
One-at-a-time sensitivity only	Parameter interactions are overlooked	Apply Monte Carlo and global sensitivity methods	Robust priorities and uncertainty ranges

Observed limitation	Why it matters	Recommended improvement	Expected benefit
Fixed policy schedules	Real implementation responds to thresholds and budgets	Use trigger-based adaptive pathways	Flexible and timely investment strategies
Low stakeholder participation	Institutional constraints and behaviour are simplified	Use participatory model building and expert validation	Higher legitimacy and implementation relevance

Table 8 demonstrates that the principal limitations of existing SD applications arise primarily from simplified system representation rather than from deficiencies in the modelling approach itself. Most recommended improvements involve expanding model boundaries, strengthening validation procedures, improving uncertainty analysis, and integrating environmental, technical, financial, and institutional processes within a unified modelling framework. These developments would substantially enhance the ability of SD models to support resilient wastewater-management policies under increasing urbanisation, climate change, and resource constraints.

Overall, the reviewed literature confirms that SD remains one of the most appropriate approaches for strategic domestic wastewater management because it integrates infrastructure development, sanitation services, environmental quality, governance, and policy adaptation within a coherent feedback-based framework. Although current applications continue to face challenges related to data availability, spatial representation, environmental complexity, and uncertainty analysis, these limitations represent opportunities for methodological advancement rather than fundamental weaknesses of the SD approach. This comparative synthesis therefore provides a strong foundation for the concluding section, which summarises the principal findings of this review and outlines future research directions for integrated domestic wastewater management.

4. Research gaps and future directions for integrated SD modelling

The comparative synthesis presented in the previous section indicates that existing SD applications remain fragmented across technical, environmental, institutional, and financial domains. Although considerable progress has been achieved in modelling individual components of domestic wastewater systems, relatively few studies integrate these components within a single adaptive decision-support framework. Consequently, future research should focus on developing integrated SD models capable of representing the complex interactions among wastewater generation, sanitation services, environmental quality, governance, and climate-related processes.

Accordingly, future models should integrate nine modules: population and water use; sanitation-service chains; collection infrastructure; treatment capacity and performance; sludge and reuse; pollutant generation and removal; receiving-water quantity and quality; finance and institutions; and climate and coastal stress. These modules should exchange a limited set of clearly defined variables, including generated wastewater, safely collected flow, effective treatment capacity, treated flow, untreated flow, pollutant load, compliance status, investment requirements, and environmental pressure. Such a modular architecture improves model transparency, facilitates calibration and validation, and enables progressive model development as additional data become available.

Spatial SD represents one of the principal research priorities identified throughout the reviewed literature. Integrating GIS with SD enables cities to be divided into service zones, sub-catchments, or river reaches, allowing each zone to represent differences in population density, sanitation systems, groundwater conditions, flood exposure, connection costs, treatment pathways, and receiving-water sensitivity. Such spatial disaggregation enables planners to identify where decentralised treatment systems, sewer expansion, scheduled desludging, or river restoration are likely to produce the greatest environmental and socioeconomic benefits (Kelly et al., 2013; Lemaire et al., 2021).

Climate and hydrological integration should also extend beyond the common assumption of constant low-flow conditions. Future SD applications should incorporate both long-term drivers, including sea-level rise, land subsidence, changing rainfall patterns, and demographic growth, as well as short-term disturbances such as extreme rainfall, combined sewer overflows, flooding, drought, tidal backwater, and changing river discharge (Cahoon & Hanke, 2019; Chen et al., 2011; Haasnoot et al., 2013; Lemaire et al., 2021). Strategic SD models can generate time-varying pollutant loads, infrastructure conditions, and service performance, whereas hydrological and hydrodynamic models can simulate event-scale flow dynamics, tidal effects, and pollutant transport. Outputs from these detailed models may subsequently be returned to the strategic SD model as indicators of infrastructure damage, regulatory compliance, operational costs, or service performance, thereby strengthening long-term policy evaluation (Chen et al., 2011; Lemaire et al., 2021).

Participatory modelling offers further opportunities to improve model realism and policy relevance. Households, utilities, municipal governments, public-health authorities, river managers, private desludging operators, and community organisations often possess different perspectives regarding system boundaries, implementation barriers, financing mechanisms, and operational constraints. Their participation can improve causal-loop development, parameter estimation, policy feasibility, and institutional representation while revealing informal discharge pathways and service barriers that may not be captured by conventional engineering datasets (Stave, 2002).

Future SD applications should also strengthen uncertainty analysis by supporting robust decision-making rather than producing only best-fit projections. Monte Carlo simulation enables estimation of the probability of achieving service and environmental targets under uncertain conditions, while global sensitivity analysis identifies the parameters that most strongly influence model behaviour. Robust decision-making and adaptive pathways further assist policy makers in selecting interventions that remain effective across multiple demographic, climatic, financial, and institutional futures (Haasnoot et al., 2013; Kwakkel et al., 2016; Pianosi et al., 2016).

Hybrid modelling provides additional opportunities for extending SD applications. Optimisation techniques can identify efficient combinations of infrastructure capacity, facility location, investment timing, and budget allocation. Agent-based models can represent household decisions regarding sewer connections and desludging behaviour. Machine-learning approaches may improve estimation of uncertain inflows, treatment performance, or pollutant concentrations using monitoring data, whereas digital twins and real-time sensors enable continuous model updating and operational decision support. These complementary approaches should strengthen rather than replace SD by enhancing predictive capability while preserving causal transparency and long-term policy interpretation. Figure 6 synthesises the principal research directions identified throughout this review and illustrates how complementary modelling approaches can strengthen future adaptive integrated wastewater models.

Figure 6 highlights six complementary research directions that extend the capability of conventional SD models. GIS-based spatial disaggregation improves geographical representation of sanitation systems and environmental conditions. Hydrological integration enables strategic models to represent extreme rainfall, tidal influence, and climate-related disturbances. Sensors, remote sensing, and digital twins facilitate real-time model updating using continuously collected environmental and operational data. Participatory modelling improves institutional realism and policy legitimacy by incorporating stakeholder knowledge throughout model development. Monte Carlo simulation, global sensitivity analysis, and robust decision-making strengthen uncertainty evaluation, whereas optimisation, machine learning, and adaptive pathways enhance long-term planning and policy exploration. Rather than replacing SD, these complementary approaches expand its analytical capability while preserving its strengths in representing feedback mechanisms, implementation delays, and long-term system behaviour.

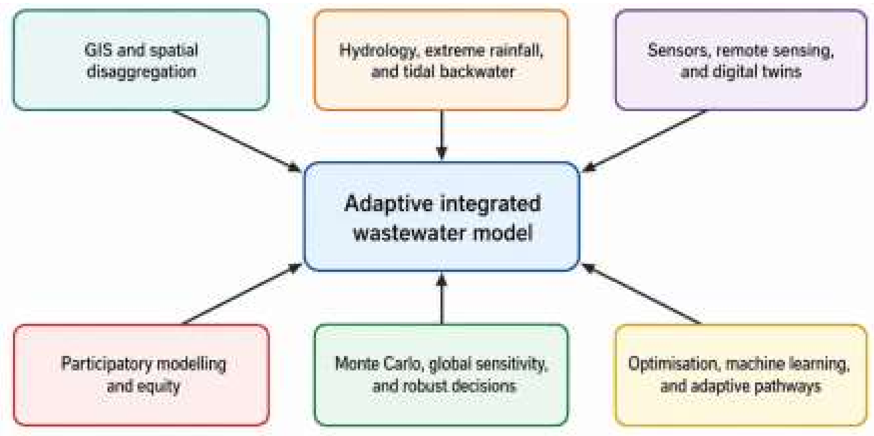

Figure 6. Future research roadmap for adaptive integrated wastewater modelling

A practical model-development sequence is recommended: (1) define the decision problem and planning horizon; (2) map the complete sanitation and pollutant service chain; (3) develop and validate causal-loop diagrams with stakeholders; (4) construct a minimum stock-and-flow model; (5) perform dimensional consistency, mass-balance, and extreme-condition tests; (6) calibrate and validate each major subsystem independently; (7) design individual, combined, and adaptive policy scenarios; (8) conduct sensitivity and uncertainty analyses; (9) introduce spatial or hydraulic coupling only where additional complexity materially improves decision support; and (10) comprehensively document equations, assumptions, parameter values, data sources, model limitations, and scenario settings to maximise transparency and reproducibility.

Collectively, these recommendations provide a practical roadmap for developing adaptive, integrated, and policy-oriented SD models capable of supporting sustainable domestic wastewater management under increasing environmental, climatic, and institutional uncertainty. By combining strategic systems thinking with spatial information, climate adaptation, participatory modelling, uncertainty analysis, and emerging digital technologies, future SD applications will be better positioned to support resilient and evidence-based wastewater management for rapidly urbanising regions.

5. Conclusion

This review synthesised recent developments in SD applications for domestic wastewater management by examining model structures, stock–flow formulations, policy scenarios, pollutant-load modelling, river-water-quality assessment, and future modelling directions. SD offers a coherent framework for analysing domestic wastewater management as an interconnected socio-technical-environmental system. The approach is well suited to long-term planning because it captures delayed infrastructure development, changing demand, asset deterioration, policy feedback, and cumulative pollutant effects. The reviewed literature demonstrates a clear evolution from infrastructure finance and wastewater estimation towards more integrated models that connect socioeconomic development, treatment capacity, pollutant loads, and receiving-water quality.

The main modelling requirement is to distinguish wastewater generation, safely managed service coverage, installed and effective treatment capacity, untreated discharge, treatment efficiency, and receiving-water response. Capacity expansion alone is rarely sufficient to achieve sustainable wastewater management. More effective outcomes arise from coordinated improvements in collection or desludging services, service uptake, operation and maintenance, treatment performance, financial capacity, institutional arrangements, regulatory enforcement, and source control. In addition, policy timing and implementation delays are as important as the nominal scale of intervention. Despite recent advances, existing models still underrepresent on-site sanitation, faecal-sludge pathways, microbiological contamination, spatial hotspots, coastal processes, climate extremes, institutional behaviour, and uncertainty arising from multiple interacting drivers. Consequently, coastal and data-limited cities require modular modelling frameworks that explicitly incorporate shallow groundwater, infiltration and inflow, flooding, tidal backwater, low-flow conditions, and the complete sanitation service chain.

The integrated framework proposed in this review combines socio-demographic, service, infrastructure, treatment, pollutant, receiving-water, financial, institutional, and climate modules within a unified SD structure. Its value can be further enhanced by coupling SD with GIS, hydrological and hydraulic models, water-quality models, optimisation techniques, agent-based modelling, machine learning, participatory approaches, and real-time monitoring systems. Rather than providing a single deterministic forecast, such an integrated framework should serve as a transparent policy-learning tool that supports the comparison of alternative development pathways, identifies trade-offs, and evaluates robust strategies for achieving sustainable domestic wastewater management under changing environmental, socioeconomic, and climatic conditions.

This review has several limitations. First, the review was restricted to peer-reviewed publications written in English, which may have excluded relevant studies reported in other languages or in the grey literature. Second, because the reviewed studies differed substantially in their objectives, system boundaries, model structures, temporal scales, and performance indicators, a quantitative meta-analysis was not appropriate. Third, although the review synthesises a broad range of SD applications related to domestic wastewater management, several studies addressed coupled watershed, water-quality, or sanitation systems rather than domestic wastewater alone. These studies were included only when domestic wastewater constituted an explicit component of the modelling framework. Despite these limitations, the review provides a comprehensive synthesis of current SD applications and identifies practical directions for future model development.

Author’s declaration

Author contribution

Widia Putri: Conceptualization, methodology, literature search, data curation, formal analysis, visualization, and writing of the original draft. **Denny Helard**: Conceptualization, methodology, validation, supervision, project administration, and review and editing of the manuscript. **Shinta Indah**: Methodology, validation, supervision, and review and editing of the manuscript. All authors contributed to the interpretation of the findings, critically reviewed the manuscript, and approved the final version for publication.

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Data availability

The data supporting the findings of this review were obtained from publicly available scientific publications cited in the manuscript. No new primary dataset was generated during this study. Information concerning the literature-search strategy, eligibility criteria, data extraction, and comparative synthesis is provided in the manuscript. Additional information related to the review process is available from the corresponding author upon reasonable request.

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Conflict of interest

The authors declare that they have no financial or non-financial conflicts of interest that could have influenced the research, analysis, interpretation, or presentation of the material discussed in this manuscript.

Ethical clearance

This research does not involve humans or animals as research subjects. The study was conducted as a structured narrative review using information obtained from previously published scientific literature. Therefore, ethical approval and informed consent were not required.

AI statements

ChatGPT, developed by OpenAI, was used during manuscript preparation to assist with English-language editing, grammatical improvement, coherence, and readability. The authors manually reviewed, revised, and verified all AI-assisted outputs to ensure their accuracy, consistency with the cited literature, and relevance to the objectives of the study. The language of the final manuscript was also reviewed and verified by [name of English-language expert or institution. The authors take full responsibility for the accuracy, originality, interpretation, and integrity of the entire manuscript.

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