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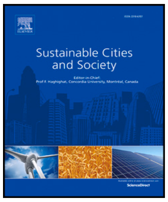

Coupled simulation of urban water networks and interconnected critical urban infrastructure systems: A systematic review and multi-sector research agenda

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ABSTRACT

Adaptive planning of water infrastructure systems is crucial to bolster urban resilience in the face of climate change while meeting the needs of rapidly changing urban metabolisms. Urban water systems maintain intricate interconnections with other critical infrastructure domains (CIDs). Multi-sector dependencies and joint management of different CIDs have gained interest in recent research to mitigate undesired cascading effects across domains. Yet, combined modeling and joint simulation of multiple CIDs needs to overcome the limitations of tools and software often siloed to individual infrastructure domains. In this paper, we contribute a systematic review of 24 recent peer-reviewed publications on coupled simulation of urban water systems (water supply and drainage networks) and other CIDs, including energy grids, mobility networks, and IT infrastructure systems, extracted from a larger set of 222 publications. First, we identify trends, modeling frameworks, and simulation software enabling the combined simulation of interlinked CIDs. Then, we define an agenda of priorities for future research. Acknowledging the opportunities provided by open-source tools, data, and standardized evaluation schemes, future research fostering coupled simulation across CIDs should prioritize knowledge transfer, address differences in spatial and temporal dependencies, scale up simulations to a network level, and explore multi-sector interconnections beyond bilateral dependencies.

1. Introduction

The world's urban population has grown rapidly in the last decades. Only 30% of the world's population (751 million) lived in urban areas in 1950. Since then, this number has increased drastically to 57% (4.5 billion) in 2022 and is expected to continue to increase and represent 68% of the total global population by 2050 (The World Bank, 2023; United Nations Department of Economic and Social Affairs, 2018). Most economic and human activities occur in cities within the urban metabolism (Chini & Stillwell, 2019), translating into more than 70% of the global energy consumption and the global greenhouse gas emissions being generated in urban environments (United Nations Human Settlements Programme, 2022).

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The compound effect of global urbanization and changing climate is confronting cities with growing water demand, increasing sewage and stormwater runoff, potential depletion of water resources, and deteriorating water quality (Koop, Grison, Eisenreich, Hofman, & van Leeuwen, 2022). Remarkable research efforts have been performed in the last decades to pursue a better understanding of the urban water systems and their dynamics to ultimately support water resources management, adaptive infrastructure planning, operation, and rehabilitation in the built environment under current and uncertain climate and socio-economic futures (Stillwell, Cominola, & Beal, 2023). Urban water supply networks and drainage networks are especially in the spotlight of this endeavor (Peña-Guzmán, Melgarejo, Prats, Torres, & Martínez, 2017).

However, these urban water systems are not independent of each other or of other critical infrastructure domains (CIDs). Interdependencies and multi-sector dynamics between these CIDs should be regarded in the modeling and management of urban systems throughout their entire life cycle (Daulat, Rokstad, Klein-Paste, Langeveld, & Tscheikner-Gratl, 2022; Ouyang, 2014). CIDs for water, energy, mobility, and information technology (IT) provide essential services to support daily life and economic activities in cities (Rinaldi, Peerenboom, & Kelly, 2001). Although urban water systems and other CIDs exhibit different spatial characteristics and are constructed in diverse forms (either above or underground, physically connected, or wireless), they are highly interconnected complex systems. For instance, a power outage incident can lead to cascading effects in other CIDs, e.g., the failure of water supply systems (Pournaras et al., 2020; Zachariadis & Poullikkas, 2012). Cyber attacks can cause the malfunctioning of urban drainage networks and hinder the collection and treatment of wastewater (Pournaras et al., 2020). In fact, these interdependencies have been found to be intrinsically integrated through the topological co-evolution of these CIDs (Zischg, Klinkhamer, Zhan, Rao, & Sitzenfrei, 2019).

Whilst many multi-sector dependencies and interconnections exist in urban CIDs, most research to date approached the task of modeling urban water systems as complex yet siloed entities (Peña-Guzmán et al., 2017). The most popular open-source software for simulating water supply and drainage networks (e.g., the Environmental Protection Agency Network Evaluation Tool, EPANET (Rossman, 2000) and the Storm Water Management Model, SWMM (Rossman, 2010)) conforms to this observation, as these specifically cater to the simulation of either water supply or drainage networks (Peña-Guzmán et al., 2017). Yet, the coupled simulation of interdependencies between urban water systems and other CIDs can enhance the understanding of the whole systems, trade-offs, and cascading effects, thus facilitating resilient planning and management of urban water systems and other related CIDs, and ensuring the well-being and safety of inhabitants in our cities (Laugé, Hernantes, & Sarriegi, 2015; Ouyang, 2014). Coordinated operation and management of urban water systems and other CIDs in a systemic manner leverages resource conservation and sustainable development, ensuring adaptive operation of CIDs under future uncertainty. For instance, Kammouh, Nogal, Binnekamp, and Wolfert (2021) propose to optimize intervention measures based on the interdependency between water pipes and transport paths to reduce 25% of the intervention costs.

Here, we contribute a systematic review of the literature on recent research on the coupled simulation of interconnected CIDs in urban areas with a focus on simulation methods and software tools. We first select 24 peer-reviewed papers from a larger sample of 222 publications. We then critically analyze them to identify relevant intersector dependencies and interconnections along with the modeling frameworks and software so far developed to co-simulate them. The CIDs considered within the scope of this review include coupled water supply and urban drainage networks (including Blue–Green Infrastructure), and their interlinks with energy grids, mobility networks, and IT infrastructure systems. For simplicity, we refer to these domains with shorter labels, i.e., energy, mobility, IT, water supply, and drainage.

The three-fold goal of this review is to:

- capture the most up-to-date applications and findings from coupled simulation of urban water networks and other CIDs;
- identify and characterize modeling frameworks and software for coupled simulation of urban water networks and their interconnected CIDs;
- highlight current trends and research gaps in modeling and coupled simulation of interconnected CIDs for sustainable management of urban infrastructure systems.

Based on our literature review and analysis, this paper also contributes a framework for analysis of the main interconnections in urban CIDs and an agenda to guide future research prioritizing a better understanding of currently under-explored multi-sector interdependencies. Overall, this review creates knowledge for the future development of coupled simulations for decision support and management of urban water systems and related critical infrastructure domains. To the authors' knowledge, there is currently no systematic review in peer-reviewed literature providing such a modeling- and simulation-centered overview of recent research and outcomes as discussed. This work extends and refines existing reviews, which focus more broadly on the identification of interconnections in critical urban infrastructure (Pietro et al., 2016; Rinaldi et al., 2001; Yusta, Correa, & Lacal-Arántegui, 2011).

This paper is structured as follows: the literature review methods are presented in Section 2; an overview of the literature search outcomes is presented in Section 3; Section 4 critically analyzes the reviewed literature with an in-depth exploration of the coupled simulation of different sub-domains of urban water systems in combination with other CIDs; Sections 5 and 6 discuss recent trends and opportunities in the coupled simulation of urban CIDs, draw final remarks, and formulate an agenda of priorities for follow-up research.

2. Literature review methods

In this section, we describe the strategy and methods we use in this review for literature search, eligibility check, selection, and feature extraction for paper tagging. This review follows the standards of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) to foster reproducibility and transparency (Page et al., 2021).

2.1. Paper search and selection

Search databases. We select Web of Science[1] and IEEEXplore[2] as databases for publication retrieval. Web of Science covers a wide range of multidisciplinary peer-reviewed papers. IEEEXplore provides peer-reviewed contributions, especially in technical disciplines including computer science and electrical engineering. We ran the final queries for paper search in these two databases in January 2023 to retrieve scientific papers published until December 31st, 2022. No lower constraint on the publication year is applied.

Keywords and queries. As *water supply* and *urban drainage* are the two central services of urban water systems (Peña-Guzmán et al., 2017; Sun, Puig, & Cembrano, 2020), this review presents coupled simulation approaches that involve either of these two components in combination with any of the three other CIDs - *energy*, *mobility*, and *IT*. Simulations that indicate interactions between *water supply* and *drainage* are also explored.

We search for combinations of keyword *simulat** and the domain-specific keywords reported in Table 1 to account for all kinds of coupled simulation approaches and related software tools available in

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[1] https://www.webofscience.com.

[2] https://ieeexplore.ieee.org.

Table 1
Keywords for paper search organized by CID. Literature search queries combine keywords for *water supply* and *drainage*, or keywords from one of these two water domains with keywords from any of the three other CIDs (energy, mobility, IT).

Water supply	Water distribution	System(s)	*Mobility*	Urban	Mobility
	Water supply			Smart	
	Water distribution	Network(s)		Individual	
	Water supply			Human	
Drainage	Stormwater	System(s)		Non-motorized	Transport*
	Sew*			Motorized	
	Wastewater			Public	
	Drainage			Vehic*	Traffic
	Stormwater	Network(s)		Car	
	Sew*			Pedestrian	
	Wastewater			Road	
	Drainage		*IT*	Fog	Computing
Energy	Power	Grid(s)		Edge	
	Energy			Sensor	Network(s)
	Electric*			communication	
	Smart			Wireless communication	
	Power	Distribution		Cyber–physical system(s)	
	Energy			Internet of things	
	Distributed energy			IoT	

the selected databases. All keywords within a sector are combined by a logical “OR”, while different sectors are combined in pairs by a logical “AND” to account for inter-domain interactions. The expert-based selection of keywords reported in Table 1 captures the most important and commonly-used terms with regard to each selected CID, with a special focus on a system perspective and high-level simulation of complex network systems. We choose the broad search terms intentionally to include a comprehensive range of results while abstracting from location or industry-specific terms. This particularly applies to water domains, where various terms are used interchangeably to describe the same basic concepts found in the search terms (Fletcher et al., 2015). For the IT sector, specific concepts such as internet of things (IoT) and cyber–physical system(s) are included to better direct the paper search toward IT concepts that are relevant to distributed urban IT infrastructure.

Exclusion criteria and paper selection. All papers retrieved by our initial literature search on Web of Science and IEEEXplore based on the above keyword combinations are automatically processed to filter out duplicates. Each paper is then screened independently by two of the authors in three different rounds: title-only, abstract, and full-text screenings. We formulate the following exclusion criteria (EC):

(EC1) No coupled simulation combining multiple CIDs is conducted (e.g., the paper is a review article), or only one critical infrastructure domain is actually simulated.
(EC2) The paper focuses on infrastructure types that differ from “network” systems or spatial domains other than “urban”.
(EC3) No multi-sector interconnection is explicitly explored in the paper.
(EC4) The publication is not in English.

Based on the above exclusion criteria and three-stage review, the two reviewers of each paper converged on a final decision on paper selection or exclusion. All selected publications are then retained for paper tagging and subsequent analysis.

2.2. Feature extraction for paper tagging

We manually extract a set of descriptive features from all selected publications to enable consistent tagging and analysis. Similarly to the paper selection/exclusion process, the extraction of features is carried out independently by two experts and subsequently merged to reduce subjective judgment. We define two main groups of features for paper tagging: *general features* and *simulation characteristics*.

General features. As part of the general features, we extract information on the *publication year* alongside the *tool name*, *target*, and *availability*. *Tool name* refers to the specific name given to the tool/method/approach presented or applied in a paper for CID simulation. *Availability* describes in a boolean fashion if the code, simulations, or software tools identified in *tool name* are published and released to the public. Finally, *target* indicates whether the paper targets an *academic* or *utility management* audience.

Simulation characteristics. The simulation characteristics are the main focus of subsequent literature analysis. First, the *simulation software* lists the software tools used for running coupled simulations. We tag the simulation as *hydraulic* or *hydrological* to further identify the type of simulations run in relation to the focus domains of water supply and drainage. We label a simulation as hydraulic when the transport of water through a network infrastructure is considered, i.e., via simulation of pipes, pumps, valves, and network nodes. A hydrological simulation encompasses processes in the hydrological cycle, e.g., rainfall-runoff processes. The *spatial scale* categorizes the spatial extent of the system simulated in a paper. Possible spatial scales in ascending order of size are *household*, *municipality*, *city* and *region*. The *resolution* and *duration* features regard technical details of the simulation setup. Resolution describes the smallest recurring simulation time step, while duration represents the simulation horizon.[3] Lastly, we define the *model* feature as the name(s) of the water supply or drainage network modeled in a study.

3. Overview of literature search outcome

Here we present the synthesis of our anthology resulting from the application of the methods presented above.

3.1. Paper selection outcome

Our initial paper search returns a set of 222 papers published before December 31st, 2022 from Web of Science (n = 129) and IEEEXplore (n = 93). From this set of papers, we remove 16 duplicates and subsequently exclude 128 papers after manual title and abstract screenings. The 78 remaining papers are assessed for eligibility based on full-text screening, yielding 24 papers included in our review for detailed tagging and analysis (see details in the PRISMA diagram in Fig. 1 (Page et al., 2021)).

Fig. 2 gives a complete overview of the number of papers filtered in each step of the screening process, with each inter-domain (i.e., a combination of two CIDs) illustrated separately. *Water supply* × *energy* (n = 10) and *water supply* × *IT* (n = 9) are the most represented inter-domains in our final set of 24 papers, covering almost 80% of it. *Water supply* × *drainage* (n = 3) and *drainage* × *mobility* (n = 2) are also represented, yet to a limited extent, while no paper about the remaining inter-domains of *water supply* × *mobility*, *drainage* × *energy*, and *drainage* × *IT* is contained in the final set for further review. This ranking of paper representation is rather consistent with the one resulting from the initial paper search before paper exclusion (after removal of duplicate record), where the inter-domain *water supply* × *IT* includes the largest amount of identified papers (n = 99), followed by *water supply* × *energy* (n = 46), *water supply* × *drainage* (n = 31), *drainage* × *IT* (n = 16), *drainage* × *energy* (n = 7), *drainage* × *mobility* (n = 5), and *water supply* × *mobility* (n = 2).

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[3] The *duration* feature refers only to the simulation horizon, but it is not linked to the computational run time of the execution of a simulation run.

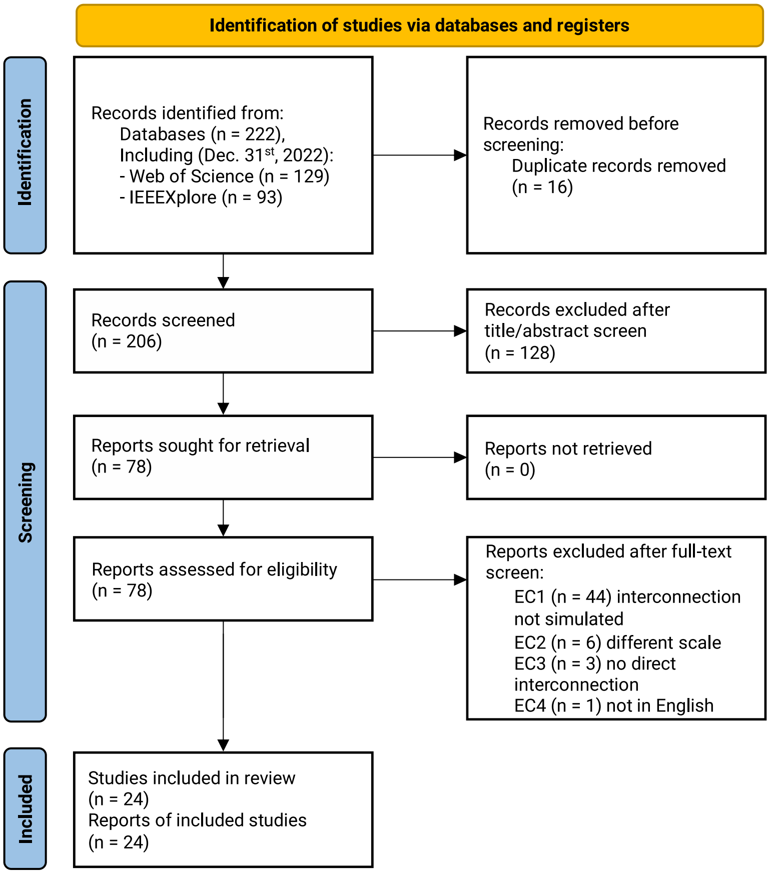

Fig. 1. Flow diagram with paper exclusion criteria. The flow diagram reports the exclusion criteria applied to the dataset of papers retrieved for review from Web of Science and IEEEXplore, adapted from the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines (PRISMA Flow Diagram, Page et al. (2021)).

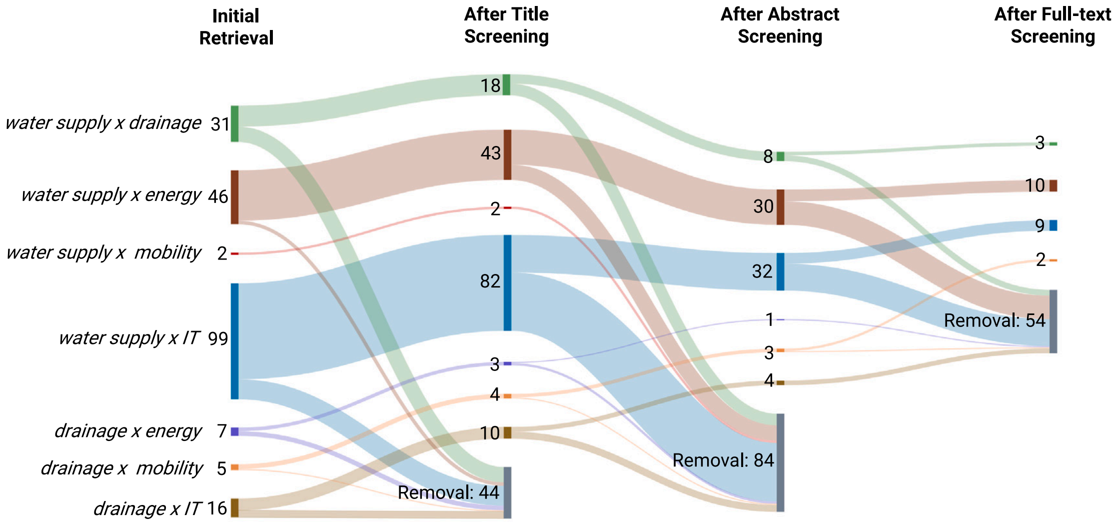

Fig. 2. Sankey diagram of the review paper selection flow. The four columns indicate the four statuses: initial paper set retrieved from online databases (after removal of duplicate records), and remaining papers after title, abstract, and full-text screenings. Each color represents an inter-domain combination. The number after each inter-domain indicates the number of remaining papers in each stage, to be distinguished from the numbers of papers being rejected from the anthology (the gray bars on the bottom of the last three columns). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

As Figs. 1 and 2 suggest, the amount of papers we exclude from final tagging and analysis is not negligible. The lack of coupled simulations combining multiple CIDs accounts for the largest percentage of papers excluded after full-text screening (n = 44, 81.5%). These papers simulate either only one CID (e.g., *water supply* network simulation and operation optimization under critical conditions such as electricity shortage, where *energy* grids are not simulated (Khatavkar & Mays, 2019; Menke, Abraham, Parpas, & Stoianov, 2016)) or none of the domains (e.g., review articles like (Zohrabian, Plata, Kim, Childress, & Sanders, 2021)). This group of papers also includes: (i) exploratory studies with lab experiments or network scale investigations, not yet providing a simulator or simulation application, such as in Dannier et al. (2015); (ii) papers proposing frameworks or methodologies to manage multiple CIDs individually, thus not considering explicit interconnections (Tellez-Castro, Quijano, & Mojica-Nava, 2016). The requirement on the coupled simulation of at least two CIDs becomes particularly relevant when considering the most represented inter-domain *water supply* × *IT* as well as *drainage* × *IT*. Setups of sensor networks, including optimal sensor placement, and using sensor data to detect leaks or water quality anomalies in *water supply* networks have been explored widely (Hu et al., 2021; Parks & VanBriesen, 2009; Zhao, Schwartz, Salomons, Ostfeld, & Poor, 2016). Aspects of detecting cyber–physical attacks are also discussed (Shin, Lee, Burian, Judi, & McPherson, 2020). Chen, Lu, Hu, Lei, and Yang (2018) conducted studies on utilizing pico-hydropower to generate electricity, which can be used by sensor networks to monitor *water supply* networks. Although the direct interconnection between water supply and IT is of focus among these papers, their missing cross-domain simulations (e.g., sensor communication networks) disqualify them from our review process. Similarly, papers such as Troutman, Schambach, Love, and Kerkez (2017), which presents a data-driven toolchain to conduct simulation and forecasting for drainage networks, or Malik et al. (2018) and Zaarour, Affes, Kandil, and Hakem (2020), which propose communication technology or schemes for higher accuracy or efficiency of drainage monitoring, are not included in our review as they lack either simulations of the IT or drainage networks.

About 11.1% of the papers (n = 6) are excluded as they do not consider network systems or urban scales. They performed simulations, e.g., at the scale of a single pumping station, or regional subsurface water systems. Birgisson and Roberson (2000), as an example, propose a sensor network and data collection system to measure moisture in the pavement. However, this is not upscaled to drainage networks, resulting in exclusion of this paper from further review. About 5.6% (n = 3) of the papers do not explicitly consider any interconnection between sectors, i.e., they cover two domains solely because they introduce methodologies or propose frameworks that could be applied or transferred to more than one relevant sector. Lastly, one paper is not written in English (except for the title and abstract).

3.2. Temporal distribution of reviewed publications and inter-domain trends

Fig. 3 illustrates the temporal distribution of the reviewed publications in different inter-domains. All papers are published after 2013. Except for the inter-domain *water supply* × *drainage*, all other inter-domains exhibit an increasing or stable trend of publications in the last decade with notable growth around 2020. Water supply and drainage infrastructure have been primarily modeled and simulated as separate systems in all works we retrieved, aside from two publications in 2013 on integrated management of *water supply* and *drainage* (Rozos & Makropoulos, 2013; Sitzenfrei, Möderl, & Rauch, 2013) and one more recent paper (Zhang, Zheng, Jia, Savic, & Kapelan, 2021) that taps into advances in smart metering and digital technology in *water supply* networks to inform and improve *drainage* network management.

After an early publication connecting the *water supply* and *IT* CIDs to develop a communication and control protocol for *water supply* infrastructure conceived as a Cyber–Physical System (CPS) (Suresh, Manohary, Ry, Stoleru, & Sy, 2014), the *water supply* × *IT* inter-domain has gained growing attention in the literature due to increasing concerns towards the security of such CPSs. Since 2015, the papers belonging to this inter-domain evaluate potential cyber–physical risks and develop strategies for mitigation of cyber–physical attacks to improve the resilience of *water supply*. Some studies in this domain also contribute to improving the system communication and computation efficiency.

The inter-domain of *water supply* × *energy* exhibits a more rapid increase in the temporal publication distribution. This suggests an increasing interest and awareness of the interconnection between water and energy supply systems. Most publications in this inter-domain are targeted at utility managers, likely acknowledging that water distribution often contributes the largest share of energy consumption of water provision, with energy-related costs that can constitute up to 65% of a utility's operating budget (Fiedler, Cominola, & Lucia, 2020; Spang & Loge, 2015). Joint management of water supply and energy infrastructure generates economic benefits for water utilities and offers opportunities to reduce their greenhouse gas emissions (Daniel et al., 2023).

Finally, although flash floods can influence urban mobility systems, the *drainage* × *mobility* inter-domain only emerges in recent papers published after 2018. The limited amount of research in this area suggests scarce availability of consistent drainage and mobility system models, or uncertainty in which benefits can emerge from transferring information from the drainage to the mobility sector.

3.3. Review method constraints and reproducibility

The scope of this work encompasses research on coupled, network-scale simulations of urban water networks (water supply and urban drainage) with three other CIDs, namely energy, IT, and mobility. As indicated in Section 2, the keywords of this systematic literature review are deliberately broadly defined to retain network-level investigations of the entire infrastructure systems and simultaneously mitigate the risk of excluding relevant publications due to potentially divergent

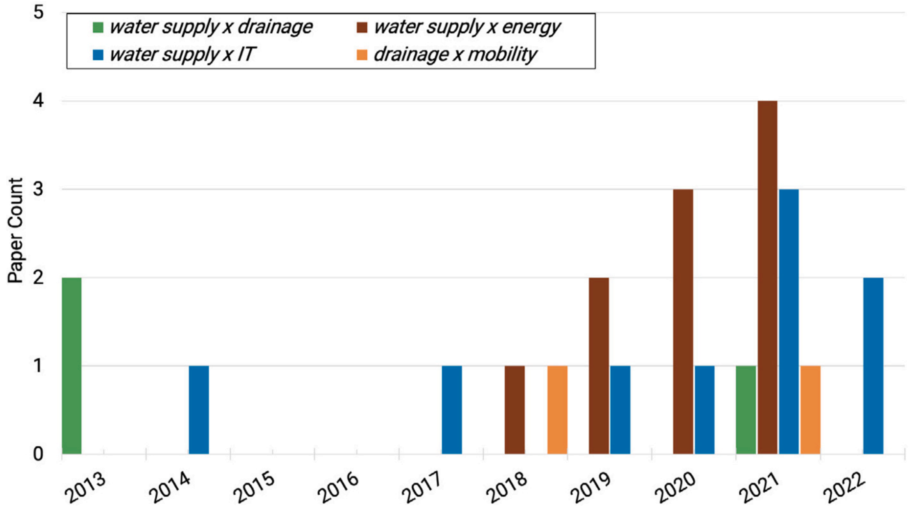

Fig. 3. Yearly count of the 24 publications reviewed in this study, categorized by type of CID combination (inter-domain).

yet interchangeable terminology for the reviewed CIDs, while only excluding research that is measured on a small or individual-sector scale. The subjective judgment of reviewers in the paper selection and analysis process presents an intrinsic limitation to any literature review. Here, we mitigate this risk by initial independent inspections and only subsequent joint discussions.

In addition, the transparently reported process from Section 2 enhances the reproducibility of this research. Based on the overview and insights provided by this work, a specific review for one selected sector can be undertaken. Similarly, an updated, modified, or more exhaustive search on this topic, as well as extended research covering other domains and/or scales can be established.

4. Intersectoral analysis

In this section, we present an in-depth analysis of the review results for each relevant CID combination. First, we analyze the coupled simulation of *water supply* × *drainage*, as this inter-domain combines two water-related infrastructure networks. All other inter-domains are then presented in descending order of representation in the set of 24 reviewed papers as shown in Section 3 and Fig. 3. Details about all 24 publications and their extracted features are represented in Table 2.

4.1. Water supply × drainage

Water supply and drainage networks are two of the most critical components of the urban water cycle. Although the urban water cycle including these two processes has been modeled and simulated in various studies (Peña-Guzmán et al., 2017), we only retrieve three studies that couple simulations of these two components at the network level (Rozos & Makropoulos, 2013; Sitzenfrei et al., 2013; Zhang et al., 2021). Their interdependency is mainly studied with two aims: (i) integrating both systems in pursuit of combined operation improvement; (ii) transferring information from water supply networks to support drainage network management. This second goal is particularly motivated by the increasing deployment of digital sensor technologies in water supply networks, which collect water consumption and supply data at higher spatial and temporal resolutions. Zhang et al. (2021) develop a method that transfers information from water supply measurements for real-time hydraulic modeling of drainage networks. Node connections between water supply and drainage network models are pre-configured to account for the fraction of water supply that ends up in the drainage system and the additional time delay for this transfer. These factors are approximated by historical data and optimized with an evolutionary algorithm, with two demonstrative case studies in China.

The temporal and spatial span and resolution of simulations differ among the three reviewed studies: Rozos and Makropoulos (2013) cover the scales of household, city, and region and a simulation extent of 100 years, but only consider monthly fluctuations of water demand and reservoir storage, while the other two studies adopt shorter simulation durations (1 month and 50 h) but higher temporal resolutions (0.5 and 1 h) (Sitzenfrei et al., 2013; Zhang et al., 2021).

In terms of software, the Environmental Protection Agency Network Evaluation Tool (EPANET) (Rossman, 2000) and Storm Water Management Model (SWMM) (Rossman, 2010) are used for simulation within two of the reviewed studies on *water supply* × *drainage* (Sitzenfrei et al., 2013; Zhang et al., 2021). By combining EPANET and SWMM simulations, for instance, Sitzenfrei et al. (2013) develop VIBe (Virtual Infrastructure Benchmarking). VIBe enables stochastic generation of water supply and drainage networks using various input data including land use, population, and network topology. Sitzenfrei et al. (2013) use VIBe to generate urban water systems for 80 fictional cities and Innsbruck (Austria) and evaluate the impacts of decentralized water management measures under water demand variation.

The third study in our sample develops UWOT (Urban Water Optioneering Tool), an alternative modeling approach that traces water demand signals back from household water appliances to water sources (Rozos & Makropoulos, 2013). Water demand from households is first estimated according to appliance categories and numbers, subsequently aggregated to a network level, and transmitted to the water source, i.e., reservoirs. Wastewater production converted from the water demand is drained together with runoffs within the system, treated at wastewater treatment plants, and disposed into natural water bodies. By linking water supply, drainage, and other components in the urban water cycle, UWOT aims at providing an environment to simulate and optimize operational strategies for integrated water systems (e.g., pursuing energy efficiency). UWOT is implemented with a parameterization–simulation–optimization algorithm and demonstrated in Athens, Greece, achieving satisfactory results in comparison with historical operations by the local water utility (Rozos & Makropoulos, 2013).

Although all simulations in the three reviewed studies are based on real-case studies and EPANET and SWMM are available open-source, only UWOT is accessible as an open-source co-simulator of water supply and drainage networks (Rozos & Makropoulos, 2013).

4.2. Water supply × energy

Water supply × *energy* is the most represented inter-domain in our review. In total, 10 papers are identified for this inter-domain, most published after 2020 (n = 7). The main interconnection between the water supply and energy CIDs resides in the actuators of a water supply network, e.g., pumps, as they require energy provision. Multiple papers analyze the operation of these interconnected networks under scenarios of limited availability of either water or energy, including extreme events like power outages. In particular, Zuloaga et al. (2019) and Zuloaga and Vittal (2021) present the formulation of resilience metrics to evaluate the infrastructure ability to cope with these extreme events. Some papers also consider electricity prices and introduce economic criteria in the optimization problem (Li et al., 2018; Sui et al., 2021). In Rasheed and Rodriguez-Moreno (2021), the interconnection between water and energy networks is extended to food production by considering the energy-water-food nexus.

A specialized application is presented in Li et al. (2018) and Oikonomou and Parvania (2020), where the water supply network is leveraged to manage the operation of the energy network. This is facilitated by introducing flexibility in water supply network operations by controlling water treatment processes, pumping schedules, and water storage capabilities. Li et al. (2018) go one step further and apply this flexibility to maximize the use of renewable energy in water supply networks.

Most of the respective simulations have a temporal resolution of one hour, with only one special case (Abhyankar et al., 2020) having a very high resolution of 0.1 s and another one lacking this information (Li et al., 2021). Further, the time span of one day is analyzed as a common planning schedule for operators of water and energy networks in most papers.

Interestingly, all publications reviewed for this inter-domain include a hydraulic model for simulation of the water supply network, but only three make use of the common simulator EPANET. All other publications introduce their own mathematical formulation and hydraulic model. This might be needed for the integration with optimization modules calculating optimal power consumption or system availability. The majority of solvers used in the studies are distributed by the AMPL Optimization Inc.,[4] making AMPL the prevalent choice to formulate the numerical models for combined energy and water supply networks simulation and optimization. Another tool used by two of the papers for

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[4] A Mathematical Programming Language (AMPL): ampl.com.

Table 2
Feature table for all publications in the anthology. The publications are grouped according to the intersectoral dependencies and signified in the table by the subdivisions. The feature *target* is classified into *academic (A)* or *utility management (UM)*. Categories of feature *Spatial Scale* include household (H), municipality (M), city (C) and region (R). Features *Resolution* and *Duration* have units of second (S), hour (H), day (D), month (M) and year (Y). The symbol ● refers to a fulfilled characteristic, symbol ○ to an unfulfilled one. The symbol – indicates the information cannot be retrieved.

	General				Simulation Characteristics						
	Publication Year	Tool Name	Target	Availability	Simulation Software	Hydraulic Simulation	Hydrological Simulation	Spatial Scale	Resolution	Duration	Model
	Water supply × drainage										
Zhang et al. (2021)	2021	–	UM	○	EPANET2, SWMM	●	○	C	0.5H	1M	Benk, Xiuzhou
Rozos and Makropoulos (2013)	2013	UWOT	UM	●[a]	–	○	○	H-C-R	1M	100Y	Athens
Sitzenfrei et al. (2013)	2013	VIBe	A	○	EPANET2, SWMM	●	●	C	1H	50H	Innsbruck
	Water supply × energy										
Sui, Wei, Lin, and Li (2021)	2021	–	–	○	GUROBI	●	○	M	1H	1D	Mashhad, Iran
Zuloaga and Vittal (2021)	2021	–	UM	○	EPANET, PSLF	●	○	C	1H	1M	Unnamed
Li et al. (2021)	2021	–	A	○	YALMIP, GUROBI	●	○	C	–	–	Richmond
Rasheed and Rodriguez-Moreno (2021)	2021	–	–	○	CONOPT, CPLEX	●	○	M-R	1H	1D	Hanoi, Vietnam
Oikonomou and Parvania (2020)	2020	FlexPWF	UM	○	–	●	○	C	1H	1D	Unnamed
Abhyankar et al. (2020)	2020	DMNetwork	A	●[b]	NA	●	○	–	0.1S	–	Unnamed
Alhazmi, Dehghanian, Nazemi, and Mitolo (2020)	2020	–	UM	○	CPLEX	●	○	C-R	1H	1D	Unnamed
Zuloaga, Khatavkar, Mays, and Vittal (2019)	2019	–	UM	○	EPANET, PSLF	●	○	C-R	1H	1M	Unnamed
Li, Yu, Al-Sumaiti, and Turitsyn (2018)	2019	–	A	○	BONMIN, GUROBI	●	○	M-C-R	1H	1D	Unnamed
Khatavkar and Mays (2018)	2018	–	UM	○	EPANET	●	○	M-C-R	1H	26H	Unnamed
	Water supply × IT										
Bosco, Raspati, Tefera, Rishovd, and Ugarelli (2022)	2022	RISKNOUGHT	UM	○	EPANET	●	○	C	60S	1D	Unnamed
Mirzaie and Bushehrian (2022)	2022	–	A	○	EPANET2, WaterNetGen	●	○	C	30S	13H	Unnamed
Bhatia, Tomić, Fu, Breza, and Mccann (2021)	2021	–	A	○	Matlab, OMNeT++	●	○	M	1S	15000S	Unnamed
Nikolopoulos, Ostfeld, Salomons, and Makropoulos (2021)	2021	RISKNOUGHT	UM/A	○	WNTR	●	○	C	300S	1D	C-town
Nikolopoulos and Makropoulos (2022)	2021	RISKNOUGHT	UM	○	WNTR	●	○	C	300S	1D	C-town
Nikolopoulos and Makropoulos (2022)	2020	RISKNOUGHT	UM	○	WNTR, NetworkX	●	○	C	1S	2D	C-town
Taormina et al. (2019)	2019	epanetCPA	A	●[c]	EPANET	●	○	M			
Taormina, Galelli, Tippenhauer, Salomons, and Ostfeld (2017)	2017	epanetCPA	A	●[c]	EPANET	●	○	C	1H	7D	C-town
Suresh et al. (2014)	2014	CPWDSim	–	○	EPANET	●	○	C	1H	12H	Micropolis
	Drainage × mobility										
Knight, Hou, Bhaskar, and Chen (2021)	2021	–	A	○	PCSWMM, SUMO	●	●	R	0.25S	8H	Harvard Gulch
Hussain, Ahmed, and Ali (2018)	2018	–	A	○	PCSWMM, VISSIM, GIS	●	●	M	–	1H	Karachi

[a] https://uwmh.eu/products/86-uwot.html.
[b] https://www.mcs.anl.gov/petsc/dmnetwork.
[c] https://github.com/rtaormina/epanetCPA.

the modeling of the power distribution network is the Positive Sequence Load Flow software (PSLF) by GE.[5] There is no hydrological simulation in any of the papers, as hydrological processes are not inherently required in urban water supply networks.

The only paper that published code open source, Abhyankar et al. (2020), is also the only one that focuses on the generalizability of their proposed approach. The presented tool DMNetwork is packaged into the larger library of PETSc: Portable, Extensible Toolkit for Scientific Computation.[6] DMNetwork is built to establish multiphysics models and parallelize their execution. These models are constructed as networks, which can have multiple attributes for the main constituents, i.e., nodes and edges. One of the demonstrative examples showcases DMNetwork on combined water supply and energy networks (Abhyankar et al., 2020). The interconnection is not explicitly detailed, but merely a proxy to showcase the capabilities of the approach. Nevertheless, with this example, DMNetwork is a viable option for the simulation of coupled networks in any of the domains referred to in this paper.

4.3. *Water supply × IT*

This inter-domain comprises a similar amount of publications (n = 9) as for *water supply × energy*, mostly published after 2020 (n = 6). The main interconnection between water supply and IT is through CPSs that integrate physical processes with computing systems (Lee, 2008). Water supply networks can be monitored and controlled by IT systems through sensors, actuators, related programmable logic controllers, and supervisory control and data acquisition (SCADA) systems (Taormina et al., 2017). However, operating water supply networks as CPSs can expose infrastructure to cyber–physical attacks (Rasekh, Hassanzadeh, Mulchandani, Modi, & Banks, 2016). This indicates another interconnection between water supply and IT: using IT to simulate the impacts of cyber–physical attacks and to improve the resilience of water supply CPSs (Nikolopoulos & Makropoulos, 2022).

All coupled simulations of water supply and IT systems require hydraulic simulations of water supply networks. EPANET or its Python extension WNTR (Water Network Tool for Resilience; Klise, Bynum, Moriarty, and Murray (2017)) are frequently used for this purpose in the reviewed studies besides Matlab/Simulink[7] and NetworkX (Hagberg, Swart, & S. Chult, 2008). For IT infrastructure, Bhatia et al. (2021)

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[5] https://www.geenergyconsulting.com/practice-area/software-products/pslf.

[6] https://petsc.org.

[7] https://uk.mathworks.com/products/simulink.html.

use OMNeT++[8] to simulate communication networks, and Mirzaie and Bushehrian (2022) use Docker[9] to emulate networks with various computing architectures. All reviewed simulations have fine resolutions ranging from 1 s to 1 h, and relatively short duration (around 4 h to 1 week).

The first group of publications in this inter-domain focuses on building more efficient CPSs. In 2014, CPWDSim was proposed to continuously monitor water supply networks using mobile sensors (Suresh et al., 2014). The proposed method consists of three components. First, mobile sensors move in the pipes of a water supply network with the water flow and transmit data to static beacons outside of the pipes (communication component). This is followed by a computation component, where the beacons execute a global view algorithm to predict the paths of the sensors and broadcast this information to them. Lastly, valves and pumps are operated under a control system to ensure that sensors traveling with the water flows are well-distributed across the main pipes of the water supply network. CPWDSim retrieves simulation results from EPANET (e.g., water flow and velocity) to simulate sensor movements, and simulates communication with and among sensors and beacons. They implement a protocol that enables devices to communicate within a shared network.

Another example with a focus on communication protocols in wide-area CPSs is Bhatia et al. (2021). This work presents Ctrl-MAC, a Low-Power, Wide-Area network (LPWA) protocol, and its associated event-triggered controller. Coupled simulations of water supply and CPSs are run to evaluate the proposed protocol, with the physical water supply network simulated by MATLAB/Simulink and the communication network simulated using OMNeT++. Results show that for large-scale systems, Ctrl-MAC has a higher average packet delivery ratio and less average end-to-end delay compared to the state-of-the-art LPWA protocol LoRaWAN++.

Finally, Mirzaie and Bushehrian (2022) explore the impact of different computing architectures on fault detection capabilities in a synthetic water supply network. First, a water supply network consisting of a household-street-region structure with 54 nodes and 3 storage tanks is generated by WaterNetGen (Muranho, Ferreira, Sousa, Gomes, & Sá Marques, 2012). Next, a simulation based on Epanet 2 (Rossman, 2000) is executed in its basic configuration to collect pressure and water head data at nodes (representing household sensors). Nodes are then clustered with an algorithm named HyCARCE (Moshtaghi, Rajasegarar, Leckie, & Karunasekera, 2011). Similarly, simulations with various faulty events (e.g., pipe breaks) are executed for 13 h with a resolution of 30 s. The paper considers three computing architectures, which vary in how information is processed through various layers. To emulate the different architectures, the authors create a Docker testbed where nodes in the hierarchy are executed as containers. Simulation data at sensor nodes are transmitted to the upper nodes at the end of each 30-min window using the IoT protocol MQTT (Light, 2017). The authors detect faulty events by applying the Majority algorithm, which determines the weighted center of gravity parameters for all clusters and calculates the distances of these clusters to their center. Their results indicate that the proposed hierarchical architecture has a higher accuracy in fault identification and localization than the other architectures, because a hierarchical hierarchy can better emulate the physical hierarchy of a water supply network.

While the above-listed applications focus on building a more efficient CPS to monitor and control water supply systems, two tools, i.e., epanetCPA (Taormina et al., 2017) and RISKNOUGHT (Nikolopoulos et al., 2020), consider risks associated with water supply CPSs, such as cyber–physical attacks. EpanetCPA and RISKNOUGHT are considered pioneering tools to foster cyber security of urban water networks and are the basis for a second group of publications in this inter-domain.

EpanetCPA is an open-source Matlab toolbox. Building on EPANET, epanetCPA enables simulations of a range of attacks on water supply CPSs, including attacks on physical components (such as sensors and actuators), attacks on programmable logic controllers and SCADA systems, and attacks on connection links between different components (Taormina et al., 2019, 2017). EpanetCPA can be used to model the hydraulic response of a water supply network (e.g., tank water levels) to various cyber–physical attacks and assess their impact. Simulation results from Taormina et al. (2017) indicate that similar impacts can be induced by various cyber–physical attacks and that hydraulic responses of a water supply network are not only dependent on specific attacks, but also on system conditions (e.g., initial water levels or water demands at network nodes).

RISKNOUGHT is a Python-based stress-testing platform that enables simulations of physical processes within a water supply network via WNTR (Klise et al., 2017) and cyber components via NetworkX (Hagberg et al., 2008). Cyber layers of water supply networks are considered as a directed graph, with nodes and edges being components (e.g., sensors) and connections (wireless communication) of cyber layers, respectively. As a tool of low fidelity, RISKNOUGHT is suitable to simulate interactions between cyber layers and water supply networks, instead of representing detailed functionalities of network devices and control systems (Nikolopoulos et al., 2020).

In later work, RISKNOUGHT is extended with complex water quality simulation in various cyber and physical attack scenarios where control schemes can be implemented as contamination mitigation measures (Nikolopoulos & Makropoulos, 2022). RISKNOUGHT is also further employed to test the resilience of a water supply network against cyber–physical attacks when implementing different sensor placement schemes (Nikolopoulos et al., 2021). Similar to epanetCPA, the C-Town benchmark water supply network is used for testing and demonstration of RISKNOUGHT. A resilience assessment framework is proposed to evaluate the resilience and risk mitigation of water supply networks under cyber and physical contamination attacks.

As reported by Bosco et al. (2022), the EU-funded STOP-IT project[10] also integrates RISKNOUGHT into its Risk Analysis and Evaluation Toolkit (RAET) to support the operation and risk management of water supply network CPSs. Here, RISKNOUGHT is adopted for scenario planning and stress testing, which simulates the impacts of risk scenarios (e.g., pressure deficiency) on both the physical and cyber layers of a water supply network CPS. The RAET platform assesses different key performance indicators of the system and visualizes these results to report to the water utility. Within STOP-IT, the RAET platform has been applied to a selected part of a real case study and full-scale implementations are planned in the future.

Although some software used to conduct simulations in this inter-domain is open-source, none of the simulators developed or codes used to conduct simulations from the cited publications are accessible, except for epanetCPA (Taormina et al., 2019, 2017).

4.4. *Drainage × mobility*

The last reviewed inter-domain combines the CIDs of *drainage* and *mobility* and contains only two papers (Hussain et al., 2018; Knight et al., 2021). Both contributions are primarily targeting an academic audience. They both present a specific case study, showcasing joint simulations and highlighting the interconnections of drainage and mobility infrastructure systems. The primary difference resides in their objectives. Hussain et al. (2018) examines the impact of conventional urban drainage networks on traffic, while Knight et al. (2021) evaluates the impact of alternative systems such as green stormwater infrastructure on traffic performance.

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[8] https://omnetpp.org.

[9] https://docs.docker.com/desktop/install/windows-install/.

[10] https://stop-it-project.eu/.

Hussain et al. (2018) model and investigate drainage and mobility aspects of a section of a six-lane, two-way road in Karachi, Pakistan. The authors develop two models, one of the surface area and underlying sewer system with PCSWMM and another with VISSIM for the simulation of traffic. Both models are calibrated with real observations and measurements. The case study is analyzed for a recorded historic rain event from 2013. The two simulations are sequentially connected, where the PCSWMM simulation delivers the extent of ponding on the road which influences the simulation of vehicular traffic in the VISSIM simulation. However, physical interactions when driving in rainy conditions, e.g., the grip of the tire or the restriction of visibility, are not explicitly simulated.

Knight et al. (2021) investigate the performance of a simulated traffic system in the presence of roadway flooding caused by rainfall. Multiple scenarios are considered, taking into account the partial conversion of directly connected impervious area to green stormwater infrastructure (GSI). Using dual drainage modeling, the research aims to analyze the impact of GSI networks on roadway flooding and identify optimal design limits for GSI systems. The coupled simulation is performed with PCSWMM and SUMO (Simulation of Urban MObility), focusing on the case study area of Harvard Gulch in Denver (Colorado, USA). Compared to the previous study, this research has a larger spatial extent spanning an entire region, and operates with a longer simulated time span and a higher temporal resolution of 0.25 s. The findings reveal the effectiveness of GSI networks in mitigating roadway flooding.

As with many publications summarized in the previous inter-domains, there is no specific name for the combined models of drainage and mobility systems. In addition, while providing a detailed case study, there is no focus on leveraging the models for other practical use cases. Finally, no code or model resources are available for the two studies.

5. Coupled simulation of urban CIDs: Discussion and research agenda

In this discussion we synthesize the overarching commonalities, trends, opportunities, and challenges in the coupled simulation of urban CIDs. We then propose a future research agenda.

5.1. Ongoing trends and opportunities in coupled simulation of urban CIDs

This review reveals trends and shortcomings in the simulation of interconnections between *water supply*, *drainage*, and urban CIDs like *energy*, *mobility*, and *IT* systems. The diagram in Fig. 4 illustrates the intersectoral connections derived from the reviewed publications and provides a framework to facilitate analysis of interconnected urban CIDs. The first key insight from Fig. 4 confirms our previous observation (see Section 3 and Table 2): most coupled simulation efforts have so far prioritized investigations in the *water supply x energy* and *water supply x IT* inter-domains. The combined simulation of *water supply* and *drainage* networks is much less researched, followed by *drainage x mobility*.

A more detailed analysis of Fig. 4 also enables a synthesis of specific trends (T) beyond paper distribution across inter-domains:

(T1) nearly all coupled simulation efforts are unidirectional, i.e., they look at the impact of one CID on another CID hierarchically, but rarely consider bidirectional interactions.
(T2) current research almost exclusively considers interconnections between two CIDs, while only a few studies consider a third domain.
(T3) connections between the two water sub-domains, *water supply* and *drainage*, are less explored than intersectoral connections between the water cycle and the *energy*, *mobility*, or *IT* CIDs.

Regarding the unidirectional interconnections (T1), a clear-cut case is represented by the *water supply* × *IT* inter-domain. Here, the investigated scenarios are all unidirectional, where the operation of an IT system influences the water supply network intended as a CPS. The prevalent motif is the need for protection against cyber–physical attacks, necessitated by the progressing digitalization in the water domain. Similarly, the relationship between *water supply* and *energy* is primarily regarded with water supply at the core of simulations and energy grids only providing electricity for operations of actuators (e.g., pumps). The inverse relationship between water supply and energy domains is only regarded in two publications (Li et al., 2018; Oikonomou & Parvania, 2020), where the operation of the energy grid is optimized by leveraging flexibility in the operation of water supply networks.

Trend T1 is strongly related to T2 when considering the role of the IT domain. While the IT sector is pervasive across all other infrastructure systems with sensors and data communication, most studies implicitly or explicitly assume data communication operates under ideal conditions, thus they do not directly simulate the IT component of a CPS. For instance, while exploring the dependency of water supply on energy supply systems, Khatavkar and Mays (2018) and Oikonomou and Parvania (2020) assume that an IT architecture exists for the communication between water and energy supply systems and that the real-time data exchange is flawless and instantaneous. This leads to the coupled simulation of only two CIDs, without explicit representation of the IT sector. As pointed out by Bhatia et al. (2021), though, energy consumption and efficiency of the proposed communication scheme for a cyber–physical water distribution system should be further researched. This might also apply to other infrastructure sectors. UWOT (Rozos & Makropoulos, 2013), for instance, also integrates energy consumption aspects (e.g., energy consumption from water extraction) to model the urban water cycle (*water supply* × *drainage*), yet without simulations of any energy network.

Finally, T3 is rather unexpected, since the *water supply* × *drainage* connection is fairly intuitive. There exists research proposing integrated asset management of municipal infrastructure including water supply and drainage systems (Abu-Samra, Ahmed, & Amador, 2020). Yet simulation of such inherently connected systems have seemingly not been subject to a heightened research focus and could be explored in much more detail, leveraging the potential of detailed knowledge of end-use water demands (Steffelbauer, Hillebrand, & Blokker, 2022). This might be due to existing silos within the structure and operations of water utilities, which currently limits the possibility of intersectoral approaches with integrated models (Stewart et al., 2018).

Overall, the network of connections among different CIDs represented in Fig. 4 is an encouraging signal that research is being done in pursuit of more coordinated urban infrastructure. However, there are further aspects to consider in our review of the literature. First, the amount of publications that we found to jointly simulate two or more urban CIDs is much smaller than the amount of publications we retrieved with our initial paper search. Hence, there is a major part of the literature that does not address joint simulation of CIDs, even when valuing multi-sector interactions. Second, there is a strong imbalance in how much research effort is devoted to the different inter-domains. Third, the three trends T1–T3 indicate that some interconnections are not fully explored even in inter-domains where literature is already present.

Our findings on aspects related to software usability and development, however, open up two main opportunities (O) to foster more and better coordinated developments in the coupled simulation of urban CIDs, thus overcoming the above limitations:

(O1) availability of open-source software and open data.
(O2) development of standardized performance evaluation schemes.

Regarding O1, many software tools are available *open source* for simulation of individual urban infrastructure domains and are often

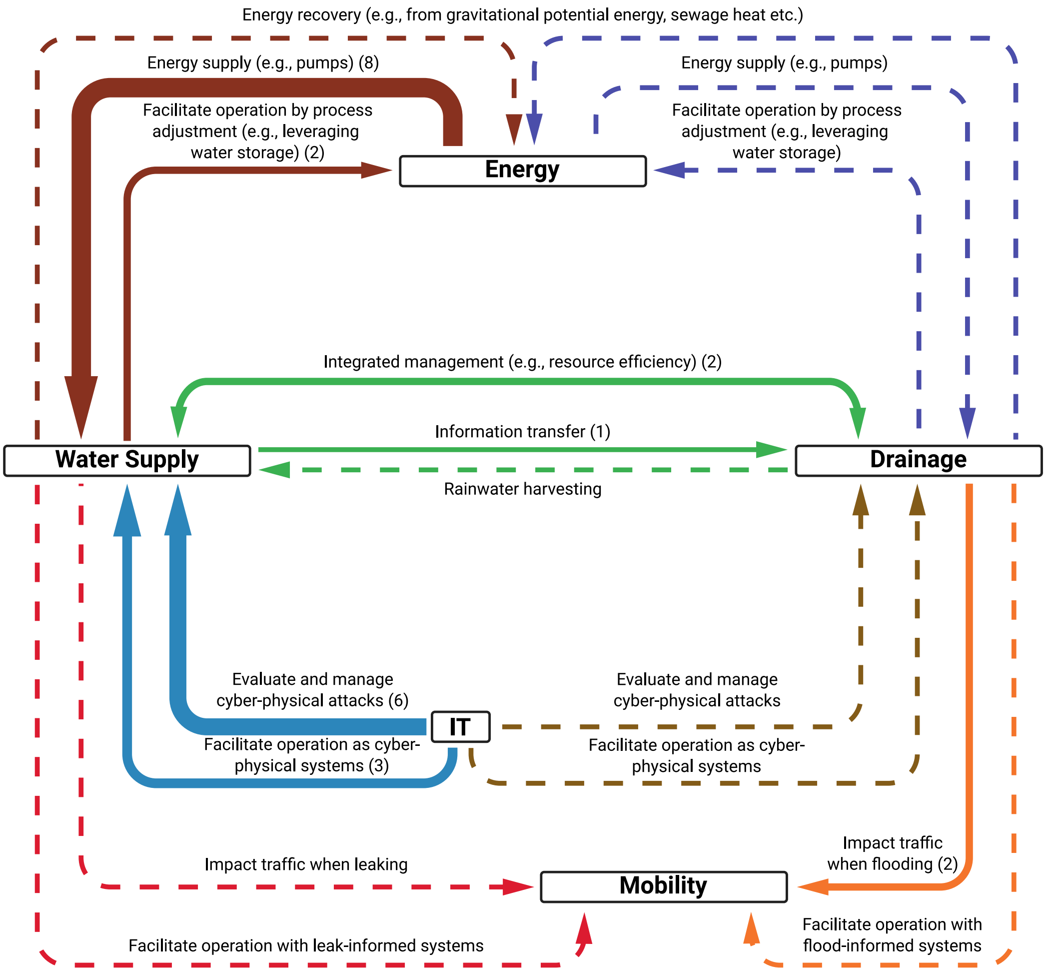

Fig. 4. Diagram of interconnections between different urban CIDs, as per data and trends extracted from the 24 reviewed papers. Solid lines illustrate the connections directly derived from the reviewed anthology, where the arrowhead indicates the direction of the interconnection. Text labels on solid lines describe the type/goal of the inter-domain connections. Solid line thickness and the numbers following each text label report the numbers of reviewed papers simulating an interconnection. The dashed lines are interconnections identified by the authors of this paper as part of the future research agenda, i.e., they are not derived from the anthology.

preferred over commercial alternatives in the literature. This is particularly apparent in the public sector, where lock-in effects from proprietary software and lack of interoperability is actively avoided. Water infrastructure simulation, for instance, is enabled by EPANET, its Python extension WNTR, and SWMM. These software tools are all open source (although they also have commercial derivatives, e.g., PC-SWMM) and are popular in the literature. Similarly, the open-source NetworkX and Docker are used to conduct cyber layer network analysis, communication network simulation, and computing hierarchy emulation. SUMO can be used as open-source software to simulate traffic systems. However, software availability for individual domains is not necessarily reflected in the availability of combined tools/frameworks for intersectoral coupled simulation. Only three tools for coupled simulations, namely UWOT (Rozos & Makropoulos, 2013), DMNetwork (Abhyankar et al., 2020), and epanetCPA (Taormina et al., 2019, 2017), are released open-source among those developed in the reviewed papers. The unavailability of developed simulators hinders the assessment, transferability, interoperability, and further development of such tools. Still, the availability of commonly used open-source alternatives for simulation of individual sectors offers an opportunity to focus future efforts towards integration rather than new development of domain-specific software. We also see the necessity to provide more open data across different critical infrastructure domains to support model development and coupled simulation of inter-domain interconnections, since most real-world case studies used in the reviewed publications are currently not available as open data.

The opportunity O2, i.e., the development of standardized performance evaluation schemes, is a requirement for enabling better coordinated inter-domain modeling. Different performance metrics are currently formulated for different simulation tools in the literature and often these tools are demonstrated in individual case studies with different challenges depending on local infrastructure and urban features, hampering a consistent assessment across domains and applications. However, even though the identified simulators are developed considering different inter-domains and performance metrics, they share similar overarching goals: to increase system efficiency and enhance system stability.

The first group of studies aims to identify scenarios with more efficient infrastructure operations in comparison to a “business as usual” case. Performance is measured by both non-monetary metrics (e.g., energy consumption) or related monetary criteria (e.g., energy costs). UWOT, for instance, is evaluated by comparing its simulation results with its counterpart Hydronomeas, a software applied by the Water Company of Athens (Rozos & Makropoulos, 2013). A similar approach can be found in *water supply* × *IT*. Suresh et al. (2014) compare their proposed communication setups with its counterpart T-Lohi to demonstrate the benefits of the proposed water supply network CPS with mobile sensors. Other examples are also reported in Alhazmi et al. (2020) and Sui et al. (2021), where performance is quantified in terms of operating costs due to shifting or decreases in energy consumption.

Another group of studies prioritizes performance assessment with metrics related to system stability under external disturbances. In the inter-domain *water supply* × *energy*, the resilience of water and energy supply systems with limited water and/or energy resources is assessed by Zuloaga et al. (2019), who present a comprehensive set of resilience metrics to evaluate the impacts of power outages and droughts on a combined *water supply* × *energy* system.

Disturbances such as cyber–physical attacks are the main motives for publications that simulate water distribution systems as CPSs (*water supply* × *IT*). Here, information about tank levels and unmet demands are the commonly assessed variables when evaluating impacts and risks of, as well as resilience against, cyber–physical attacks on water supply network CPSs. Taormina et al. (2017) additionally use relative variation in the pumps' power consumption between normal and attack conditions to evaluate cyber–physical attacks on pump operation. Nikolopoulos et al. (2020) alternatively consider the temporal–spatial variation of affected nodes after attacks occur. In the later publications that assess the impacts of cyber–physical attacks on water quality and detect and mitigate contamination, variables including contaminated nodes, contamination spread over time, and earliest detection time are additionally analyzed (Nikolopoulos & Makropoulos, 2022; Nikolopoulos et al., 2021).

Simulations in the inter-domain *water supply* × *drainage* have the same general goals, but the interplay is demonstrated primarily for normal operating conditions, hence there is no performance assessment of their resilience to external disturbances. Finally, heavy rainfall-induced flooding drives simulations of the interconnection between drainage and mobility systems. While simulating the impact of flooding on traffic systems, both Hussain et al. (2018) and Knight et al. (2021) compute and compare vehicle speed reduction. Apart from this, Hussain et al. (2018) use parameters including average time delay due to queue and queue length, which Knight et al. (2021) simplify as total travel time.

While more multi-faceted metrics are used in the reviewed publications, there is a commonality that, in general, the concepts of efficiency and resilience are pursued. This commonality opens opportunities for the development of standardized quantifiable performance metrics that would, in turn, enable comparative studies. Besides evaluating simulators from a model performance angle (e.g., model accuracy and computational requirements), a comprehensive and consistent set of Key Performance Indicators (KPIs) would allow quantifying the potential of simulated solutions for climate change mitigation and infrastructure resilience in our cities (Talwar et al., 2023), thus enhancing support for improved planning and monitoring of infrastructure investments (Jeuland et al., 2023).

5.2. Future research agenda

A number of links between several inter-domains remain currently unexplored or only weakly analyzed in the framework diagram in Fig. 4. Based on this diagram, we define a future research agenda in different inter-domains.

Water × *IT*. Although the interconnection between *water supply* and *IT* is already explored in several publications, there is still a lack of coupled simulations. Publications such as the works of Hu et al. (2021), Parks and VanBriesen (2009) and Zhao et al. (2016) propose algorithms for setting up sensor networks and usage of sensor data to detect anomalies in water supply networks. However, they do not provide simulations as evidence. Overall, no publication is found to simulate the impact of sensor network architecture and different communication protocols on anomaly detection. A major challenge for implementing such a simulation architecture is the different time scales of water supply and IT simulations. Sensor readings in water supply networks are commonly only needed in a resolution of less than minutes. Additionally, the amount of collected data is rather sparse, since distributed sensors in a city-wide water supply network are still expensive and budget needs to be allocated for initial deployment and maintenance (Stewart et al., 2018). Current research in communication technologies, on the other hand, is focused more on the reliability of high-frequency data transmission, maximizing throughput while minimizing latency. Therefore, future research across these two CIDs should prioritize reconciling the existing mismatch between the time scales and frequencies of the two individual domains. Already existing technical solutions operating with different time scales at a low level of abstraction could support this task (Beilharz et al., 2021).

The scenarios investigated for the *water supply* × *IT* are also applicable to *drainage* × *IT* since drainage networks can be operated as CPSs as well and modeled with digital twins (Pedersen, Borup, Brink-Kjær, Christiansen, & Mikkelsen, 2021). Furthermore, the CPSs of wastewater collection and treatment facilities can also be subject to cyber attacks. Future research can thus target knowledge transfer between water supply and drainage networks for better exploration of inter-domain connections.

Water × *energy*. Water, stormwater, and wastewater within water supply and drainage networks contain a significant amount of gravitational potential or kinetic energy depending on their elevation and flow rate (Boroomandnia, Rismanchi, & Wu, 2022). Recent studies evaluate the feasibility of recovering or harvesting energy from water supply or drainage networks (Boroomandnia et al., 2022; Chen et al., 2018; Dannier et al., 2015; Kostner et al., 2023). However, these publications lack comprehensive inter-domain simulations on a network scale. Although such papers are excluded during our standardized systematic screening, their indication of sector interconnection should be noted and can be further explored on a network scale.

There is a relatively unbalanced distribution of interconnection research on inter-domains that entail water supply and drainage networks. Many more simulations are identified for inter-domains that include water supply than those that include drainage networks. The connections between water supply and energy systems are similarly applicable to drainage networks, though: pumps within drainage networks need energy to operate and there is potential flexibility in the operation of such systems, e.g., treatment facilities (Zohrabian et al., 2021). In addition, heat energy contained in sewage within the drainage system can be recovered and used to cool or heat buildings (Zhuang et al., 2023) - simulation of this kind on a network scale is yet still missing.

Water × *mobility*. In general, both water supply and drainage domains lack research on their interdependency with the mobility domain and demand further research. As some prior works on *drainage* × *mobility* have addressed, a large number of cities globally with less developed drainage systems and high precipitation suffer from significantly reduced transport flows from flooding and hence negative macroeconomic impact (Bhuiyan, Hasan, Reza, & Pereira, 2018; Evans et al., 2020). The less researched connection of *water supply* × *mobility* is also subject to similar interdependencies. One exemplary scenario is the disturbance of traffic due to leakages and subsequent maintenance work on and nearby roads. Geographical proximity of water supply and mobility systems or urban drainage and mobility systems means that failures in any of the urban water systems can impact the structural integrity and functionality of the mobility system. As information becomes more readily accessible from various sources like smart sensors and vehicular communication systems, data in each domain is likely to include information from other domains. We expect that the most profound interconnection between water supply and mobility systems or urban drainage and mobility systems is characterized by information transfer from water system anomalies to the traffic sector. In particular, advances in vehicular communication technologies could motivate research to develop applications to improve traffic safety or efficiency by assessing real-time events in water systems. Future research in this inter-domain should thus prioritize the formulation and identification of relevant interconnections, along with their potential impacts. Incentives for strategically implementing green infrastructure assets or similar measures to reduce incidents in stormwater flooding-prone areas can motivate research on joint benefits to the mobility sector (Knight et al., 2021).

An additional connection between the two domains originates from the underlying infrastructures. Surface sealing of roads and exhaust emissions from vehicles within mobility networks majorly contribute to the increasing urban heat island effect and worsening air quality. Blue–Green Infrastructure measures from the water domains have proved to mitigate these impacts, presenting another opportunity for inter-domain benefits (Back, Bach, Jasper-Tönnies, Rauch, & Kleidorfer, 2021; Hami, Abdi, Zarehaghi, & Maulan, 2019; Li et al., 2023; Yang et al., 2020; Zhuang & Zhongming, 2021).

Water supply × drainage. Rainwater harvesting systems, such as rain barrels retain stormwater and mitigate flooding and combined sewer overflow. The harvested rainwater can subsequently be used as domestic water, e.g., for irrigation, which reduces water demand from water supply networks. This builds up another interconnection between *water supply* and *drainage*. Although such systems have been implemented and simulated worldwide (Ali & Sang, 2023; Nachson et al., 2022; Sepehri, Malekinezhad, Ilderomi, Talebi, & Hosseini, 2018), current research is focused on scales smaller than networks, e.g., buildings. Simulating such interconnections at network scale will be an interesting avenue for future research.

Multi-sector interconnections. Finally, the exploration of interconnections among more than two CIDs has only been covered to a limited extent in the reviewed publications. Future research should include explorative studies leveraging multi-sector dependencies, trade-offs, and cascading effects.

As previously discussed, rainwater harvesting systems are mostly studied on small scales. In the work of Oberascher et al. (2021), exceptionally, smart rain barrels are deployed on a municipality scale. The rain barrels are equipped with Long Range Wide Area Network (LoRaWan) antennas that transmit measurements and control commands powered by a solar panel and a battery. Although this or other similar publications are not retrieved during our keyword-based literature search, we would like to point out the interconnection established by rainwater harvesting systems and suggest that simulation of such systems can be prioritized in future research to develop adaptive management solutions for urban water systems under future climate scenarios.

Additionally, current research is primarily conducted assuming ideal operation in the other CIDs, as discussed in Section 5.1. To build up the resilience of the urban water systems and encourage the implementation of such simulation tools in practice, such simulation should be extended and multi-sector dynamics need to be considered. Among the sectors, the interconnection between urban water systems and IT networks should be especially studied, since digitalized water systems are crucial to jointly manage the urban water systems with other CIDs. This will also speed up digitalization in the urban water sector (Daniel et al., 2023; Oberascher, Rauch, & Sitzenfrei, 2022).

In the reviewed anthology, one publication and corresponding tool stand out in this regard: DMNet (Abhyankar et al., 2020). As introduced in Section 4.2, this tool is presented as a general solution to modeling network structures. It provides approaches to connect multiple networks with different characteristics, therefore, enabling the simulation of interconnected domains and systems. Its exemplary application of a water supply and energy network could be further developed to be coupled with other CIDs in the future.

6. Conclusion

In recent years, research on the interconnections and multi-sector dependencies among critical urban infrastructure systems has gained interest, motivated by the compelling need for adaptive planning and management strategies to deal with changing climate and urbanization. In this study we comprehensively review 24 peer-reviewed publications, selected after screening a larger set of 222 publications, to identify trends, modeling frameworks, simulation software, and research gaps in coupled simulations of urban critical infrastructure systems. Our review analyzes literature on the interconnections between water supply and drainage networks and their interlinks with energy grids, mobility networks, and IT infrastructure systems.

Our review acknowledges that, while a rich body of literature identifies and conceptualizes interconnections among different urban infrastructure systems, only a limited fraction of the available studies develop coupled simulation tools. Nearly all coupled simulation efforts (i) limit their scope to a maximum of two infrastructure sectors and (ii) do not consider the bidirectional interaction between two sectors, but rather investigate the impact of one specific sector on the other. Moreover, while belonging to the same domain of *water*, connections between water supply and drainage networks are simulated only to a limited extent.

We argue that a future research agenda on coupled simulation of interconnected urban infrastructure systems should focus on the following four priorities:

(i) Overcoming disparities in spatio-temporal scales and resolutions is a crucial challenge in simulating diverse domains. Infrastructure networks are currently in the process of adapting to contemporary challenges, such as climate change, compelling operators to collaboratively address the entirety of the water cycle — encompassing processes from groundwater formation to wastewater reuse. This undertaking involves navigating significantly extended adaptive pathways and stakeholder groups, reflecting the intricate interplay between various components of the complete water cycle.

Consequently, (ii) facilitating knowledge transfer from similar domains and identifying co-benefits from joint operations become imperative for the adaptive management of urban infrastructure systems. This includes the identification and quantification of overarching climate change mitigation Key Performance Indicators (KPIs) to provide evidence for urban retrofitting schemes, thus ensuring informed decision-making and sustainable development.

(iii) Upscaling small-scale demonstrative concepts to urban, network-scale simulations. Pilot projects play a crucial role in the assessment of innovative digital solutions, serving as initial testing grounds. Nonetheless, the common challenge of failed upscaling to large-scale implementation, often referred to as the "death-by-pilot" phenomenon, underscores the need for an enhanced evidence base. Leveraging network-scale simulations and meticulously simulating the evolutionary transitions between pilot and full-scale operations emerge as imperative measures. By embracing these advanced simulation techniques, researchers and practitioners can gain valuable insights into the potential challenges and fine-tune scalability strategies.

(iv) Fostering exploration of multi-sector interconnections, beyond bilateral investigations. The task of overcoming siloed operations is indispensable for reaping the full advantages of multi-sector approaches. Providing simulations to analyze the respective benefits and interdependencies between each sector serves as a compelling means to build convincing evidence and business cases.

The current available open-source software for the simulation of individual infrastructure domains and the overall common intent towards efficiency and resilience can facilitate coordinated research efforts to meet this research agenda and break sector-specific silos, thus enabling better knowledge transfer and comparisons across domains.

CRediT authorship contribution statement

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Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing, Project administration, Investigation. **Philipp Wiesner:** Data curation, Formal analysis, Methodology, Writing – review & editing, Investigation, Writing – original draft. **Dóra Hegyi:** Formal analysis, Methodology, Visualization, Investigation, Writing – original draft. **Muzaffer Citir:** Formal analysis, Methodology, Writing – review & editing, Investigation, Writing – original draft. **Margaux Huth:** Formal analysis, Methodology, Investigation, Writing – original draft. **Sangyoung Park:** Methodology, Writing – review & editing, Funding acquisition, Resources, Supervision. **Jochen Rabe:** Writing – review & editing, Funding acquisition, Resources, Supervision. **Lauritz Thamsen:** Writing – review & editing, Funding acquisition, Methodology, Resources, Supervision. **Franz Tscheikner-Gratl:** Conceptualization, Methodology, Writing – review & editing. **Andrea Castelletti:** Supervision, Writing – review & editing. **Paul Uwe Thamsen:** Supervision, Funding acquisition, Resources. **Andrea Cominola:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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