

**URBAN WATER DISTRIBUTION INDUSTRY THROUGH THE LENS OF AN
OPC UA INFORMATION MODEL**

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Abstract

Urban water distribution systems has a diverse and geographically distributed set of physical and logical assets. These are typically sourced from multiple vendors and integrated over long operational lifecycles. Traditional supervisory control and data acquisition (SCADA) systems often represent such infrastructure using flat, vendor-specific data models. The main limitations of traditional SCADA was interoperability, scalability, and long-term maintainability. This paper examines the urban water distribution industry through the lens of an OPC UA information model. The paper also emphasizes on information-centric representation over device- or protocol-centric integration.

The proposed approach models core water distribution assets like reservoirs, pumping systems, sensors, control devices, and logical operational entities like using standardized OPC UA ObjectTypes and semantic relationships. By abstracting assets based on their functional roles within the distribution process, the information model provides a unified and vendor-independent view of different field equipment. This enables supervisory and cloud-hosted SCADA systems to interact with urban water infrastructure without dependence on vendor-specific implementations or communication protocols.

The study demonstrates how OPC UA information modeling supports semantic interoperability and extensibility in multi-vendor environments. The findings indicate that vendor independence in urban water distribution is most effectively achieved at the information layer. The proposed model serves as a foundational framework for cloud-based monitoring, advanced analytics, and future smart water applications, at the same time it remains compatible with legacy infrastructure.

Keywords Urban Water Distribution, OPC UA, Information Modeling, Industrial IoT, SCADA, Semantic Interoperability, Cloud-based Monitoring

1. Introduction

Urban water distribution systems is an essential part of modern city infrastructure. Different components of this system are complex network of water sources, storage

facilities, pumping stations, pipelines, sensors, and control systems distributed across wide geographic areas. These systems typically composed of verity of equipment procured from multiple vendors at different points in time. As cities grow, managing water becomes more challenging. To handle this, water industry increasingly use data monitoring systems. These systems help ensure reliable and efficient service to meet regulatory requirements.

Water industry infrastructure is largely device-centric and vendor-dependent. Conventional SCADA systems commonly represent field assets as flat collections of tags. These tags are derived from proprietary device. Although these tags enable basic monitoring and control, but they doesn't provide semantic context about asset roles, relationships, and operational intent. As a result, when system complexity increases, scalability, and extensibility degrades, particularly in multi-vendor and multi-site deployments.

More widely, cloud-based SCADA systems and centralized analytics are being used in industry. However, traditional tag-based integration has many limitations in cloud environments. Cloud systems need data that is well structured, easy to understand, and consistent to support flexible setup, monitoring across multiple sites, and advanced analysis. Many water distribution systems do not have a common information model which will bring data from different field devices together in a clear, vendor-neutral way.

OPC UA offers a standardized framework for information modeling. Information model enables data exchange which includes semantic description. OPC UA information model supports an object oriented approach which enables to manage relationships among assets [1]. OPC UA define system components as structured information objects. This enables a shift from protocol-centric integration to information-centric system design. This paper examines the urban water distribution industry through the lens of an OPC UA information model, exploring how such a perspective can provide a unified semantic view of physical and logical assets while considering verity of field infrastructures.

This study focuses on the lack of a common and well-defined information model for urban water distribution systems. Current systems are often developed for specific vendors so are not suitable for cloud-based monitoring applications. As a result, it is difficult to use them in modern cloud environments. This paper also studies how water distribution assets can be modeled using OPC UA ObjectTypes and standard relationships. This will help to improve interoperability, scalability, and long-term maintenance.

2. Background and Motivation

2.1 Challenges in Urban Water Distribution Systems

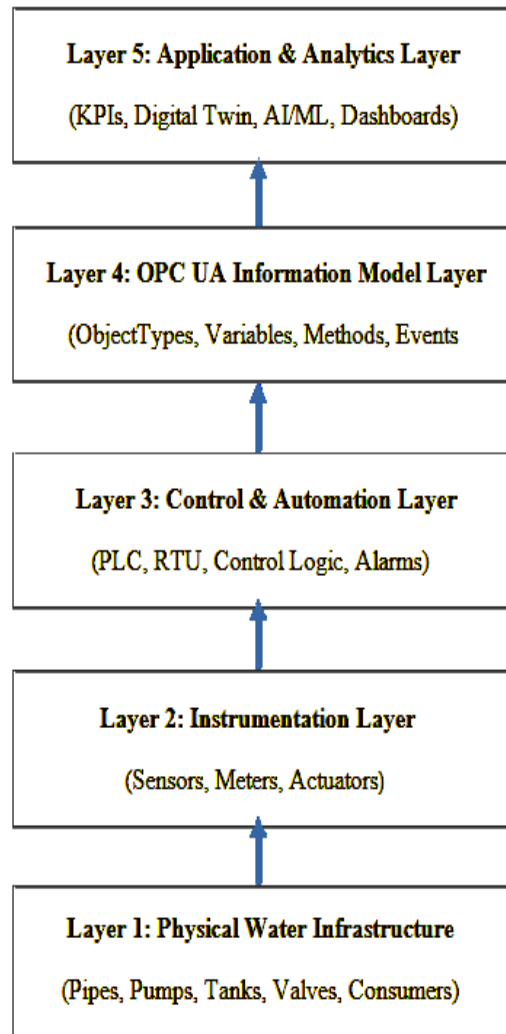
Urban water distribution systems usually have assets that last for many years. They are upgraded gradually over time and use equipment from multiple vendors. Sensors, pumps, and control units are often purchased at different times from different manufacturers. This leads to many different protocols and data formats. Because of this, a lot of customization and protocol conversion required to bring the data to system.

Moreover, conventional SCADA systems primarily focus on signal-level data exchange, so it provides limited semantic context. For example, a value representing water level may not be able give information about the reservoir type, measurement unit, or operational constraints. This lack of semantic richness complicates advanced applications such as predictive maintenance, cross-site comparison, and automated reasoning.

2.2 OPC UA as a Semantic Integration Framework

OPC UA provides an object-oriented information modeling framework. It enables to define ObjectTypes, Variables, Properties, Methods, and References. OPC UA also supports services for discovery, subscription, historical access, and alarms, real-time control and higher-level analytics.

The motivation for adopting OPC UA in urban water distribution lies in its ability to act as a unifying semantic layer. By modeling physical water infrastructure components as OPC UA objects with well-defined relationships, it becomes possible to integrate heterogeneous devices into a coherent, cloud-ready architecture.



High-Level Framework Layer Diagram

3. Urban Water Distribution System: Physical Infrastructure Overview

Urban water distribution systems has large-scale cyber–physical infrastructures which includes diverse mechanical, electrical, and digital components operating in a coordinated manner. These systems are responsible for sourcing, storing, treating, and distributing water across urban zones. From an information modeling perspective, the accurate identification and abstraction of physical components is essential. This will be helpful to achieve semantic consistency and interoperability within a cloud-based OPC UA architecture [2]

3.1 Core Water Storage Infrastructure

Water storage in urban distribution systems is primarily achieved through **ground water reservoirs** and **tank-based reservoirs**. Ground water reservoirs typically include borewells or tube wells. These reservoirs are highly dependent on seasonal recharge. So they have fluctuating water levels. In contrast, tank-based reservoirs—such as overhead tanks, elevated service reservoirs, and ground-level storage tanks—act as intermediate storage units.

Tank reservoirs are equipped with various mechanical accessories like inlet and outlet pipelines, manual and motorized isolation valves, overflow arrangements, drain valves, and vent pipes. These accessories ensure safe operation, facilitate maintenance, and prevent structural or hydraulic failures. From an information modeling aspect, such accessories are critical components. So they must be represented as distinct but related entities within an OPC UA information model.[3]

3.2 Pumping Systems and Drive Mechanisms

Pumping systems form the backbone of urban water distribution. This enables water movement from sources to storage and storage to distribution zones. Multiple types of pumps are deployed depending on hydraulic requirements, elevation differences, and flow demands.

Centrifugal pumps are the most commonly used pumps for water transfer and distribution. These are simple and efficient in handling large flow volumes. **Submersible pumps**, typically used in ground water extraction. They are installed directly within borewells and are designed to operate under submerged conditions. **Booster pumps** are deployed within distribution networks to maintain adequate pressure in distant or elevated zones. **High-lift pumps** are used to transport water over significant elevation differences, particularly from ground reservoirs to overhead tanks.

Each pump is mechanically coupled with an electric motor, which may be an induction motor or synchronous motor depending on efficiency and control requirements. To optimize energy consumption and regulate flow dynamically, **Variable Frequency Drives (VFDs)** are commonly employed. VFDs allow precise control of motor speed based on demand, reducing mechanical stress and improving system efficiency. Supporting electrical components include motor starters, protection relays, and control panels.

3.3 Electrical Power and Backup Systems

Electrical power is very important for continuous operation of water distribution systems. Pumping stations and control rooms are typically supplied through the main power grid. It is also supported by backup systems to handle outages and load fluctuations. Uninterruptible Power Supply (UPS) systems are used to ensure

uninterrupted operation of critical control equipment such as PLCs, RTUs, communication gateways, and monitoring instruments. In addition, diesel generators or solar power systems may be integrated to support prolonged power failures.

Energy meters are used to monitor electrical consumption, voltage stability, and load characteristics. These measurements are needed for energy optimization and cost management in large-scale water distribution networks.

3.4 Sensors and Monitoring Instruments

Sensors are main component of primary data acquisition layer of urban water distribution systems. They provide real-time data about hydraulic, mechanical, and quality-related parameters. Commonly used sensors are **water level sensors, flow meters and pressure meters**. Water level sensor can be ultrasonic, pressure-based, or radar based sensor. This sensor measures storage levels in reservoirs and tanks. **Flow meters**, such as electromagnetic or ultrasonic flow meters, are used to measures water transfer rates across pipelines. **Pressure sensors** monitor pipeline and pump pressures. This helps in leak detection and pressure regulation.

Now a days, water quality monitoring instruments are also used in modern water systems. These include **pH sensors, turbidity sensors, temperature sensors, and residual chlorine analysers**. These sensors generate time-dependent data that must be accompanied by context such as units of measurement, calibration settings, and location metadata. This makes them strong candidates for semantic modeling using OPC UA Variables.

3.5 Field-Level Control and Automation Devices

Programmable Logic Controllers (PLCs) and Remote Terminal Units (RTUs) mainly are used at the operational level. PLC and RTU are used to handle control and automation. PLCs are used in pumping stations and treatment plants. They are used for fast response times and reliable control logic. RTU are the smart devices which are mainly used to gather the data from remote reservoir, pipeline junctions and valves. Usually reservoir, pipelines and valves are spread over large and distanced geographical places. At such places, an efficient and low power communication device is needed. RTU are best suitable for this situation.

PLCs and RTUs communicates directly with sensors, actuators, motors, and valves. They run control logic and handle local interlocking. These devices also generate alarms when predefined limits are exceeded. In many modern systems, these devices work as OPC UA servers or connect through OPC UA gateways. OPC UA allows to share the data in standardized way. [4]

3.6 Smart Sensors and IoT Gateways

The smart water network requires smart sensors with processing capabilities and communication capability. These smart sensors data processing at local level, finding and fixing problem. These sensor should also support OPC UA, MQTT, or REST-based communication.

IoT gateways acts as mediator between field devices and cloud-based SCADA system. IoT gateways collects data from different sources on different protocols like Modbus, HART, or any proprietary fieldbus. This data is then sent to OPC UA interfaces. From an information modeling angle, IoT gateways works as OPC UA server. IoT gateways just not pass the data but also organizes the data in a meaningful way.

3.7 Valves and Tank Accessories

Valves are very important part of water system. Valves controls flow of water and also helps to isolate the zones. Gate valves, butterfly valves, check valves, pressure reducing valves and motorized control valves are commonly use in the system. Motorized control valves may have actuators and position feedback sensors. This helps to monitor remote operation through SCADA.

Tank accessories includes overflow sensors, hatch sensors gives additional operational information. These are very important component so it must be included in OPC UA information model.

3.8 Implications for OPC UA Information Modeling

Due to verity of machines and devices which are used in urban water distribution system, it has now become necessary to have structured information model. OPC UA provides an extensible information model approach. OPC UA provides the necessary abstractions to represent pumps, motors, sensors, controllers, and accessories as interoperable objects with well-defined semantics. By capturing not only real-time values but also contextual metadata and relationships, the information model enables cloud-based SCADA systems to achieve a holistic and vendor-independent view of the entire water distribution infrastructure.

4. OPC UA Information Modeling Approach

This paper uses OPC Unified Architecture (OPC -UA) based information modeling approach to represent different component of urban water distribution system. OPC UA provides an object-oriented and service-oriented framework that enables the structured representation of various industrial assets as well as related data and their relationships. The conventional SCADA data model usually represents flat data.

The information model represents physical components such as reservoir, pumps, tanks, valves, sensors, controllers and power systems into reusable OPC UA

ObjectTypes. Each ObjectType encapsulates variables, properties and contextual metadata. This allows uniform representation of devices from different vendors with same functionality. This abstraction supports interoperability in multi-vendor situation and also facilitates seamless integration with cloud-hosted supervisory system.

This model supports reusability as it uses the concept of hierarchical inheritance. A base ObjectType defines common attributes which are applicable to all water distribution assets. Specialized ObjectTypes are derived from the base type. The specialized ObjectType represents domain-specific asset such as ground water reservoir and tank based storage units. Although specialized type share common structural elements, they may also use additional variables and properties to reflect unique operational characteristics. This way, specialized ObjectType maintain both generality and speciality within the model.

The key aspect of the proposed modeling approach is semantic enrichment [5]. Measurement data may have engineering units, data quality indicators and operational states. This added context ensures that application can clearly and correctly interpret the data. OPC UA reference types are used to model structural and functional relationships among assets. For example, Pumps are linked to associated motors, derives and sensors using composition relationship.

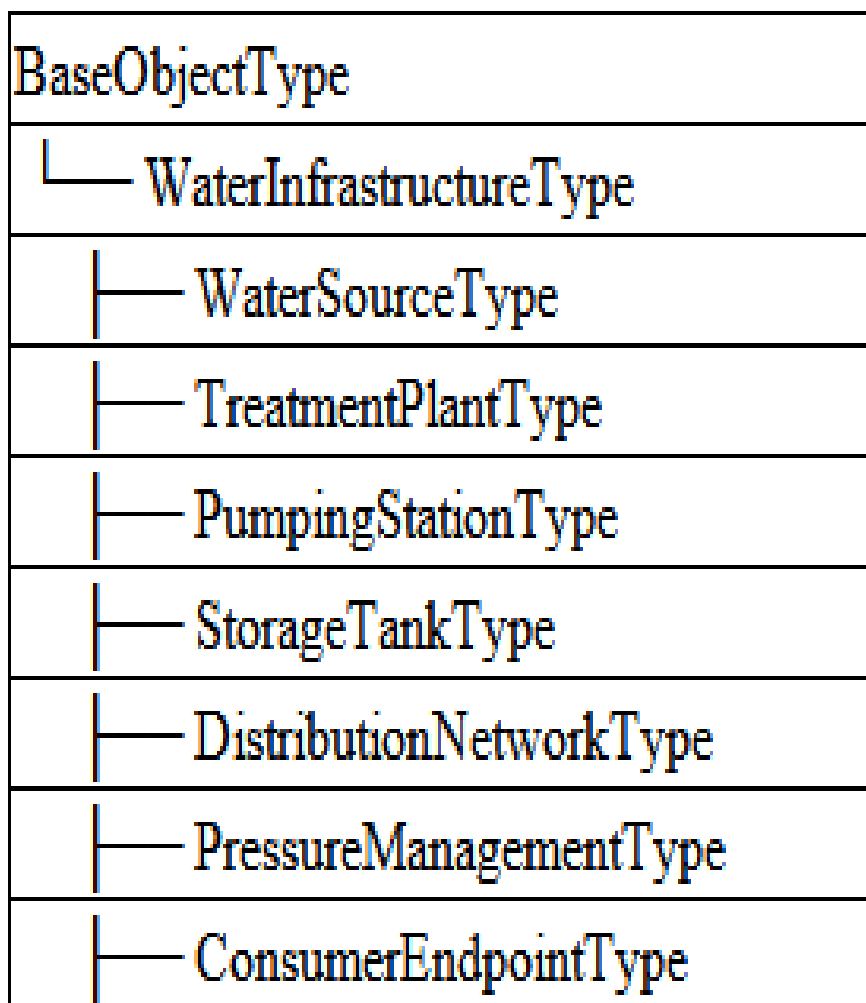
The information model can be designed to support cloud-based SCADA. SCADA can be hosted on a private cloud infrastructure [6]. Standard OPC UA supports services like discovery, data subscription and historical data access. This services helps to discover assets, real time monitoring, and analysis of data gathered from distributed sites. By exposing semantically structured objects rather than raw data points, the model enhances scalability and simplifies supervisory system configuration in large urban water networks.[7]

Interoperability and long-term adaptability are central considerations in the modeling design. The model avoids dependency on specific field protocols or controller platforms and instead encapsulates field-level diversity—such as PLCs, RTUs, smart sensors, and IoT gateways—within the OPC UA abstraction layer. This design enables legacy automation systems and modern IIoT devices to coexist within a unified semantic framework.

Overall, the proposed OPC UA information modeling approach provides a systematic foundation for integrating physical water distribution infrastructure with cloud-based supervisory systems. By aligning heterogeneous assets under a common semantic model, the approach facilitates interoperable monitoring, control, and future extensions toward advanced applications such as digital twins and data-driven optimization of urban water distribution systems.

4.1 Information Modeling Strategy

To represent the heterogeneous physical infrastructure of urban water distribution systems, the OPC UA information model follows an **asset-centric, hierarchical modeling strategy**. All physical entities are abstracted as OPC UA ObjectTypes derived from a common base type, ensuring semantic consistency, reusability, and vendor neutrality. The model explicitly separates **physical assets, monitoring variables, control interfaces, and metadata properties [8]**, enabling structured access for cloud-based SCADA systems.



BaseObjectType					
WaterInfrastructureType					
WaterSourceType	Variables	SourceID	String	Unique identifier	
		SourceType	Enum	River / Borewell / Reservoir	
		AvailableFlowRate	Double (m ³ /s)	Real-time capacity	
		WaterLevel	Double (m)	Source depth	
		Turbidity	Double (NTU)	Water quality	
		pH	Double	Chemical property	
	Properties	Temperature	Double (°C)	Environmental context	
		MaxExtractionLimit			
	Events	EnvironmentalClearanceLevel			
		LowWaterLevelEvent			
PumpingStationType	Variables	ContaminationDetectedEvent			
		StationStatus	Enumeration	Overall operating state	
		InletPressure	Double	Suction header pressure	
		OutletPressure	Double	Discharge header pressure	
		TotalFlowRate	Double	Total discharge flow	
		EnergyConsumption	Double	Total energy consumed	
	Method	SpecificEnergy	Double	Energy per cubic meter	
		StartStation()	Method	Start pumping station	
	StorageTankType	Variable	StopStation()	Method	Stop pumping station
			TankID	String	Unique identifier of storage tank
Capacity			Double	Maximum storage capacity (m ³)	
CurrentVolume			Double	Current stored water volume	
FillLevel			Double	Water level in meters	
LevelPercentage			Double	Tank fill percentage	
Method		Status	Enum	Normal / Filling / Draining / Isolated	
		EnableTank()	Void	Enable tank operation	
Event		DisableTank()	Void	Disable tank operation	
		TankOverflowEvent	EventType	Tank overflow detected	
DistributionNetworkType	Variable	TankEmptyEvent	EventType	Tank empty condition	
		NetworkID	String	Unique identifier of distribution network	
		TotalLength	Double	Total pipeline length (km)	
		AveragePressure	Double	Average network pressure	
		NetworkStatus	Enum	Normal / LeakSuspected / Isolated	
		NonRevenueWaterIndex	Double	NRW performance indicator	
	Method	IsolateNetwork()	Void	Isolate network section	
		RestoreNetwork()	Void	Restore network operation	
	Event	NetworkFailureEvent	EventType	Major network failure	
		PMU_ID	String	Unique identifier for pressure management unit	
PressureManagementType	Variable	TargetPressure	Double	Desired downstream pressure (bar)	
		ActualPressure	Double	Measured downstream pressure (bar)	
		OperatingMode	Enum	Manual / Auto / Remote	
		PressureDeviation	Double	Difference between target and actual pressure	
		EnablePressureControl()	Void	Enable pressure management	
	Method	DisablePressureControl()	Void	Disable pressure management	
		PressureViolationEvent	EventType	Pressure outside limits	
	ConsumerEndpointType	Variable	ConsumerID	String	Unique consumer identifier
			ConsumerType	Enum	Domestic / Commercial / Industrial
			ConnectionStatus	Enum	Active / Disconnected
ServiceStatus			Enum	Normal / Restricted / Suspended	
Location			String	Geographical or zone location	
Method		ActivateConnection()	Void	Activate consumer connection	
		DeactivateConnection()	Void	Deactivate consumer connection	
Event		UnauthorizedUsageEvent	EventType	Illegal usage detected	

5. Observations and Discussion: Urban Water Distribution Through an OPC UA Information Model Lens

Viewing the urban water distribution industry through the lens of an OPC UA information model reveals a fundamental shift in how infrastructure, operations, and interoperability are conceptualized. Rather than treating water distribution systems as collections of devices and communication endpoints, the OPC UA paradigm enables the system to be understood as a structured network of semantically defined assets and relationships. This perspective emphasizes *what an asset represents and how it behaves within the water distribution process*, rather than *who manufactured it or how it communicates*. [9]

When modeled using OPC UA ObjectTypes, core elements of the urban water distribution domain—such as reservoirs, pumps, pipelines, sensors, and control devices—are represented as standardized, reusable abstractions. Each asset is described in terms of its operational role, state variables, and contextual relationships to other assets. This modeling approach exposes the logical and functional structure of the water distribution system, allowing supervisory applications to interpret system behavior in a consistent and meaningful manner. From this viewpoint, the physical heterogeneity of field equipment becomes secondary to the semantic coherence of the overall system.

A significant observation from this study is that vendor independence emerges naturally when urban water infrastructure is modeled at the information level rather than at the protocol or device level. In traditional SCADA systems, vendor-specific tag naming conventions, register mappings, and proprietary data structures often define how assets are perceived by supervisory software. In contrast, the OPC UA information model abstracts these differences by mapping device-specific data into common ObjectTypes, such as PumpType, ReservoirType, or SensorType. As a result, equipment from different manufacturers performing equivalent functions is presented uniformly to higher-level systems.

This information-centric representation enables the supervisory and cloud-based SCADA layers to interact with the water distribution system without requiring awareness of vendor-specific implementations. For example, a pump is accessed as a logical object with well-defined variables representing flow, head, efficiency, and operational state, regardless of whether the underlying device is controlled by a PLC, RTU, or embedded controller from different vendors. Optional extensions within the OPC UA model allow vendor-specific features to be exposed without compromising the generic structure, thereby balancing interoperability with extensibility [10].

From the perspective of urban water utilities, this modeling lens offers practical advantages across the system lifecycle. As infrastructure evolves through incremental

upgrades, asset replacements, or network expansions, new devices can be integrated by conforming to the existing information model rather than by re-engineering supervisory logic. This is particularly relevant in urban environments where water distribution assets are deployed over long periods and sourced from multiple vendors. The OPC UA information model acts as a stable semantic interface, insulating higher-level applications from changes at the field level.

Aspect	Traditional SCADA	OPC UA Information Model
Data representation	Flat tags	Structured objects
Vendor dependency	High	Low
Context awareness	Limited	High
Cloud readiness	Moderate	High
Extensibility	Low	High

6. Conclusion and Future Work

This paper has examined the urban water distribution industry through the lens of an OPC UA information model, demonstrating how information-centric modeling can reshape the integration and management of heterogeneous water infrastructure. By representing physical and logical assets as standardized OPC UA ObjectTypes, the proposed approach provides a unified semantic view of reservoirs, pumping stations, sensors, and control systems across the distribution network.

One of the key outcomes of this modeling perspective is the ability to achieve vendor independence at the supervisory and cloud layers without constraining field-level technology choices. The OPC UA information model serves as a stable abstraction layer that decouples higher-level applications from vendor-specific device implementations, thereby supporting long-term system evolution and multi-vendor interoperability. This is particularly important for urban water utilities operating complex, geographically distributed systems with diverse equipment lifecycles.

While the study focuses on conceptual modeling rather than large-scale deployment, the findings indicate that OPC UA-based information modeling provides a viable foundation for cloud-hosted SCADA, advanced analytics, and future smart water applications. Future work will focus on formalizing the proposed model as a standardized NodeSet, validating it through pilot deployments, and extending it to support digital twin integration, predictive maintenance, and cross-domain interoperability with other urban infrastructure systems.

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