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District Information Areas: A Distributed Decision-Making Approach for Urban Water Systems †

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Abstract: This paper presents a comparison between traditional District Metered Areas (DMAs) and an innovative concept called District Information Areas (DIAs) in managing water distribution systems (WDSs). Both aim to improve efficiency and resilience, but differ in approach. DMAs use physical segmentation with measurement devices mainly for leak detection, while DIAs employ smart sensors and data analytics for decentralised management. DIAs operate semi-autonomously, making local decisions based on data analysis and coordinating with neighbouring areas. While traditional methods still play a role in maintenance, DIAs aim to enhance sensor coverage and support future digital twin development. The advantages of DIAs include reduced latency, increased flexibility, improved efficiency, and enhanced resilience during disruptions.

Keywords: district metered areas; urban water; asset management; digital twin; network science

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1. Introduction

This paper offers an alternative to the traditional District Metered Areas (DMAs) management model with the novel District Information Areas (DIAs) concept in the context of water distribution systems (WDSs). Both approaches share the common objective of enhancing efficiency and resilience [1], but they differ in their fundamental principles and implementation strategies. Conventional DMAs employ physically segmented subnetworks, each equipped with measurement devices to monitor water flow and pressure. This segmentation facilitates the identification and isolation of leaks within each DMA. However, the physical and hydraulic constraints imposed by traditional DMAs require physically coordinated mechanisms that limit their ability to adapt to evolving conditions [2]. DIAs, on the other hand, utilise virtual subnetworks defined by connectivity and shared data, rather than physical partitions. Operating semi-autonomously, each DIA independently collects and analyses data from its sensors, making localised decisions. These decisions are informed by the self-evaluation of the local network health and condition, along with the information of the neighbouring information areas. Traditional inspection and maintenance practices will still be employed to ensure the overall health and system performance. DIAs will also inform future sensor placement, enhancing the current sensor network and aiming to achieve comprehensive WDS coverage. This capability to accurately represent the physical infrastructure of a WDS is crucial for a future development of a digital twin at scale.

2. District Information Areas Formation: Main Characteristics

The current proposal is based on a complex network modelling of the urban water infrastructure. WDS assets such as pipes and valves are considered network links connecting consumption points and water sources (reservoirs and tanks), which are considered network nodes. The creation of DIAs can be understood as a (graph) clustering process over such a network. The novelty lies in the clustering algorithm, which is now conditional to the presence of key nodes or links acting as centroids. These key nodes (WDS assets) are defined by the sensor locations, and each of them provides a local view of the WDS. What DIAs represent is what sensors know about the network and, consequently, to what extent they can support automated, distributed, and data-driven decision-making for the WDS operations and management.

The methods for the automatic construction of DMAs can be roughly classified into optimisation, usually heuristic, models that blend with any of the following: spectral clustering (proposing network partition at the most loosely connected pipes), community detection (creating subnetworks, DMAs, made of highly connected areas), and agent-based methods (adding to the same subnetwork neighbour assets of highest similarity) [3]. The case of DIA comes with a different perspective than DMA, since the objective is not an actual network partition but the network division into areas informed by sensors. To this end, the division starts at each network element on the multiple sensor location in a WDS and extends from each sensor to a neighbours' assets until they are considered out of sensor range. In this regard, the process of DIA's network division is as easy as considering a label-propagation process up to the k-nearest neighbours (kNNs) of each sensor, with k being the depth of asset neighbourhood under the sensor's reach, or sensor radius. Similarly to the work of Benazi et al. [4], the DIA formation algorithm has the following main steps:

Initialise the labels of each network node with a value indicator, l, such that $\{l = 0\}$ for the nodes without a sensor and a unique value $\{l = s: s = 1, \ldots, S\}$ for the nodes with a sensor. Initialise k as the sensor radius for the kNN.

For each node labelled with $s > 0$ (sensor node), update the label of their direct neighbours (one-link distance) to the value of the own label, s, only if the neighbours have value $s = 0$. Otherwise, update the value only if the current node is its most similar neighbour.

$k = k - 1$; If: $k > 0$ {Go to 2.} Else: STOP.

It is important to note the limit of k neighbours in the DIA division. DIA division creates areas or subnetworks that do not necessarily cover the entire WDS. This is due to each DIA being associated with its corresponding sensor reach, or capability to obtain insights within a certain radius from the sensor. Areas outside of the sensor's reach (not part of the DIA) will be prioritised for future sensor placement.

3. District Information Areas as Multilayer Complex Networks

The aim behind DIA is not just to propose an information management framework, but to extend it to relate such distributed information into the areas of the physical network monitored by smart sensors susceptible to undergo automatic decision-making. Given the heterogeneous nature of this endeavour, a multilayer complex network approach is proposed as the mathematical model to represent and further analyse a WDS partitioned into DIAs.

In the context of DIAs and their relation to sensor networks, a multilayer complex network comprises two layers. One represents the usual physical infrastructure network, and the other represents the sensor network. Sensors are related to one another by geographical and metering similarities, composing the sensor network [5]. Additionally, sensors are also related to those parts of the physical network from which they can gather information. These inter-layer connections are represented by hyperlinks connecting the two network layers.

Multilayer complex networks strengthen decision-making in water systems by combining hydraulic data with sensor feedback. DIAs enhance control beyond fixed valve areas, aligning local actions with broader network management through sensor communication. This system allows for continuous verification against historical data and neighbouring readings, facilitating automated adjustments in DMAs for optimal network performance.

4. District Information Areas: Application to a Utility Network

This section proposes the application of DIAs to the utility network of Parete (Italy) and showcases the preliminary results and advantages of working with DIAs as complement to DMA partition. This water distribution system comprises 182 demand nodes, with 282 pipes and two water sources.

Let us consider five DIAs in Parete WDS. Each DIA is defined by a sensor that is taken as a central point (centroid). Without loss of generality, let us consider that each sensor can accurately obtain hydraulic information in a two-pipe-distance radius. Figure 1 shows the network distribution DIAs including the sensor location, marked with a larger size symbol, that is projected to an additional network layer in which sensors can be analysed separately and in relation to the WDS.

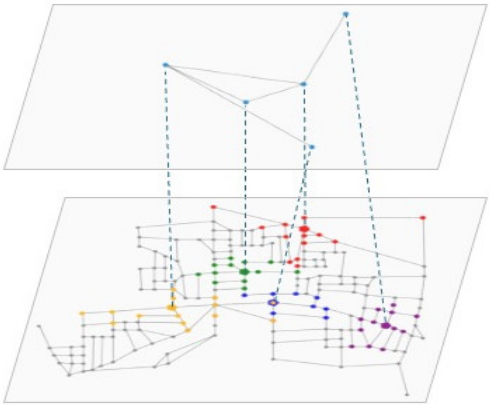

Figure 1. Multilayer complex network representation of Parete WDS compressing the physical network layout, divided into DIAs, and the sensor network layout.

In Figure 1, it is important to note the uncoloured areas (grey nodes) uncovered by sensors, as these are outside the scope of current monitoring. This allows them to identify areas for future sensor placement, reducing the search for where to place them rather than trying the entire WDS. In this example, the area automatically monitored by sensors is 35% of the total infrastructure.

One example of analysis showcasing the use of DIAs and distributed decision-making in Pareto WDS is on DIA sensors that can autonomously monitor water pressure levels in different zones and associated DMAs. Each sensor can locally analyse pressure data and adjust valve settings or pump speeds to maintain optimal pressure within its respective DMA in a decentralised manner. Figure 2 shows a simulation of pressure readings in the event of a leakage (time of leak event marked by a vertical, dashed line). The affected areas, DIA1 and DIA3, pinpoint the leak location through their local sensors and data analysis. This distributed approach facilitates faster and more targeted repairs, minimising disruptions to the overall system.

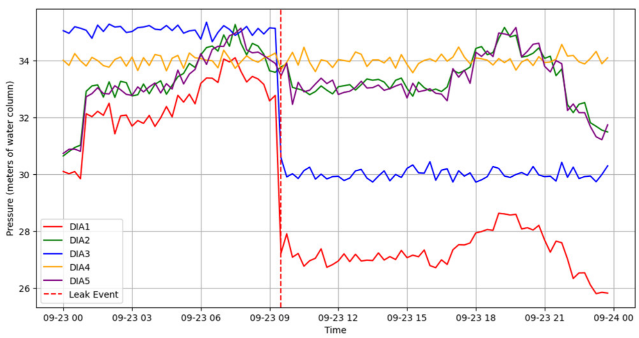

Figure 2. Simulated pressure from sensors of the 5 DIAs with the add-on of a leakage simulation.

5. Conclusions

This paper introduces the innovative concept of District Information Areas (DIAs) in Water Distribution Systems (WDS), defined by the coverage of sensors. The paper highlights the benefits of employing DIAs in utility networks, including more efficient sensor placement for detailed monitoring within DMAs, decentralised and scalable decision-making, and the facilitation of digital twins for WDS. DIAs complement DMAs, allowing for precise data triangulation and improved WDS control. The decentralised nature of DIAs ensures the effective regulation of hydraulic parameters like pressure, thus enhancing the network's efficiency and resilience. Future research will aim to integrate DIAs with existing DMAs to enhance monitoring and control, helping water utilities to achieve more reliable and sustainable WDS operations.

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