A Tool to Facilitate the Design of Smart Contracts in Smart Water Distribution Networks

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***Abstract*—The integration of smart contracts within water distribution networks presents a transformative approach to addressing challenges in water management. In this context, we propose a pioneering tool aimed at streamlining the design and implementation of smart contracts tailored specifically to smart water distribution networks. This tool allows stakeholders to input essential parameters such as water sources, distribution points, consumption patterns, and contractual stipulations. Through the utilization of predefined templates and adaptable contract logic, the tool automates critical processes including water allocation, usage monitoring, and penalty imposition based on predefined criteria. Furthermore, seamless integration with blockchain technology ensures the security and integrity of contract execution. By addressing scalability, compliance, and regulatory considerations, this tool represents a significant advancement in empowering stakeholders to optimize water management practices through the deployment of efficient and transparent smart contracts.**

***Index Terms*—Smart meters, Water supply, Data analysis, Smart Contracts, BlockChain, LoRaWAN, IoT, WDS, WDN**

I. Introduction

Smart water management systems offer significant advantages by enhancing water conservation, improving leak detection, and enabling cost savings. Those systems use smart metering and data analytics to provide real-time monitoring and detailed insights into water usage patterns, which facilitate informed decision-making and efficient resource management [1]–[4]. Such technologies not only help in reducing water consumption and operational costs but also assist in complying with regulatory standards and increasing customer engagement [5], [6]. By promoting sustainable practices and optimizing water distribution network (WDN), smart water management systems are vital for long-term resource sustainability and infrastructure planning in regions facing water scarcity and growing urban demands.

Smart contracts have the potential to facilitate various applications in the retail water market, including contract signing, and secure data management of water usage for billing purposes. A smart contract for the water sector is essentially a set of rules encoded on a blockchain that automates the execution of agreements and transactions among participants. This process starts by registering each smart meter to the smart contract. Water suppliers can then offer their services through the smart contract, which authenticates customers based on their smart meter address and requires a monetary deposit. Following this, payments are processed automatically after the water consumption is monitored and confirmed. Additionally, smart contracts enable real-time tracking of water consumption, allowing for automatic adjustments in demand and supply, defining water costs, and setting payment policies and timings for water trading. Those features significantly enhance the efficiency, reliability, scalability, and security of transactions within the WDN [7].

Today, smart meter installations are becoming increasingly popular among utility providers in various sectors, yet the water sector remains notably behind in adopting this technology. This introduces certain difficulties in deploying novel services in pilot infrastructures and/or acquiring access to real-world datasets to enable experimentation of novel data-driven applications. It is therefore critical to replicate experimentation environments developed for other smart city services, such as [8]–[10], for the smart water distribution domain. To address this need, we propose here an ecosystem of experimental tools with the goal to streamline the design, implementation and evaluation of smart contracts tailored specifically to smart WDN. This ecosystem allows stakeholders to input essential parameters such as water sources, distribution points, consumption patterns, and contractual stipulations as well as technical information related to the ICT infrastructure. Through the use of predefined templates and adaptable con-

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tract logic, the tool automates critical processes including water allocation, usage monitoring, and penalty imposition based on predefined criteria. Furthermore, seamless integration with blockchain technology ensures the security and integrity of contract execution. By addressing scalability, compliance, and regulatory considerations, this tool represents a significant advancement in empowering stakeholders to optimize water management practices through the deployment of efficient and transparent smart contracts.

II. Related Work

Smart contracts can significantly enhance the management of water resources in smart cities by allowing citizens to participate actively by proposing, voting on, and implementing water management policies, which ensures transparency and collective responsibility [7], [11]. The proposed approach encourages sustainable water and empowers citizens by involving them directly in resource management decisions, fostering a sense of community and shared goals within the smart city.

The use of smart contracts in smart water management for the case of agriculture is presented in [12]. The article emphasizes automated, real-time adjustments in water distribution based on IoT data, where smart contracts manage the water allocation and ensure policy adherence.

In contrast to the previous articles, a different approach is followed in [13] that looks into residential water management, aiming to conserve water through a system that allows direct interaction between consumers to share resources effectively. Unlike the previous models which focus on broader policy implementation and agricultural applications, this system is more focused on individual and household-level transactions and conservation efforts. It proposes a decentralized system where households can manage water resources efficiently by sharing surplus water peer-to-peer. This system is underpinned by smart contracts on the Ethereum platform, which automate transactions and enforce agreements among participants, promoting transparency and effective water usage.

The development of integrated tools for the simulation of leaks in smart WDN have been recently studied in the LoRaSURFING [14]. This tool enables the design and evaluation of leak-detection methods for efficient monitoring, analysis, and optimization of WDNs that are integrated with Long-Range Low-Power Networks. The study indicates that this smart system can significantly enhance leak management, prediction, and overall water resource management by processing data locally, reducing latency, and conserving bandwidth.

Mohanta *et al.* [15] presents a simulation implementation of a smart home system using Ethereum blockchain. Temperature and humidity sensors are connected to a Raspberry Pi device which collects the data. The operation of the system, i.e. the collection and processing of data to extract useful information, is carried out by smart contracts on the local Ethereum blockchain that is installed.

III. High-level Architecture

In this section, we introduce the basic building blocks that constitute our experimentation ecosystem. The WDN forms the base layer of our architecture. The pipes, pumps, valves, junctions, tanks, and reservoirs that constitute the WDN are modeled in terms of the hydraulic and quality dynamics using the EPANET tool [16]. We assume that the WDN infrastructure provider can deploy smart meters and smart valves at any location that are connected with the internet through a low-power wide area network (LPWAN). The smart devices and gateways that constitute the LPWAN are simulated using the NS-3 environment. This allows the evaluation of the different LPWAN technologies that depend on cellular infrastructure, such as NB-IoT; or third-party infrastructure, such as SigFox; or even standalone LPWANs, such as LoRaWAN. The simulated data provided by EPANET that are collected via the NS-3 simulator feed into a blockchain infrastructure through a dedicated API. Finally, on top of the blockchain, smart contracts can be implemented to enable automated and secure management of water-related transactions. The resulting architecture is depicted in Fig. 1.

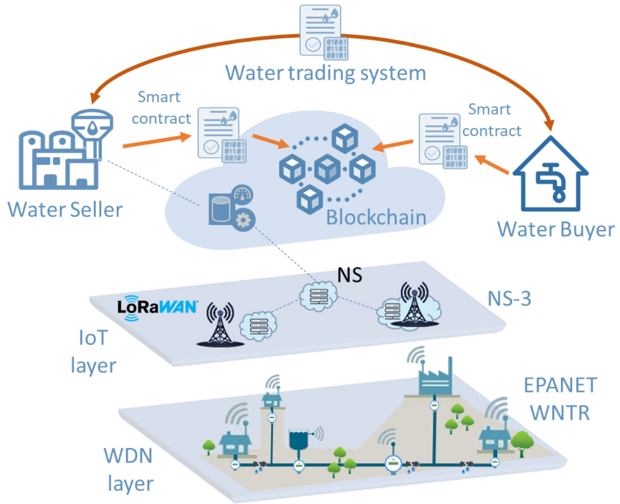

Fig. 1. Smart contracts architecture in WDNs

The proposed architecture allows to experiment either at individual levels of the infrastructure or on the entire hierarchy. This flexibility allows to focus on specific elements, allowing various tasks, such as real-time payment based on realistic consumption patterns, automatic detection and reporting of any leaks or anomalies, data synchronization among the various stakeholders involved in water network management. This connection setup ensures that smart contracts remain accurate and reliable, based on real-world conditions and data.

A. Profiling of water consumption

Our starting point is the analysis of real data collected from IoT infrastructures, such as [1], and using machine learning techniques such as K-Means clustering [17] to effectively segment consumers into distinct groups based on their water usage patterns. Advanced deep neural network models can be used to demand curve forecasting, and consumer behavior analysis [4]. The resulting consumer profiling will become the basis for understanding different water use behaviors, which is critical for creating realistic simulation scenarios.

By incorporating these detailed consumer profiles, simulations can more accurately model the actual water demand and usage patterns across different consumer segments in a water distribution network. This enhances the realism and utility of simulation models for planning and managing urban water resources efficiently.

B. Modeling water distribution networks

A WDN consists of a series of interconnected links and nodes. The links are composed of pipes, pumps, and valves that facilitate water flow, while the nodes represent the junctions, tanks, and reservoirs within the system. Junctions act as connection points where multiple pipes converge. They also function as crucial points for water supply or demand within the network. Tanks and reservoirs are key components that supply water to the system, with tanks providing a finite supply and reservoirs offering an essentially infinite supply of water.

In the model utilized, water flow is analyzed using the Hardy-Cross method [18]. This method is based on the premise that water distribution across each junction adheres to the continuity principle. According to this principle, the combined flow rates of all pipes converging at any given junction must balance with any water demand at that junction, ensuring that the total algebraic sum of these flows equals zero.

In WDNs, base demand and satisfied water requests are two distinct concepts related to the amount of water needed and the amount of water that can be successfully supplied to the consumers. In summary, while base demands represent the foreseen water consumption by users in a WDN, satisfied water request reflects the actual amount of water provided to them, taking into account the network's capacity and available resources and is labeled as demand value.

We use the EPANET (US Environmental Protection Agency water NETwork) tool, an open source software, to model the hydraulic and quality dynamics of a WDN [16]. The consumption profiles indicated in the analysis presented in Sec. III-A are used to create a simulation using EPANET.

We integrate the EPANET with the Water Network Tool for Resilience (WNTR). WNTR examines the geometric structure of the pipeline system along with a set of initial conditions (e.g. pipe roughness and diameter) and rules of how the system is operated, so that it can compute flows, pressures and water quality (e.g. disinfection concentrations and water age) throughout the network for a specific period of time. It is capable of simulating complex WDN infrastructure and obtaining all main hydraulic values by a demand-driven analysis (DDA) and a pressure driven analysis (PDA).

C. Smart metering based on Long-power wide area networks

In the realm of wireless technology, there is no universal standard for monitoring WDNs. However, LPWAN devices are expected to dominate the IoT industry [19], with different infrastructure requirements: (i) dependent on cellular infrastructure, such as NB-IoT; (ii) dependent on third-party infrastructure, such as SigFox; and (iii) standalone LPWANs, such as LoRaWAN [20]. Cellular-based LPWANs offer extensive coverage, capacity, battery life, quality of service, and security, but are not cost-effective due to subscription costs and dependence on commercial networks. Among LPWAN technologies, LoRaWAN stands out due to its advantages, including low power consumption, extensive coverage, simplicity, and ease of management.

LoRaWAN is based on a cell-free architecture in which IoT devices are connected to multiple Gateways (GWs), depending on the GW's coverage area. All GWs receive and forward appropriately demodulated packets to a central Network Server (NS) as presented in Fig. 1. Our approach involves implementing an IoT system comprising smart water meters placed at the end user of WDNs to measure their consumption as well as smart water valves that can control the flow of water across the pipes.

D. Connectivity of smart metering data with blockchain

The data collected from the smart meters and delivered through the LPWAN are connected with the smart contracts through a so called "blockchain oracles" [21]. Oracles act as bridges between the blockchain (on-chain) and external data (off-chain). In particular, the data arriving on the application server via the LPWAN are fed into the oracle via a dedicated API. This connection setup ensures that smart contracts remain accurate and reliable, based on real-world conditions and data.

In particular, the *Ethereum blockchain* [22] is used due to its capability to host not only transaction logs but also smart contracts – self-executing programs that can be activated by other nodes within the blockchain network. The smart contracts are securely stored and executed on the blockchain, thus guaranteeing code integrity and the system's reliable performance. This feature makes the Ethereum blockchain an ideal platform for Internet of Things (IoT) applications, offering enhanced security measures. Remark however that other blockchain technologies can be used instead of the Ethereum.

E. Smart Contracts

Smart contracts reside at the top-most level of the hierarchy and embody the system's functionalities. The compiled code of the smart contract along with specific pieces of information, e.g. related to the wallet, are embedded in the blockchain to execute transactions. After the consensus mechanism concludes and the smart code is executed for the first time, the initial state of the smart contract is established. The smart contract remains active for a predefined period, automatically executing transactions when the pre-specified conditions are met and the outcome is stored in the blockchain. In Listing 1 where the client of each water contract can create the smart contract, and add or update their base demand value every hour. The water supplier can then update the demand value on regular intervals, and check if the demand was met. If the demand was not met, they need to fund the contract with the penalty amount. Then, only the owner of the contract can request to withdraw the amount stored in it to a wallet they want to receive the

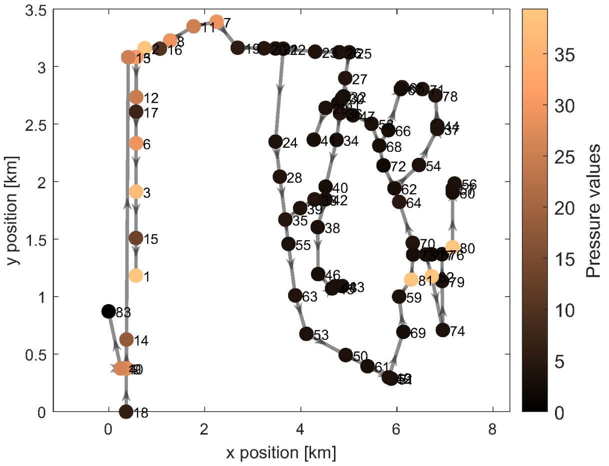

Fig. 2. Example of WDN branch with 1 reservoir, 83 nodes. Node colors are associated to the pressure values.

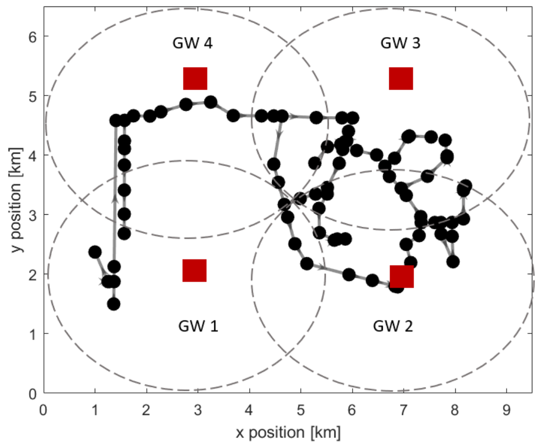

Fig. 3. Example of a LoRaWAN network used to interconnect the IoT devices monitoring the WDN with the Ethereum blockchain.

compensation. Volume-based pricing is much simpler and left out of this paper due to space restrictions.

In the contract mentioned above we store only the minimal information needed to validate that the current water provided to the customer meets the requirements of the user. If we want to store additional information, or historical data that can be used to validate that the supply was adequate for prolonged periods of time, solutions incorporating off-chain storage can be used, as storing huge amounts of data is inefficient and costly. Such a solution is recommended in cases like NFTs or medical records. Our work can be used without that, as updates to the chain are limited.

IV. Evaluation

In this section, we present the evaluation of smart contracts operating on data collected from a WDN to implement two different smart contracts for the retail market. The first one is a simple one that replicates the billing mechanism of a conventional water distribution network. The second contract explores more advanced billing mechanisms that take into account the demand of the end users and the actual flow delivered.

A. Water distribution network

We use a pre-defined network model offered by the Open Water Analytics's community public repository [23], also available as topology and blockchain dataset at this link[1]. Fig. 2 depicts the WDN used that is comprised of 85 junctions and 1 reservoir. Each node is configured with a specific base demand pattern which represents the water request of the user during the whole simulation changing at a step size of an hour.

In the WDN representation of Fig. 2, for a specific measurement interval, color scales are used to plot nodes and pipes pressure. The reservoir is positioned on the left side of the network (element with identifier 83), with flow primarily moving from left to right. Moving further away from the reservoir, the total demand value and pressure at the junctions decrease due to the demand from left-side junctions.

Each node has a base demand which represents a constant consumption of water during the whole simulation. Each simulation is performed for a duration of one month. For each scenario, different node interval demand and pattern are set: *Simple Demand*: all water demand is satisfied; *Complex Demand*: not all water demand is satisfied.

We assume that LoRaWAN-enabled smart metering devices are positioned at each junction of the WDN and the entire area is serviced by four LoRaWAN GWs. Fig. 3 depicts the smart metering devices (black bullets are the nodes) together with the GWs deployment (red squares are the GWs and circles their coverage area at Spreading Factor 7). According to the coverage area, each GW is able to receive only a subset of the total WDN measurements, so we consider a zero padding process to fill missed data measurements at the edge.

B. Case 1: Volume-based pricing

We start by designing a smart contract that replicates the billing mechanism of a conventional water distribution network. The billing period of the contract can be defined at creation time, ranging from long periods like two or four months, or even short periods of one month or even on a weekly basis.

C. Case 2: Differential pricing

The simulated WDN includes a scenario where the user demand for specific hourly water flow is not met. An example of such a customer for node 8742 and for 24-hour period is depicted in Fig. 4. For this scenario, we design a differential pricing smart contract with more complex notions of billing where specific penalties are stipulated when the WDN does not match the requested water flow. The calculation of the potential per-node penalties – or savings for the perspective of the customer/user – need to calculated on regular intervals, e.g., on an hourly basis.

```
contract DifferentialContract {
```

[1]https://github.com/WITS-Restart/WDN-Dataset-Workbench

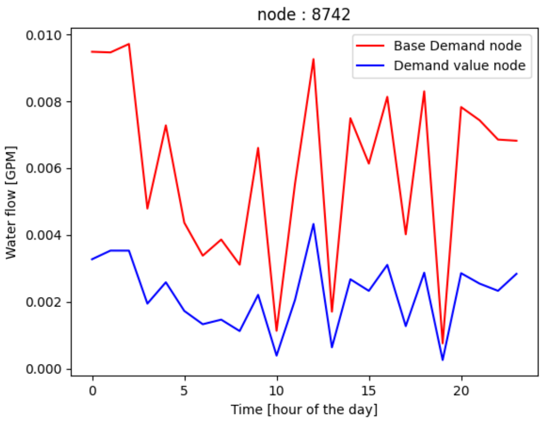

Fig. 4. Example of a node where hourly pressure demand is not met

```
    string public nodeID;
    int public baseDemand;
    int public demandValue;
    ...
    address public owner;

    constructor() {
        owner = msg.sender;
    }
    function setBaseDemand(int _value) public {
        baseDemand = _value;
    }

    function setDemandValue(int _value) public {
        demandValue = _value;
        satisfied = baseDemand <= demandValue;
    }

    fallback() external payable {}
    receive() external payable {}

    modifier onlyOwner() {
        require(msg.sender == owner);
        _;
    }

    function withdraw(address payable to) public
        onlyOwner {
        to.transfer(address(this).balance);
    }
}
```

Listing 1. Example of the Differential Pricing Contract in Solidity

D. *Evaluation of Scalability*

In Ethereum-based applications using smart contracts, costs are calculated using the concept of *gas*, which measures the computational effort needed to perform operations on the network. Each operation, whether it's a simple Ether transfer or a more complex contract function call, requires a specific amount of gas depending on its computational complexity. Users set a gas price in Gwei (1 Gwei = 10^{-9} ETH), which indicates how much they are willing to pay per unit of gas. This price can fluctuate based on the network's demand and the miners' preferences, as miners prioritize higher-paying transactions. The total cost of a transaction is the product of the gas used and the gas price a user agrees to pay. This cost is paid in ETH.

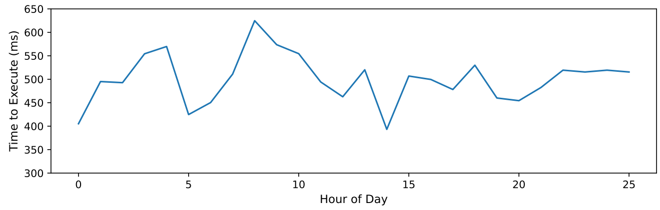

Fig. 5. Average time needed to complete a transaction on the contract by the user in a 24-hour billing period.

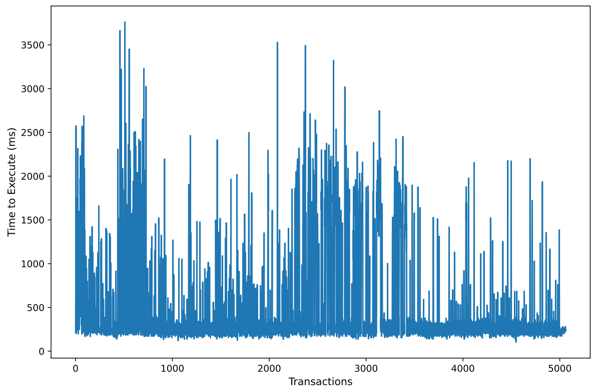

Fig. 6. Time needed for all the transactions by the water supplier for a 24-hour billing period and 82 clients.

To prevent spending too much in case of unexpected complications or inefficiencies in the contract code, users also set a gas limit, which is the maximum amount of gas they authorize for that transaction. If a transaction consumes more gas than this limit, it will fail, and the gas spent up until the point of failure is not refunded, even though the transaction itself does not succeed. Thus, managing gas efficiently is essential for cost-effective operation and ensuring transactions are confirmed by the network.

In our application it is expected that shorter billing periods will require more frequent transactions for the updated values of the smart meter for a given user, thus increasing the maintenance costs of the smart contract and creating a negative impact on the overall scalability of the resulting system. Fig. 5 showcases the amount of time needed to update the client's base demand for the differential pricing scenario, on average 498 milliseconds. These operations cost an average of 32367 of Gas, which sums up to 0.015 Ether per day for 24 hourly transactions. For the water supplier, we see the time needed to do every transaction needed, for the 82 clients participating in our evaluation scenario, in Fig. 6. On average these operations take 470 milliseconds each, and cost 31700 Gas, translating to 0.000644 Ether each, and 1.26 Ether in total (for 24 hourly updates, for all 82 clients).

To evaluate the system's scalability in relation to the performance of the LoRaWAN network, we utilized the traffic model as introduced in [24]. We then extracted the Data Extraction Rate (DER) versus the number of smart contracts generated per hour per user, considering a scenario where 400 smart

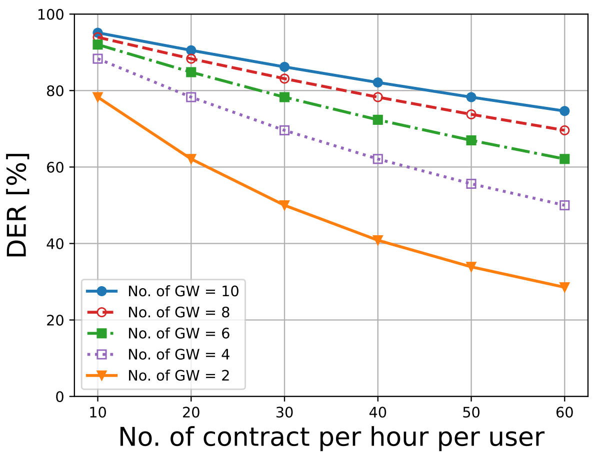

Fig. 7. DER versus number of smart contract updates for a scenario with 400 users.

meters are present. The DER is a metric that measures the efficiency of data extraction from devices or sensors connected to the LoRaWAN network. This was done for various numbers of GWs deployments. As depicted in Fig. 7, in this scenario, deploying 6 GWs is sufficient to maintain a DER above 60%. This holds true even when a contract is updated every minute.

V. Conclusions and Future Work

Smart meter installations are becoming increasingly popular among utility providers in various sectors, yet the water sector remains notably behind in adopting this technology. The implementation of smart contracts has the potential to introduce into the water distribution networks concepts that are currently being tested in smart grids. For example, a smart contract could facilitate peer-to-peer water sharing, where households can lend or borrow water based on their needs, tracked and managed via blockchain. The contract enforces the rules of the transactions, such as validation of water requests and ensuring that transfers are completed as agreed, without the need for a central authority. This can help in optimizing water usage and preserving this critical resource more effectively.

This work presents an architecture for experimenting with smart contracts for WDN and it has been applied on a small network. Future work is necessary to test the method on a bigger water distribution network. However, our architecture is complete as it allows to experiment on the entire hierarchy, ensuring that smart contracts remain accurate and reliable, based on real-world conditions and data. At the same time it offers the flexibility to focus at individual levels of the infrastructure.

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