An Urban Water Infrastructure Management System Design with Storm Water Intervention for Smart Cities

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***Abstract*—Cauayan City is one of the hubs of economic development and activities in the northern part of the Philippines. Since this is an urban area, there is a tendency for people and businesses to converge, which results in higher water demand. At present, the combined distribution efficiency of its water infrastructures under the management and supervision of the Cauayan City Water District (CCWD) is only 87% or with a combined distribution loss of 10%, which is 1282.50m3 losses per day. This study suggests the necessity to introduce new and innovative water management technologies and systems adapted to climate change to address the city's needs. Problems that need to be addressed include a low-efficiency performance of the existing water infrastructure systems, lack of management tools for more efficient delivery of water services, limited service coverage of the water district due to limited water resources, and depletion and contamination of aquifers and other water sources since shallow aquifer is mainly utilized. Hence, a decision-support application based on geographic information systems (GIS) for managing urban water infrastructure with Storm Water intervention is a designed solution to address the needs of the city. The combination of decision support systems (DSS) and geographic information systems (GIS) was presented in this paper to maximize and properly utilize water infrastructure. One of the tools used as DSS is MIKE Operation. This is a complete GIS-integrated modeling tool that enables users to make sound decisions and create future concepts for urban storm water systems - cost-effective and resilient to change. A conceptual framework and relevant methodologies were presented as a guide for the success of the designed new technology.**

Keywords—Water infrastructure; geographic information systems; storm water; decision support systems; water management

I. Introduction

Cauayan City in Isabela is one of the country's first smart cities and one of the Philippines' premier agro-industrial hubs [1]. This advancement in science and technology is being acknowledged by the Department of Science and Technology (DOST). Since urban areas, such as Cauayan City, are the hub of economic development and activity, there is a tendency for people and businesses to converge, which results in higher water demand.

At present, Cauayan has a total of fifteen (15) water pumping stations and eight (8) elevated water tanks serving only 12,067 households (29%) out of 30,207 households (71%). The combined distribution efficiency of these water infrastructures under the management and supervision of the Cauayan City Water District (CCWD) is only 87% which is accounted for the 9,229.63 cubic meters of metered water out of the distributed water of 10,518.13 cubic meters daily or with a combined distribution loss of 10% which is 1282.50 cubic meter losses per day [2]. This study suggests the necessity to introduce new and innovative water management technologies and systems adapted to climate change to address the need of the city like improving the performance of the existing water infrastructure systems, lack of management tools for more efficient delivery of water services, limited service coverage of the water district due to limited water resource and depletion and contamination of aquifers and other water sources since shallow aquifer is mainly utilized. Hence, a GIS-based decision support tool in managing urban water infrastructure with the Storm water invention is a designed solution to address the need of the city.

To maximize and properly utilize water infrastructure, the merging of decision support systems (DSS) and geographic information systems (GIS) is required to provide a visualization tool and the necessary spatial database for turning a basic geographical query into a sophisticated spatially and analytical distributed modeling tool [3], [4]. Reitsma [5] defines a DSS for water resource applications as computer-based systems which integrate state information, dynamic or process information, and plan evaluation tools into a single software implementation. One of the tools used as DSS is called MIKE Operation. It is a complete GIS-integrated modeling tool that enables users to make sound decisions and create future concepts for urban storm water systems - cost-effective and resilient to change [6], [7].

The general goal of this paper is to establish a management tool for urban water infrastructure to help decision-makers, policymakers, and managers in Cauayan City, Isabela. Its specific goals are to assess and analyze the risk of urban water infrastructure systems in Cauayan City, establish a decision support system for optimal water infrastructure management, and design, build and test an urban Storm water storage system integrated with monitoring sensors.

II. Literature Review

A. Rain/Storm Water Harvesting

In the municipality of Erisos, on the island of Kefalonia in northern Greece, rainwater is collected in twenty-three ferroconcrete rainwater storage tanks. This was developed in the 1970s and positioned at the bottom of cement-paved hill slopes acting as catchment areas ranging from 600 cubic meters to 3,000 cubic meters [8].

This Storm water harvesting infrastructure system was constructed at Brimbank Park, Melbourne, Australia, to irrigate 1.47 hectares of park public open space, utilizing a 1.7 hectares carpark as the principal storm water catchment. The system design featured a 2,000 cubic meter storm water storage tank, a 450 mm storm water collecting pipe, a 600 m^2 bioretention/filtration system, a 150 mm pressure main with a 35 kW pump, and a sprinkler system with a 125 mm manifold and 50 mm laterals [9].

Rainwater harvesting [10] supplies water for drinking, sanitation, and increasing the productivity of agro-ecosystems in Kenya's semi-arid savannah towns of Kaijado and Lare. Roof water harvesting for residential reasons (drinking and sanitation), runoff collecting in ponds for small gardens, trenches for groundwater recharge, and afforestation were among the technologies implemented [11].

The rainwater harvesting system built at Sapilang, Bacnotan, La Union, which consists of roofs, gutters, downspouts, a filter, and a storage tank, can collect rainfall to feed and maintain the drinking water requirements of 8-12 family members [12].

B. Storm Water Infrastructure

To augment the existing water supply, G.C. Dandy et al. (2019) emphasized the significance of having alternate water sources in many cities, such as storm water collection and processed wastewater. Harvesting schemes for Storm water that complement current water systems, according to them, are complicated because they are made up of integrated components set that execute the duties of collecting, storing, treating, distributing, and discharging. Furthermore, while selecting and evaluating Storm water harvesting solutions, factors must be considered. These are environmental, economic, environmental, technical viability, and social variables [13].

According to the International Water Association, IWA (2019), population increase and urbanization are adding strain on urban water supplies. According to UN predictions, by 2025, fifty percent of the world's demographic would be residing in water-stressed regions. Furthermore, the current worldwide health catastrophe caused by COVID-19 emphasizes the availability of clean water to ensure a healthy population [14].

K.A. Feehan et al. Rainwater collecting has been performed for generations and was formerly the principal technique of acquiring water for home usage, according to (2012). Increasing water needs, water consumption limitations, new storm water management rules, and the expansion of low-impact development (LID) and "green construction" methods have rekindled interest in rainwater collection [15].

C. SWH Management

Stormwater harvesting (SWH) is one alternative water resource that might replace typical urban water supply while also providing a variety of social and environmental advantages. This addresses water scarcity by increasing resilience to the effects of climate change [16].

Urban planning for Water Sensitive Urban Design (WSUD) has been inconsistent, lacking direction and yielding sub-optimal results. Green storm water management infrastructure is being used more widely throughout the world to mitigate the negative effects of climate change and urbanization while also delivering several ecosystem services. WSUD is also used in Australia, Low Impact Development (LID) in the United States, Sponge City systems in China, and Nature-Based Solutions (NBS) in Europe [17].

D. GIS-Based Decision Support Tool for SWH

In the research of Shao, H. et al. (2017) said that an open-source geographic information system (GIS) based decision support system (DSS) for constructing modeling economic costs, water quality/quantity advantages, and BMP scenarios at the farm field, watershed scales and subbasin can be established. This DSS included a Soil and Water Assessment Tool (SWAT), a farm economic model, and an optimization model in an open-source GIS program called Whitebox Geospatial Analysis Tools, The DSS was applied to 14.3 square kilometers of Gully Creek watershed in southern Ontario, Canada, a coastal watershed that flows directly into Lake Huron [18].

Rainwater harvesting systems (RWHSs) have been recognized as a simple and effective technique to alleviating the deterioration of urban water stress. A recent study addressed the temporal-spatial complex of rainfall and proposed a GIS-simulation-based decision support system (DSS). Sensitivity study confirmed that, as compared to the previous generalized technique, this DSS increased the information value. As a result, the DSS, which provides more holistic and complete support, has been highlighted as a valuable instrument for mitigating the problem of urban water stress. This is a comprehensive method for promoting domestic RWHSs in a large-scale water-saving scheme that incorporates water consumption reducing equipment (WCRE) and gray water reuse (GWR) [19].

B. Mbilinyi and colleagues introduced a decision support system (DSS) based on a geographic information system (GIS) that employs remote sensing (RS) and a short field survey to identify possible areas for RWH technologies. The DSS receives soil texture, maps of rainfall, soil depth, slope, drainage, and land use as inputs. This produces maps of suitable locations for bench terraces, water storage systems, borders, and stone terraces as outputs. The findings of their study, which included testing and validation of the generated DSS, suggested that the tool may be used to anticipate probable locations for RWH technologies in semi-arid environments with high accuracy. The majority of anticipated RWH innovations were identified through testing in extremely high and highly appropriate places (41.4 percent and 40 percent, respectively). During the assessment, 36.9 percent of RWH techniques were located in moderately appropriate sites, with 23.6 percent discovered in very highly suitable and extremely suitable places [20].

MIKE OPERATION consists of MIKE 11 and MIKE Basin modeling tool, which has GIS features, and an easy-to-use online modeling framework for water prediction and operational control. It is intended for model-based forecasting services as well as online operational management of river systems, water collecting systems, and water transportation systems. This is also a simple real-time system for real-time modeling, optimizes water distribution collection systems, and controls the groundwater (CTNN Report, 2017) [21].

The MIKE 11 program was used to assess the water resources in the catchment of the Strymonas River. It also simulated unstable water movement in surface water bodies and catchment runoff [22].

MIKE basin software is used in the Pinho river's hydrographic basin. This is helped by a geographic information system to represent the basin both spatially and temporally. Thus, allowing for easier visualization and interpretation of findings. According to the acquired data, it was confirmed that the hydrographical basin now satisfies the considered water demands. The DSS has proven to be a valuable instrument in assisting decision-making in the examined river basin [23].

III. Materials and Methods

A. Conceptual Framework

Fig. 1 shows the conceptual framework of this paper. For the inventory of existing water infrastructure, the list of existing water infrastructure will be obtained from the City Planning and Development Council (CPDC) and from the Cauayan City Water District (CCWD). These infrastructures will be validated using a handheld Geographic Positioning System (GPS) and will be assessed. In Data Processing, Design, Construction, and Evaluation of the Storm water Storage System and Water Distribution Control System, all the data collected will be processed using MIKE Operations with GIS software.

Risk analysis of urban water infrastructure systems in Cauayan City will be done using Fuzzy Fault Tree Analysis (FFTA). Data about natural hazards, human-made hazards, and operational hazards will be obtained from internet-based information and survey form. At the same time, the development of urban digital model/system for water infrastructure involves the development of an urban digital model/system for water infrastructure will be implemented based on two steps (Fig. 2), such as the establishment of the urban digital model and utilizing a sensing layer for data collection. The Geographic Information System will play a role in these steps.

B. Construction of the Urban Digital Model

The first stage is to create an urban digital model that emphasizes the contents of the urban constructed and natural surroundings. The digital model gives geolocation and characteristics for each urban component (attributes). GIS will be used to produce a digital model of urban 'horizontal components' including the natural environment, urban networks, and transit facilities while establishing information modeling will be used to represent vertical components like structures. The combination of BIM and GIS results in a powerful tool for constructing an urban digital model utilizing georeferenced data and presenting this data in an intuitive manner. The combination of which will be integrated with MIKE Operations to come up with real-time simulation-based optimization. MIKE Operations will be used to optimize water distribution and collection systems. It will also be used to establish real-time data management and forecasting and monitor leaking water in the distribution system, minimizing the losses within the water infrastructure.

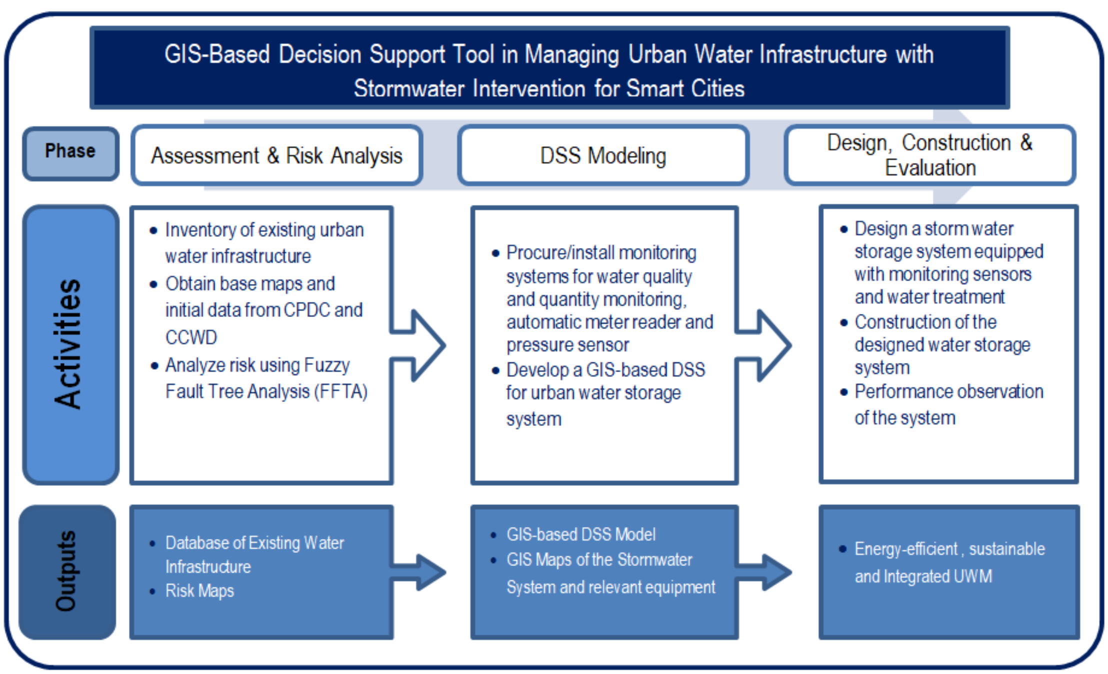

Fig. 1. Conceptual Framework.

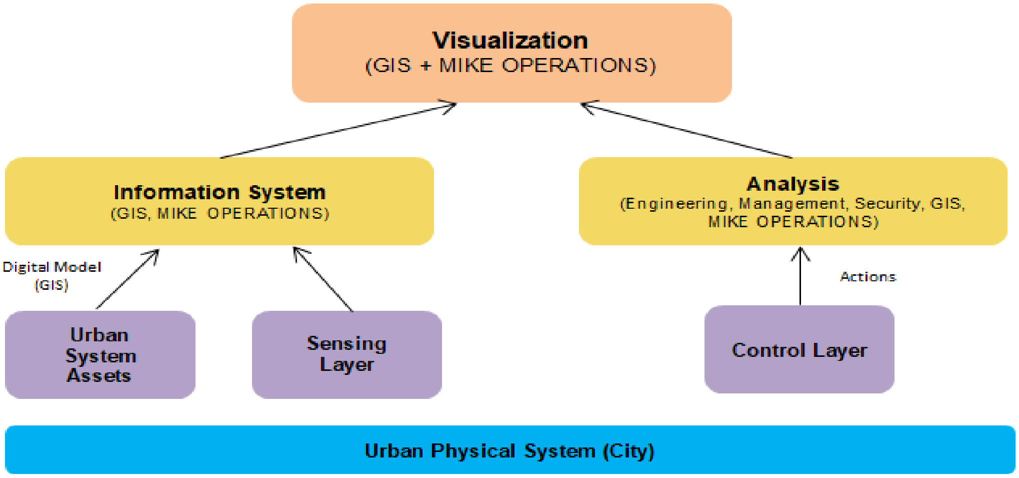

Fig. 2. Steps for the Implementation of Smart City Programs.

C. Sensing Layer

The second phase is to build the sensing layer, which will convey urban operational data to the smart city information system. This layer's sensors will be employed to monitor urban networks and infrastructure. Data can also be complemented with audio recordings, videos, and images, resulting in urban big data. Some of the sensors that will be utilized to monitor energy and water utilities are seen in Fig. 3. Water usage will be tracked using automatic meter readers (AMRs), water pressure will be tracked using pressure sensors, and water quality will be tracked using water quality devices (conductivity, turbidity, chlorine, pH). In the drainage system, sensors will be employed to monitor water level, flow, and quality (pH, temperature, turbidity, etc.). It enables the early identification of floods. Sensors will be installed in the district heating system to record fluid temperature, pressure, flow, and the status of the valve. It enables early defect identification and system performance enhancement. GIS + Mike Operations allows you to view the monitoring system and the characteristics and state of the sensors. It also allows you to see real-time and historical data on GIS maps.

1) Input Data: Since the rainfall and design method are site-specific, the rainfall data should be gathered for the design site. The capacity of nearby sewer systems should be analyzed.

2) Design Data: The tank will be designed according to the choice of controllable measures. The pumping rate and operation rules will be specified. The infiltration capacity will be determined based on site conditions and soil characteristics.

D. Design and Construction of Intervention Storm Water Infrastructure Systems

The storm water intervention facility has a total catchment area of three hectares with a storage capacity of 1750 cubic meters. Fig. 4 depicts a schematic diagram of the planned storm water infrastructure system, including the various components (examples include a storage tank, a flushing treatment device, groundwater recharge tank, UV treatment, elevated tank, suction pumps, valves, piping, and a water quality monitoring system). The recommendation to consider runoff water from the surface/roads aside from rainwater and Storm water falling from the roof is not feasible because the design storage capacity of the storm water is limited only to one (1) hour rainfall duration, which is enough to fill the storage tank. On the other hand, elevating the water storage tank in the new design and system is much appreciated. However, the said recommendation is not feasible considering that the building structures in the proposed site were not uniform regarding the number of the storey (i.e., BJMP and PNP buildings are four storey buildings while others are two-storey and one-storey buildings). Elevating the storage tank with this physical condition still requires motor pumps and heavy foundation structures. In addition, the space of the proposed site had limited space. Hence, when covered, the space occupied by the proposed subsurface storage tank will be useful for other purposes. Nevertheless, the recommendations will still be considered a possible option when scaled up to other areas.

E. Water Distribution Control System

The water distribution control system illustrates in Fig. 5. The monitoring and control system will measure values for pipe steel analysis through online and offline systems. The pipe steel analysis can distribute pressure control to the appropriate distribution amount and set values for the monitoring and control system. The demand assignment, parameter setting, and database update are also under pipe steel analysis.

F. Statistical Data Analysis

The statistical analysis to be employed is the following Rainfall Frequency Analysis for rainfall data analysis, Regression analysis for the performance of the storm water infrastructure. Secondary statistical data on the projection of population, water demand, and a groundwater abstraction rate from 2020 to 2050 was obtained from the study of Alvarez et al. (2020) on Benchmarking of the water supply and wastewater management system of a Smart City: the case of Cauayan City.

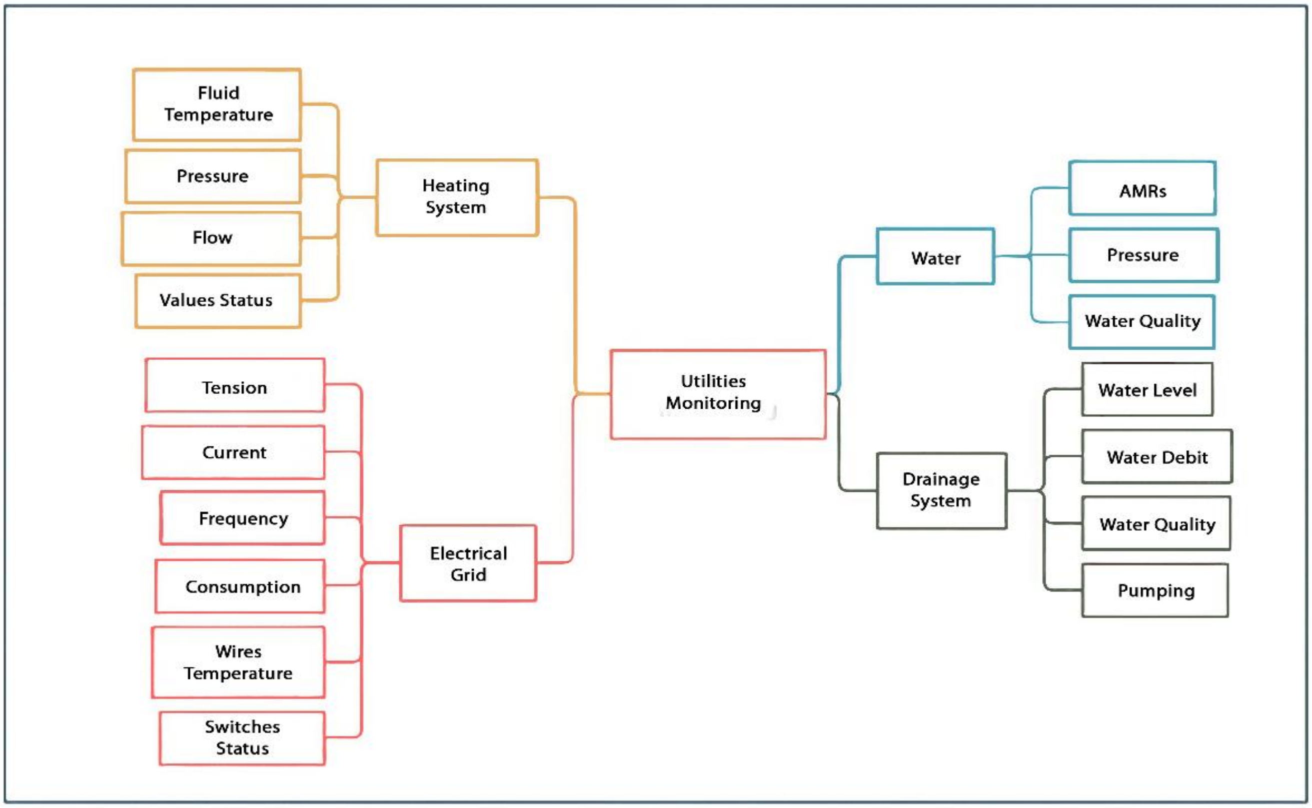

Fig. 3. Sensors in Water Monitoring.

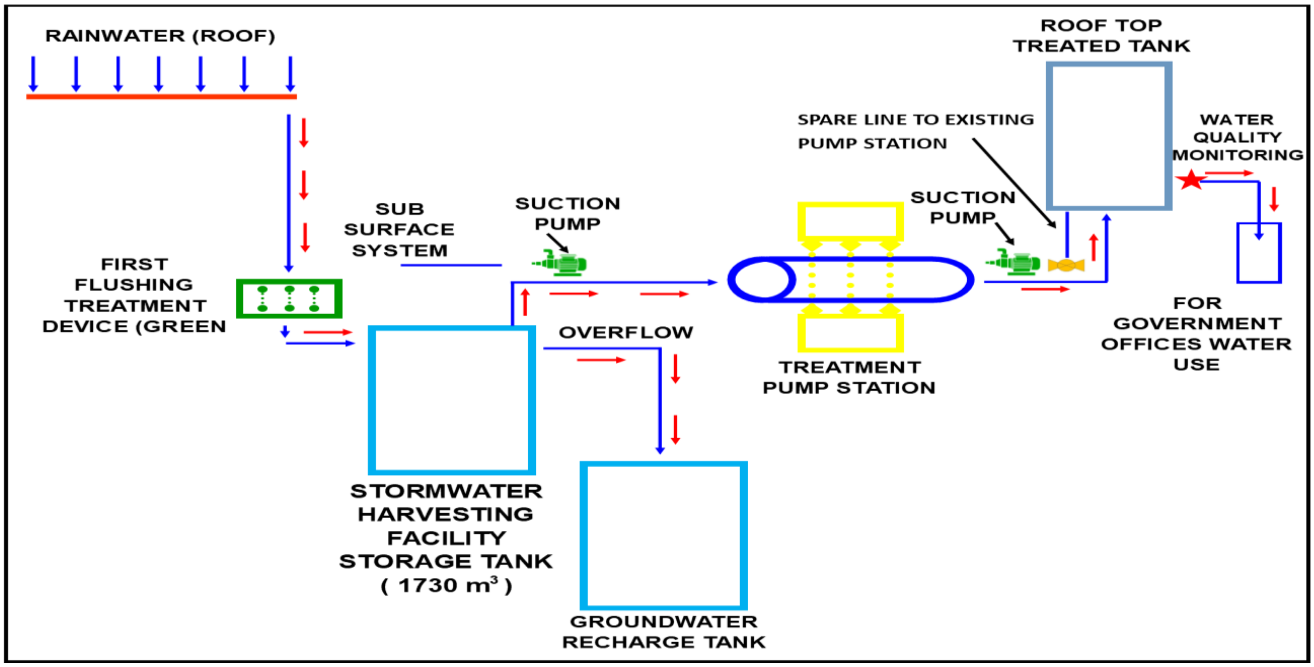

Fig. 4. Schematic Diagram of Subsurface Storm-Water Storage System.

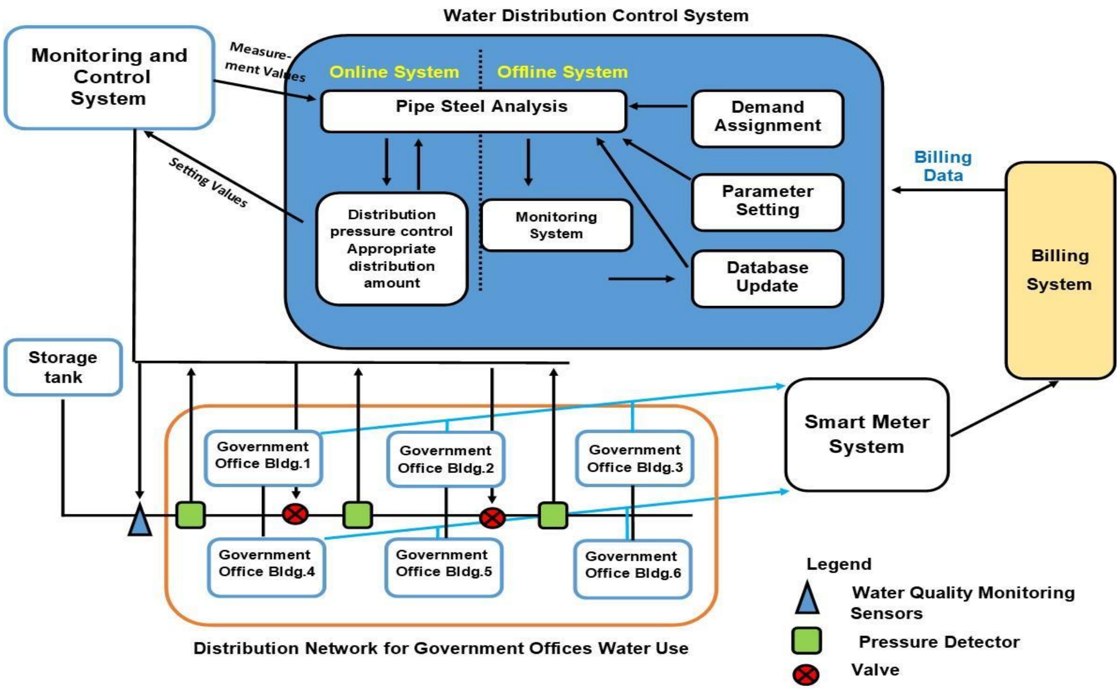

Fig. 5. Water Distribution Control System.

IV. Result and Discussion

A. *Differentiation (GIS-Based Decision support Tool in Managing Water Infrastructure)*

The authors compared the designed methods versus the existing practices locally and abroad regarding the various GIS-based decision support tools in Managing water Infrastructure. This is presented and summarized in Table I.

B. *Differentiation (Storm Water Harvesting Infrastructure)*

In terms of comparison between the designed methods over existing Storm water Harvesting Infrastructure, Table II presents the difference in various parameters indicated.

C. *Risk Management Plan*

Table III and Table IV show the risk management solution or a proposed contingency plan in case there will be challenges that will happen during the duration of the designed method.

TABLE I. Differentiation (GIS based Decision Support Tool in Managing water Infrastructure)

Parameters	Designed Method	Existing Practices (Local)	Abroad
Management Practices	GIS-based decision support tool in managing urban water infrastructure with storm water intervention.	Conventional - Non ICT tool management without water intervention (CCWD) as a practice	GIS-Based Management Tool
Performance Distribution Efficiency	Low distribution losses (2%)	Distribution Losses is 13 %	Distribution Losses 3-4%
Equipment tools	- Instruments with digital output (meters and sensors), such as water quality monitoring, flow meters, rain gauges, and other environmental parameters. - Real-time acoustic leak detecting devices - video camera-based asset management - Smart water measuring devices to monitor its use - Pressure monitoring to identify leaks and optimize pumps, UV treatment - GIS software	Manual monitoring pressures, flow meters, and leakages	- Flowmeters, rain gauges, monitoring of water quality as well as other environmental parameters. - Acoustic leak detecting devices in real-time - Asset management using video devices - Smart water systems to monitor their use - Pressure monitoring to detect leaks and optimize pumps - GIS/SCADA software

TABLE II. DIFFERENTIATION (STORM WATER HARVESTING INFRASTRUCTURE)

Parameters	Designed Method	Existing Practices (ISWM-Cebu))	Abroad
Design function of storm water infrastructure	Storm water collection and groundwater recharge facility equipped with water monitoring (quality) and treatment system. For flooding control, groundwater recharge and water supply for government offices will be implemented.	Rain and storm water collection with wastewater treatment Water supply for cleaning and gardening	SWH was designed to harvest rainwater with an infiltration facility and redirect rainwater to sewer systems. Other designs were used for irrigation and toilet flushing.
Design Capacity	-1750 cubic meter + groundwater reservoir	- 60 cubic meter	4 -40 cubic meter
Efficiency	90%	75%	30% to 90%
Cost of Investment	Php 3Million Or Php 1714.30/ cubic meter	Php 2Million Or 33,330.33 per cubic meter	Php 30,000,00/cubic meter
Water Dependence	-Reduced water dependence to 90%	-Reduced water dependence to 75% during month	
Component	-Primary storm water treatment facility (Green filter) - Storage Tank - pipe and fittings *Groundwater recharged Tank *Elevated water Tank *UV treatment *Water quality assessment facility	-Primary storm water treatment facility (Green filter) - Filtration system based on the micro membrane (MF System) - Rainwater Remote Administration System Integrated - Rainwater Drainage in Case of Emergencies - Water Treatment System for Reuse	-System of its collection -An inlet filter -Diverter for the first flush -Tank for storing items -Overflow -Treatment methods -Pump -Flow metering -An indicator of water level

TABLE III. RISK MANAGEMENT

Cause of delay	Solution
The foreseen major risk of the paper may be caused by a change of Leadership in the LGU and the procurement of needed materials.	There must be a signed Memorandum of Agreement (MOA); involve the university finance department during the inception activity, and perform intensive monitoring during the procurement process.

TABLE IV. OTHER POSSIBLE RISKS

Item	Risk	Designed Contingency Plans
Conduct Training and meetings	Restriction in the conduct of trainings and meetings	Activities will be undertaken using a combination of a face-to-face meeting in small groups and video conference with those affected by travel restrictions. A fully-equipped virtual conference venue will be set up at ISU.
Acquisition of software/ and equipment	Difficulty in the purchase and delivery of equipment due to travel restrictions	Sets of software will be acquired online; All equipment for purchase is locally available; hence delivery mode would be made by couriers or using ISU official vehicles under special permits
Data gathering	Restriction to travel due to community quarantine protocols	Since travels are in the provincial/ regional jurisdictions, special permits will be secured, and gathering in the field will be made using local assets.
Coordination with stakeholders	Travel difficulty for a face-to-face coordination meeting	Coordination will be made by online calls and videoconferencing.
Reports presentation and submission to PCIEERD	Travel restrictions to Manila for meetings and submission with the presentation of reports	It will be done by video conferencing and online mode.

V. CONCLUSION AND RECOMMENDATIONS

The authors determined the potential outcomes, socio-economic impact, and environmental impact through various analyses of the designed methods and materials identified. It improved the efficiency and quality of urban water services of Cauayan City and developed an integrated, energy-efficient, and sustainable urban storm water management. The potential socio-economic impacts of this paper are; at least 90% of distribution losses will be reduced (from 13% to 2% distribution losses), at least 10% of the energy used from water supplies of government offices situated in the area will be reduced, reduces the cost to build storm drain Infrastructure and at least 10% increase of income by laundry businesses. In terms of environmental impact, the construction of the GIS-based decision support tool in managing urban water infrastructure includes reduced standing water and localized flooding, reduced storm water runoff into the combined sewer system, promote infiltration and groundwater recharge, removal or reduction of contamination of hazardous elements to the surface water or groundwater resources, protection or rehabilitation of natural and artificial waterways and conserved water by increasing distribution efficiency.

For its sustainability plan and scaling-up, pilot intervention and its feasibility and acceptability are demonstrated in this pilot scale, the steps that will be undertaken for scaling-up are a policy recommendation for adoption. This is through city legislation and a roll-out of technology in clustered urban watersheds will be conducted. The technology set-up will also be incorporated in the designed Cauayan City Drainage Master Plan study in 2022 since LGU-Cauayan City and Cauayan City Water District (CCWD) are committed to accept and adopt the paper and they are willing to scale up to other areas within the city.

Finally, in terms of the coverage of the paper, the urban water infrastructure with the storm water infrastructure will be piloted at Cauayan City, Isabela. The storm water infrastructure has a catchment area of 3 hectares only. The design specification of the said storm water infrastructure was based on hydrologic data obtained from the site (i.e., from a roof to a storm water harvester).

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