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Design and Evaluation of Irrigation Piped Water Distribution Networks

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Abstract—**Sustainable agriculture largely relies on efficient irrigation because freshwater is a natural resource that is being depleted more and more because of growing populations, variations in climate, and the growing need for water. There are piped irrigation networks (drip and sprinkler irrigation networks) which provide accurate water delivery and less loss than the traditional irrigation methods, however, they are susceptible to operational problems like irregular pressure, leakage, and water distribution. The piped water distribution networks of irrigation grounding hydraulic modelling are thoroughly analyzed and designed in this paper, GIS-oriented spatial analysis, and operational evaluation to streamline irrigation system performance. The EPANET hydraulic modeling was done to determine node pressures, hydraulic heads, and pipe flows in the steady-state conditions, and the GIS visualization allowed determining areas with high demand, low- and high-pressure areas, and critical nodes in urgent need of intervention. It was used to test three heterogeneous areas of the study and found a considerable imbalance of hydraulics that was caused by topography, demand of a node, and network layout. Among all nodes, Node 71 at the highest elevation exhibited the best performance, with a head of 586.65 m and moderate pressure of 26.66 m, effectively meeting its water demand. These findings illustrate the extent to which the delivery of water can be made more efficient with the application of local measures such as changing the pump, resizing the pipe, and controlling the flow. This work, as a means of water systems enhancement, is basically a theme that combines simulation, spatial analysis and operational insights to lower unbilled water losses and to encourage clean, drought-tolerant irrigation which is not only cheap but also can vary over time.**

Keywords—Irrigation Networks, Hydraulic Simulation, EPANET, GIS-Based Analysis, Water Distribution, Pump Optimization, Sustainable Agriculture.

I. INTRODUCTION

Agriculture is still the largest consumer of fresh water on the planet, which makes the issue of irrigation efficiency not only a necessity for crop production but a most important factor for sustainable water management. These drivers, i.e. population growth, changing climate patterns, and water scarcity, have been influencing the world in general and a need for irrigation systems that not only can provide water reliably but also can cause as little waste as possible has emerged. Efficient irrigation has an immediate effect on crop yield, soil quality, and agricultural productivity for the future, and it is a key instrument in the attainment of food security [1]. Over the last several years technological changes have resulted in the use of more modern irrigation methods that are more efficient in water distribution, facilitate precision farming, and provide the possibility to integrate the real-time monitoring systems, thus enhancing efficiency and sustainability.

Drip and sprinkler irrigation systems are now the most popular piped irrigation systems used in modern farming because of their capacity to supply water to the root zone of crops at controlled pressure [2]. These systems minimise loss of water as opposed to the traditional surface irrigation techniques, there is even distribution over fields and can be coupled with automation technologies in order to tailor the flow as per crop demands [3][4][5]. These networks are pressurized, therefore, allowing efficient control of water delivery, which limits labor needs and serves massive irrigation processes. Nonetheless, in spite of these numerous benefits, the piped irrigation networks have operational challenges that are capable of undermining their efficiency, reliability and generally the effectiveness of the systems [6].

Non-revenue water (NRW) is considered to be one of the most urgent issues and is defined as the water generated but wasted due to leaks, illegal connections, or faulty metering

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[7]. NRW not only wastes a vital resource but also leads to economic losses for irrigation utilities, decreasing the financial viability of maintaining and expanding such networks. Uncontrolled losses also have the potential to impact water availability for crops, thus possibly leading to a decrease in yield and the disruption of agricultural planning [8][9]. Efficient management of NRW needs to be achieved through various measures, such as frequent leak detection, pressure regulation, network maintenance, and the use of monitoring devices that facilitate real-time detection of losses. As a result of the reduction in NRW, irrigation systems are able to keep their level of efficiency high and make sure that water is delivered to the areas that need it [10].

To provide intelligent management to irrigation systems, the pumping unit conditions are guaranteed to match the comparable pump operating points for the whole flow range and pumping height by a novel operating algorithm that also operates at safe intervals. The parameters that need to be tracked and gathered for every vertical pump are the flow, frequency (speeds), voltage, and current of each hydraulic operating mode [11]. The method is based on the concept of building an expert system to maximise the energy consumption of the pumping groups. A fully method was tested with an irrigation system comprising five pumps and a pumping group to show its effectiveness in reaching the best solution with a relatively low computational load and without violating.

A. *Motivation of the Study*

As agriculture is going through the dual challenges of increased water demand and limited water supply, efficient irrigation management is still the most important. Piped irrigation networks are very efficient in delivering water with precision, but they are often affected by leakages, pressure fluctuations, and variable crop demands thus, these problems can lead to the reduction of water use efficiency and energy performance. It is necessary to apply innovation in several ways if one is to solve the problems successfully. The methods should include hydraulic optimization, the use of smart sensors, and rational pump operation strategies in order to minimize non-revenue water, reduce operational costs and at the same time maintain a stable water supply to the agricultural fields. It is actually a move that goes beyond just improving system performance when they develop these integrated solutions, as it guarantees system sustainability for a longer period of time, thus making irrigation networks climate-resilient systems and solving the problem of food security. The main contributions of the paper are as follows:

- Used GIS-based spatial analysis and EPANET hydraulic simulations together to look at the distribution of head, pressure, and flow at certain nodes. This strategy gave a complete picture of how well the irrigation network worked.
- The differences in pressure and head at the high, mid, and low elevation nodes were pointed out. figured out which places need particular help, including changing the size of pipes and pumps.
- Evaluated possible efficiency improvements and cost-benefit effects of network optimization. This let people make better choices about how to supply water in a way that would last.
- Used the strategy in three distinct types of networks: village-scale, closed-loop, and urban. This showed how the method might work in many situations for watering and distributing water.

B. *Novelty and Justification*

This research is distinguished from others by its comprehensive methodology. The authors employed EPANET-based hydraulic simulation coupled with GIS-driven spatial analysis and operational assessment to evaluate irrigation network performance at different scales. Most of the time, researches only focus on hydraulic modeling, but this study also takes into account the elevation of the node, demand, head, pressure, pipe attributes, and system elements. This, in turn, facilitates identifying the most affected areas and hydraulic imbalances. Such an approach is indispensable for data-driven interventions in irrigation networks, which can still be efficient and sustainable even though changes in the terrain and water demand occur. By using this technique in different study areas such as village-scale, closed-loop, and urban networks, the authors demonstrate the method's adaptability and provide real-world solutions to water delivery optimization, operational efficiency improvement, and sustainable resource management support.

C. *Outline of the Paper*

Section II presents the Background on irrigation challenges, While Section III examines pertinent literature, Section IV outlines the Methodology utilising GIS and EPANET analysis, Section V discusses the Results and Discussions on hydraulic performance, Lastly, Section VI offers Conclusions and Future Directions.

II. BACKGROUND

The discussion focused about hydraulic design, GIS/SCADA integration, economic and policy challenges, and the roles of different people involved. When these things are put together, they decide how well and how long piped irrigation systems last.

A. *Irrigation Engineering and Water Resources Management*

The primary objective of irrigation engineering is to create and improve systems for delivering water. These techniques assist keep farming steady while saving important freshwater supplies. Since agriculture accounts for almost 70% of the freshwater used on the planet, the proper distribution and sustainable use of both surface and groundwater are of utmost importance. Besides enhancing crop yields, irrigation systems that are planned properly also maintain soil fertility, lower the chances of salinization, and discourage the excessive withdrawal of aquifers [12]. Contemporary watering systems mainly rely on the use of pressurized methods such as drip and sprinkler irrigation that provide water directly to plant roots, thus, saving water that would have been lost through evaporation and percolation. In addition, to ensure the sustainability of agriculture in the long run, a greater number of mathematical and computational optimization techniques are being used to conserve water for the environment while still meeting the water needs of agriculture.

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B. Civil and Hydraulic Engineering in Irrigation Networks

The two fields of civil and hydraulic engineering provide the technical base for piped irrigation networks, which makes it possible to transport water over long distances and diverse terrains in an efficient way. Such systems are complicated networks in which the water supply system function must be optimized to meet the changing demands and still be stable [13]. The layouts for the pressure pipes are very accurate because they have to maintain the flow and the pressure at the peak and the off-peak periods. In addition, the pumping stations should be arranged so that the energy costs are minimal. What is most important are, for instance, the following:

- **Pipeline hydraulics:** Understanding the link between pressure and flow and lowering head losses.
- **Large-diameter pipelines:** Making sure that long-distance transportation is fair and efficient.
- **Pumping station design:** determining the proper pump heads and capacity to fulfill changing needs.
- **Pressure management:** Using tools like valves, regulators, and optimization can help stop leaks and malfunctions.
- **Hydraulic modeling tools:** Use software like EPANET to see how the network works in different conditions.

C. Geospatial and Control System Integration

The integration of geospatial technologies and control systems has pretty much altered the way irrigation water is managed by directly associating the analysis of spatial data with the monitoring that is carried out in real-time. GIS are employed to identify the demand zones, study the earth, and draw irrigation plans. Remote sensing is very accurate in the calculation of evapotranspiration and crop water requirements. These instruments empower the decision-makers to visualize the network bottlenecks and thus they make a choice to modernize the infrastructure first [14]. On the control side, the information about flow, pressure, and leaks is given without interruption by the sensor networks, which are IoT-based, along with Supervisory Control and Data Acquisition (SCADA). Operators are able to minimize non-revenue water losses and prevent the occurrence of expensive failures if they detect anomalies in real-time. It is the integration of GIS for spatial planning and SCADA for operational control that facilitates the irrigation systems to become smarter, more reliable, and capable of responding to both demand variability and external factors like climate change.

D. Economic and Policy Considerations

Sustainability of irrigation systems depends on the engineering efficiency and also on economic viability and favourable policy frameworks. The piped networks are large in diameter and have advanced technologies in monitoring which are very costly to adopt and this necessitates financial analysis to adopt [15]. The cost-benefit analysis and life-cycle costing can be used in determining payback periods, operation and maintenance costs, and long-term water savings. These subsidies and financing schemes of development banks make further adoption through government subsidies and mechanisms of financing to farmers and cooperatives. Moreover, the water pricing policy, energy tariffs on pumping, and regulation guidelines also affect the allocation and consumption of water. Good governance structures are useful in ensuring investments in irrigation infrastructures are turned into equitable benefits, higher efficiency in water use, and congruence with national food security objectives.

E. Business Verticals and Stakeholder Perspectives

The effective introduction of the piped irrigation networks entails a number of stakeholders who play different roles at various phases of planning, construction, operation and monitoring. These systems enable farmers and agricultural cooperatives to have stable crop production and utilities and agencies in charge of large-scale planning and financing [16]. Technical engineering skills in hydraulic design and commissioning are introduced by an engineering consultancy, and the physical components of an infrastructure, including pumps, pipes, and valves, are provided by the contractors and manufacturers. Key stakeholders include:

- **Farmers and cooperatives:** End-users requiring reliable and cost-effective water supply.
- **Water utilities and public agencies:** Responsible for financing, managing, and regulating irrigation schemes.
- **Engineering consultancies:** Provide knowledge in hydraulic design, purchasing, and commissioning.
- **Manufacturers and EPC contractors:** Supply pumps, pipes, valves, and installation services.
- **Technology providers:** Offer SCADA/IoT platforms, GIS software, and leak-detection systems.
- **Development banks and NGOs:** Act as funding partners and helpers. Make sure that new technologies get to rural and underserved communities.

III. LITERATURE REVIEW

The research articles have been very diverse and have introduced varied approaches to improving irrigation systems, such as the optimization of hydraulic networks for water distribution systems, monitoring of water consumption by IoT devices, land suitability analysis using GIS, and decision-making guided by machine learning. The technologies discussed in these papers are, in fact, key enablers for the realization of irrigation efficiency and sustainability, as evidenced in Table I.

Ame, Shouhua and Khailah (2022) results suggest that the diameter of the economic pipe does not influence the changes of irrigation water quota. At any lateral length, the economically feasible pipe diameter at an emitter discharge of 2 L/h is De12. The most economical pipe diameters are De12 and De16 when the lateral length is 40 m − 70 m and 80 m − 120 m, respectively, and the emitter discharge is 4L/h. When the lateral lengths are 40–50 m, 60–80 m, and 90–120 m, respectively, and the emitter discharge is 8L/h, the economic diameters are De12, De16, and De20 [17].

Zamani, Fatahi and Provenzano (2022) The trials were conducted at pressures of 50, 100, and 150 kPa, and measurements were made at 1, 2, 3, and 24 hours to determine the irrigation pattern geometry associated with each lateral. The results were contrasted with the model simulations. Furthermore, for the soaking depth below the lateral, the revised index of agreement, mean absolute error (MAE), and root mean square error (RMSE) were 0.013 to 0.03 m, 0.002

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to 0.004 m, and 0.886 to 0.927 m, respectively. At the first and last cross-sections of the laterals, the previously mentioned index values similarly ranged from 0.011 to 0.035 m, 0.814 to 0.942 m, and 0.001 to 0.004 m, respectively. These findings demonstrated that there are no appreciable disparities between the measured and predicted wetting pattern dimensions, and that a thorough model yields accurate estimates of the flow rates of the emitters along with realistic wetting patterns [18].

Wang et al. (2022) the experiment of unidirectional flow technologies was used as the control when the effectiveness of commutative flow technology was evaluated. The commutative and unidirectional flow drip irrigation pipes emitter blocking rates were 7.7 and 35.9%, respectively, and the emitter average relative discharge (Dra) decreased to 92.8 and 62.9% at the end of the testing. Sediment comparing the commutative and unidirectional flow laterals accounted for 37.5% less in the former. Commutative flow technology can efficiently control the emitter blockage rate, the amount of lateral silt, and the decrease rate of flow discharge as compared to unidirectional flow technology. So, the introduction of commutative flow technology into the drip irrigation field pipe network can not only facilitate the muddy water drip irrigation expansion but also improve irrigation quality [19].

Bwambale et al. (2022) these sources of information would be very helpful in understanding the use of GIS and RS for irrigation water management and the role of technological innovations in the irrigation water sector for water saving. It is still equally necessary to introduce the technology that can cut water losses, match the available water with demand, and monitor performance if the aim is to make water use in irrigated agriculture more efficient. Remote sensing (RS) and geographic information systems (GIS) are two technologies that can be utilized in the management of water and land resources in the irrigation sector. The current study is going to explore the current status of GIS and RS in the irrigation system with the coverage of such aspects as agricultural water requirements, irrigation scheduling, land suitability for irrigation, performance evaluation, and other related applications [20].

Scarlatache et al. (2021) examined studies on the combination of a variety of machine learning algorithms that can provide the most effective irrigation recommendation. The deployment of proven ML models for farmers to utilize in the direction of sustainable irrigation management is reviewed in this article, along with the research trend and application of ML techniques. Additionally, it talks about how digital agriculture technology, such as mobile and web platforms, can be used to control intelligent irrigation practices, which can help farmers and researchers feel less stressed because they can monitor and control their operations remotely. There is also discussion of the difficulties and the future course of the study [11].

Joshi, Raval and Patel (2021) A smart irrigation system with sensors and a microprocessor to maximise irrigation water consumption and minimise electricity waste. Anywhere in the world can be used to operate the system described in this book. For irrigation purposes, a farmer does not have to be on the farm. With a few adjustments, to maximise water and electricity use, gardens can also benefit from this low-cost smart watering system [21].

Saad, Benyamina and Gamatie (2020) emphasis on the problem of water management in general, current strategies seek to maximise water use and enhance the quantity and quality of agricultural products while reducing the need for direct human intervention. There are several water-related problems in agriculture, such as tracking water pollution, recycling water, and monitoring the system of water pipelines for animal drinking water and irrigation. Thus, with the help of advanced technology, this paper offers a summary of current research on agricultural water management and monitoring [22].

Irrigation management has been significantly improved; however, there are still several research gaps uncovered. Research has been done on hydraulic optimization, emitter performance, and flow technologies, but in general, these studies concentrate on the components of irrigation systems separately without considering the performance of the whole system. Some experiments have been carried out to verify the accuracy of wetting patterns and emitter flows at a local scale, and these results are sometimes not applicable to larger or different networks. The use of the latest technology such as GIS, remote sensing, and smart irrigation systems may be a solution to water saving; however, to date, the integration of these technologies with real-time hydraulic modeling and network optimization is still at a very early stage. Additionally, machine learning and digital farming solutions show promise for decision support, but practical implementation challenges, scalability, and adaptability across varied topographies are not fully addressed. Overall, there is a need for comprehensive, data-driven approaches that combine hydraulic modeling, spatial analysis, and smart technologies to optimize irrigation efficiency, manage water resources sustainably, and support large-scale deployment across heterogeneous agricultural landscapes

TABLE I. COMPARATIVE SUMMARY OF STUDIES ON IRRIGATION NETWORK DESIGN AND SMART IRRIGATION SYSTEM

Authors / Year	Objective	Methodology / Tools	Key Features	Application / Case Study	Findings / Outcomes
Ame, Shouhua & Khailah (2022)	Evaluate economic pipe diameters under varying emitter discharges	Hydraulic analysis, emitter flow experiments	Analysis of emitter discharge (2, 4, 8 L/h) and lateral length influence on economic pipe diameter	Irrigation lateral design	Economic pipe diameter varies with emitter discharge and lateral length; insensitive at low discharge
Zamani, Fatahi & Provenzano (2022)	Assess wetting pattern geometry and emitter flow accuracy	Experiments at 50, 100, 150 kPa; model simulations	RMSE, MAE, refined index of agreement	Drip irrigation laterals	Predicted wetting patterns closely match measurements; model provides accurate emitter flow estimates

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Wang et al. (2022)	Compare commutative vs. unidirectional flow technologies	Drip irrigation experiments	Flow discharge rate, emitter blockage, sediment deposition	Drip irrigation lateral pipes	Commutative flow reduces discharge decline, lowers blockage rate, and decreases sediment deposition
Bwambale et al. (2022)	Explore Applications of RS and GIS in Irrigation Water Management	Literature review / GIS & Remote Sensing tools	Land suitability, Crop water requirements, scheduling of irrigation, and performance assessment	Irrigated agriculture	GIS & RS improve water use efficiency, enable monitoring, and support optimized irrigation planning
Scarlatache et al. (2021)	Review machine learning for smart irrigation	Literature review / ML techniques	Predictive irrigation decision-making, digital farming solutions	Smart irrigation systems	ML models and digital platforms enable remote monitoring and sustainable irrigation management
Joshi, Raval & Patel (2021)	Develop low-cost smart irrigation system	Microcontroller & sensors	Remote operation via mobile, real-time monitoring	Small farms and gardens	Optimizes water and electricity use; allows global remote management
Saad, Benyamina & Gamatie (2020)	Survey water management and monitoring in agriculture	Literature review / smart technologies	Optimization of water usage, automated monitoring	Agriculture water management	Highlights modern tools for water management, identifies challenges, and suggests future research directions

A. Choosing and Identifying Important Irrigation System Data.

In order to discover entities and attributes and to make it easier to classify and code the data, a crucial step in creating normalised and non-redundant table structures, the available data was reviewed. To determine every element that comprise the irrigation system database's entities, from the primary input to the farm-level turnouts, the different components of the irrigation system were identified according to their functions within the system [23]. The significance of the records, the criteria for the irrigation distribution model and system management, and the parameters for system evaluation and optimisation were used to determine the irrigation data.

1) Establishing the Necessary Estimation Parameters

As a prerequisite for developing an irrigation distribution model, it was discovered that estimation parameters were used for both system administration and derived metrics computation. Typically, it is not possible to directly extract these estimation parameters from the system's available data. These were calculated or deduced and applied to the assessment of system elements. The built database in the GIS environment incorporate these properties.

2) Development of GIS

The three most crucial database components are chosen as part of the GIS creation process: (1) GIS software with the ability to execute process analysis models, save and modify databases, and display stored data and the analysis that results [24], (2) design of system geographic characteristics, properties, and structures, a lightweight, opensource (free) relational database management system that is simple to distribute, access, and manipulate offline, and (3).

3) Development of an irrigation network distribution model

Based on the current real flow distribution, a network model was created. Elements of governing hydraulics and flow dynamics were applied while taking into account the field's data and the practices and operations of irrigation.

B. Choosing Appropriate Methods for Evaluating Water Distribution

1) Evaluation of the Distribution of Volumetric Irrigation

The Relative Water Supply (RWS) Index was used to evaluate the volumetric irrigation distribution [25]. The supply and demand ratio compares the amount of water available at the field level with the amount required for crop production throughout the cropping period to assess whether the irrigation supply is sufficient. All of the irrigation water delivered from the source is the supply, and the predicted amount of water required for farming is the demand.

Fig. 1. Schematic representation of the irrigation network's flow process.

The Mapping Evapotranspiration at High Resolution with Internalised Calibration (METRIC) model and crop evapotranspiration (ET) obtained from remote sensing data were used to forecast crop water demand (CWR) [26]. Figure 1 displays the ET determination schematic diagram. Using the surface energy balance, Weather data, DEM, service area, and Landsat satellite imagery were utilised to estimate ET using the METRIC model.

2) Evaluation of the Temporal Distribution of Irrigation

Effective irrigation scheduling can increase water efficiency in rice farming by preventing crop water stress and excessive irrigation, both of which can impair plant growth and development. The Water Stress Coefficient (Ks) calculated in order to characterize the crop water condition [27]. A crop is deemed water-stressed by the FAO when the soil water's potential energy falls below a certain threshold. The Ks scale ranges from 0 to 1 and shows how much moisture is in the soil. A reading of 0 means the soil is completely dry, while a reading of 1 indicates a water penalty.

IV. MATERIALS AND METHODS

The different methodologies treated the analysis of water distribution systems as the first step to using EPANET for

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hydraulic simulations and GIS-based spatial analysis to assess network performance and optimize water delivery. EPANET facilitated the computation of pressures at nodes, heads, and flows of pipes with the help of local data such as altitude, consumption, diameter, and length of the pipe, roughness, pumps, and tank levels. Steady-state simulations pinpointed the areas where changes in head and pressure were most significant, for instance, at very high-elevation nodes like 71 and at medium-elevation nodes such as J8, resulting in the formulation of instructions for pump adjustments and pipe resizing. The main parameters that were taken into account were node ID, elevation, demand, head, pressure, pipe attributes, and system elements, which allowed performing a detailed hydraulic check, identifying the most critical points, and planning a reliable and sustainable water distribution system efficiently. This method has been extensively applied in past research to analyse irrigation and distribution of water. The methods and parameters that are used in this research study as follows:

A. Techniques and Parameters Used in the Study

The irrigation system was tested to determine the hydraulic performance, distribution of pressure, and patterns of water demand. The method employed was a hydraulic modeling of EPANET along with spatial analysis and operational evaluation of the data via GIS to locate the main nodes and maximize system efficiency.

1) Hydraulic Simulation

The irrigation network's hydraulic performance was digitally simulated by EPANET, a standard water distribution network model software. EPANET carries out the operations of node pressures, hydraulic heads, and flow distributions in pipes with the help of the given inputs that have: node elevation, water demand, pipe diameters, lengths, roughness coefficients, pump capacity, and tank elevations [28]. The present study used EPANET to conduct an examination of the water distribution system concerning its hydraulic performance at the chosen junctions, the influence of the terrain, and demand patterns on the network. Moreover, the simulation results were decoded and presented through GIS to make the strategic planning process for delivering water that is both efficient and sustainable easier.

They additionally performed steady-state simulations to understand the distribution of the head, pressure, and flow at the nodes and pipes that map the system's operation, considering the existing demand conditions. The outcomes of the simulations indicated that the difference of head and pressure was very significant both at very highly elevated nodes like node 71 and at moderately elevated junctions such as J8, thus they were used to determine local actions, for instance, changes of pump speed and pipe rescaling.

2) GIS-Based Spatial Analysis

The spatial distribution of surface height, water demand, head, and pressure over the network was revealed and studied through a GIS-based method. By expressing these criteria in maps, it was feasible to expose the area of high water demand, the zones of low and high pressure, and the most critical nodes for operation [29]. The combination of GIS visualization with hydraulic simulation provided a complete picture of network performance, thus making it easier to plan strategically for hydraulic balancing and sustainable water delivery.

3) Operational and Economic Insights

The study went on to calculate the possible economic impact of network optimization. A cost-benefit view was created by factoring in elements like water savings, pump efficiency, and system interventions to facilitate the decision-making process and investment prioritization that would not only improve the hydraulic performance but also the operational efficiency.

B. Study Area (1-3)

The study spans three different regions, implementing similar methodologies as the previous studies. The first Study Area (Nelatur Village) comprises a tree or dead-end network which caters to 2,807 people over 10 km^2 with 80 nodes and a single reservoir, where high-demand zones are depicted by tightly packed node areas, thus, localities with dense node concentrations represent the highest-demand zones, following the procedure of comparable village-scale analyses [30]. The second Study Area is a network in a closed-loop with 14 nodes, 16 pipes, and one overhead tank, using the Hazen-Williams method for the design and the pipe diameters being at least 150 mm with the pressures at all junctions being adequate, as implemented in previous engineering studies . The third Study Area (Zone 3) is about 103,500 population calculated by geometric growth with an annual growth rate of 3.5%, the water demand estimated at 100 LPCD for the design horizon to 2031, in line with the methods of the previous urban water demand studies [31]. The hydraulic modeling and network analysis for all these regions were done with the support of EPANET, which helped to understand the connectivity of nodes, flows in pipes, distribution of pressure, and points that are very important for system optimization, thus, implementing the techniques that were used in the earlier research.

1) Study Area 1

Nelatur Village's water supply system has been designed. Nelatur Village has a population of 2807 and is the 7th most populous village in Maddipadu sub-district, Prakasam district, Andhra Pradesh, India. The village has a total area of 10 km^2, thus it is the 6th largest village by area in the sub-district, with the population density being 291 persons per km^2 and the number of houses is 745 [30]. Nelatur is the area served by Nelatur Panchayat, which is 7 km away from the sub-district headquarters, Maddipadu, and 21 km from the district headquarters, Ongole. The distribution system planned for the village is a tree or dead-end type layout with 80 nodes and one tank as shown in Figure 2.

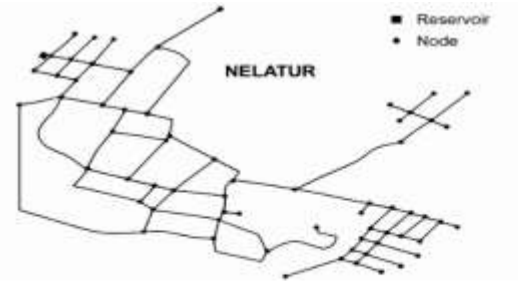

Fig. 2. Water Distribution System of Nelatur Village

Figure 2 shows the water distribution network map for NELATUR depicts a reservoir supplying water through an interconnected system of pipes (lines) and multiple nodes

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(filled circles). The reservoir serves as the main source for the branching sub-networks across the area. High concentration of nodes in the lower right and upper left areas typically point to residential or high-demand zones. The diagram is a clear representation of the hydraulic connectivity and thus, can be used as a basis for the analysis of water flow and pressure changes across the network.

2) Study Area 2

The water distribution network of the study area consists of one large overhead tank, fourteen nodes, and sixteen pipes [32]. The Hazen-Williams Method is employed to determine the pressure. It is found that there is enough pressure in all the connectors. The smallest pipe diameter of 150 mm was chosen. There are changes in the pressure head. The pipe's roughness coefficient along the 120-pipe network.

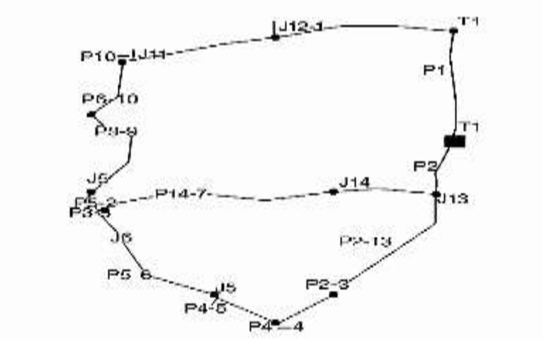

Fig. 3. Study Area Distribution Network Diagram

Figure 3 illustrates a diagram of a closed-loop pipe network utilized for the analysis of water distribution. The nodes referred to as 'J' (J1-J14) are connected to each other by pipes like P1 or P2-13, thus constituting a perimeter circuit with a center branch that connects J7 and J13 through J14. A unit named 'T1' on P1 could be a pump, a valve, or any other a hydraulic component that is changing the flow. The figure demonstrates the network layout, which is the basis for the calculation of flow rates, pressure, and head requirements.

3) Study Area 3

The population of 103,500 for Zone 3 was based on a 1995 study conducted by consultants and projected using the geometric growth formula: $P\ t = P\ i\ (\ 1 + r\ )\ n$, where the starting population is denoted by $P\ i$, the yearly growth rate by r, the number of years by n, and the projected population by $P\ t$ (UNESCO, 2008). As per Sustainable Development Goals, water demand over a design horizon up to 2031 was estimated by using an annual growth rate of 3.5% (Tahal Consultants, 1995) and multiplying the result by 100 liters per capita per day (LPCD) [31].

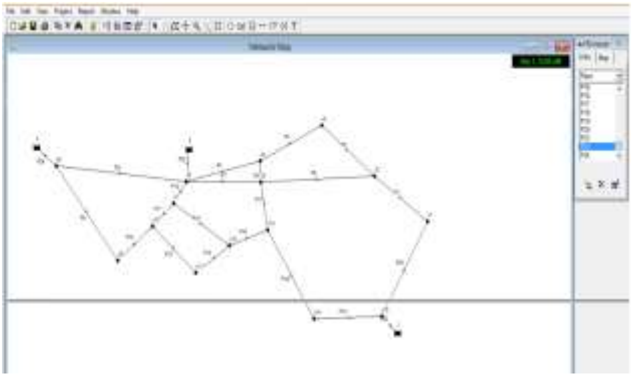

Fig. 4. EPANET Network Map

Figure 4 shows a network map within a hydraulic modeling software interface, likely EPANET. It depicts a pipe network with interconnected pipes (P1–P24) and junctions (J1, J2, J3, etc.), with lines representing pipes and dots representing nodes. A small window highlights pipe P24 and shows user interaction. The top bar displays standard menus and toolbar icons. The map time is “Day 1, 12:00 AM”.

C. Key Parameters Considered

- **Node Characteristics:** The research examined the influence of topography and demand patterns on network performance. The variables comprised elevation, water demand, hydraulic head [33], and pressure at each junction.
- **Pipe Attributes:** It had the diameters, lengths, and roughness coefficients of pipes so that friction losses and flow capacity could be figured out.
- **System Elements:** They looked at the heights of the storage tanks and the pumping stations to determine how they helped keep enough head and pressure in the network.

The irrigation network was well assessed through the integration of EPANET simulations with GIS-based spatial analysis and operational evaluation. The method used showed that the system not only functioned efficiently in certain areas but also revealed the places that needed to be improved for enhanced hydraulic performance and system optimization.

D. Network.

The examination of the irrigation network showed how effectively it works and helped find the exact improvements that need to be made. It looked at a few crucial things for each node [34]. These factors included:

- **Node ID:** To be able to track the hydraulic properties of the nodes and do geographical analysis, each junction or node in the network was given a unique identification.
- **Elevation (m):** Each node was raised high in relation to a reference level in order to determine its effect upon the hydraulic head and pressure distribution throughout the network.
- **Demand (m^3/s):** Water demands of the nodes were also included to model realistic flow and determine the areas of high demand.

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- **Head (m):** The total energy in each node has been computed to get better picture of the capability of the network to supply water at its present state.
- **Pressure (m):** The calculated pressure at each node gave information of areas that were over-pressurized or those that were under-pressurized and were the points where optimization was vital.

Besides the parameters of the nodes, the pipe parameters like diameter, length, roughness coefficients, and system parameters such as pump capacities and tank elevations were taken to represent the friction losses, flow distribution and the system performance as a whole. These characteristics worked together to give a full image of how hydraulic behavior works. This helped find problems and come up with solutions to make water distribution more efficient and long-lasting.

V. RESULTS AND DISCUSSIONS

The EPANET simulation of the irrigation network reveals the specific hydraulics of the system at selected nodes. Node 71 which is the highest point with an elevation of 559.99 m had a head of 586.65 m and a pressure of 26.66 m which indicated a water demand of 28.35 m^3/s. J8 at the middle level (336 m) was the place with the highest demand of 55 m^3/s, and the head and pressure were 356.01 m and 20.01 m, respectively, which meant that the water requirements here were very high. The low elevation nodes like Ju 23 (25 m), Junc n2 (99.15 m), and Junc J4 (60.64 m) had lower heads than the others and their pressures varied with Ju 23 being the location where the highest pressure of 65.65 m was recorded, while Junc J4 was at 41.3 m. These data demonstrate the presence of significant hydraulic variations across the network that is referred to in Table II which have a strong correlation with elevation as well as demand at each node determining the distribution of head and pressure. The results point to the places in the system where the implementation of measures, such as pump adjustments or pipe resizing, could improve the hydraulic performance and ensure that water delivery remains efficient

TABLE II. EPANET SIMULATION RESULTS

Ref	Node ID	Elevation (m)	Demand (m^3/s)	Head (m)	Pressure (m)
[35]	71	559.99	28.35	586.65	26.66
[36]	Ju 23	25	5.38	90.65	65.65
[30]	Junc n2	99.15	3.44	93.69	15.05
[32]	Junc J4	60.64	2.44	101.94	41.30
[31]	Junction J8	336.00	55.00	356.01	20.01

Table II provides the local heights of the different points of an irrigation water distribution network in meters. These points include Junction J8, Junction J4, Junction J2, Ju J23, and node 71. According to the graph, node 71 is located at the highest point with an elevation of 559.99 m. Consequently, Junction J8 is the next highest with 336 m, whereas find that Junction J2, Junction J4, and Ju J23 have very low elevations of 99.15 m, 60.64 m, and 25 m, respectively. The difference in elevation is, indeed, very important to figure out the distribution of the hydraulic head and the regulation of the pressure in the system.

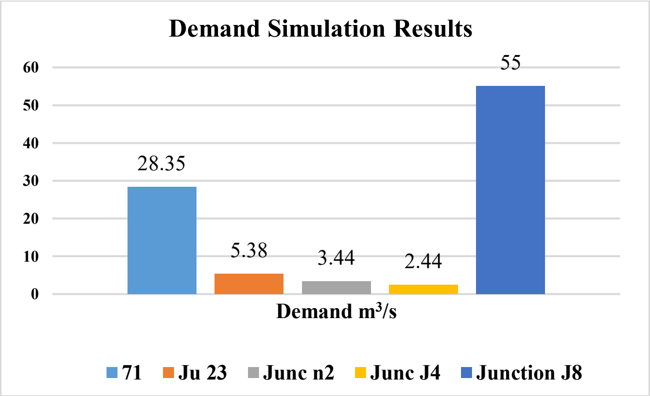

Fig. 5. Demand (m^3/s) at Selected Junctions in Rrigation Distribution Network

Figure 5 displays a wide range of differences between the nodes, the most notable being the demand at the Junction J8 that reached 55 m^3/s, then node 71 with 28.35 m^3/s, while Ju 23, Junc n2, and Junc J4 had relatively low demands of approximately 5.38, 3.44, and 2.44 m^3/s, respectively. Such a spread of consumptions emphasizes the necessity of water balancing in the system as well as its design based on the given network.

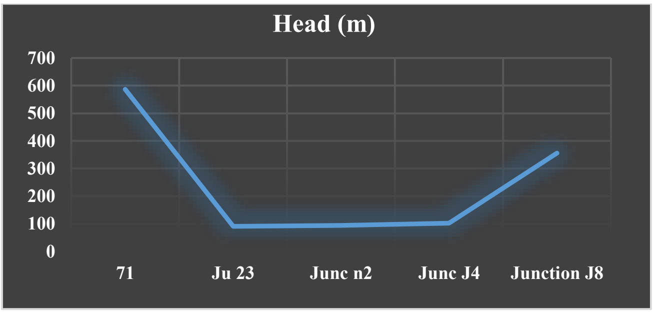

Fig. 6. Head (m) Distribution Across Selected Nodes in The Irrigation Network

The maximum head at node 71 is captured by Figure 6 (around 590 m) and subsequently, the head drops sharply at Ju 23 and Junc n2 (close to 100 m), with Junc J4 still holding a similar level and then a slow rise is noticeable at Junction J8 (approximately 350 m). Such a change in head is indicative of the water distribution system that is out of balance in terms of hydraulics due to the effect of elevation and pressure differences on the operation of the system.

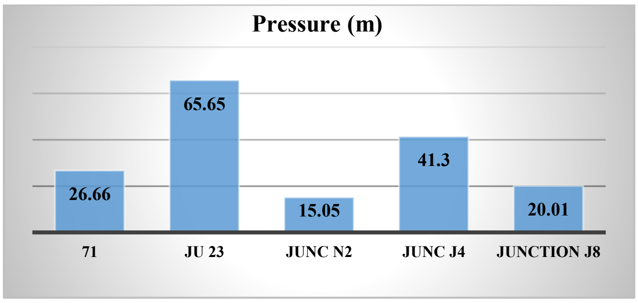

Fig. 7. Measured pressure at various locations (in meters)

The pressure values at different points in the system are given in Figure 7 in meters. According to the graph, the pressure at location JU 23 is the highest with 65.65 m, and that

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at JUNC J4 is the second-highest with 41.3 m. Besides these places, 71, JUNC N2, and JUNCTION J8 also have lower pressures of 26.66 m, 15.05 m, and 20.01 m, correspondingly. Such a distribution of pressure ensures that there are significant differences in pressure at the points where it is checked, which can also be used for pointing system areas to be optimized or checked further.

A. *GIS-based Network Insights*

Analyzing the irrigation network spatially brings out the operational patterns that are very clear. The areas of high water demand are the elevation extremes, for instance, node 71 which is at a higher elevation with moderate demand and Junction J8 at mid-elevation with peak demand. The differences in pressure indicate that there are still areas where the pressure is not balanced and hence nodes such as Ju 23 and Junc J4 have somewhat higher pressures than other nodes. Such results constitute a very loud signal for the necessity of a target intervention. These measures should include the installation of extra pumping capacity in elevated areas to maintain adequate head and the resizing of pipes or flow control measures to be used in lower-elevation, high-pressure zones so as to prevent over-pressurization. The use of GIS visualization facilitates the identification of the most important nodes, thus it is a great tool for making the right decisions regarding hydraulic balancing, energy saving, and sustainable water delivery.

B. *Discussions*

The irrigation network shows large changes in the water distribution through the pumping system in the different parts of the network, from the results of the simulation. As illustrated in Figure 8, the elevation of selected junctions varies significantly, influencing the hydraulic behavior across the network. Node 71 is the node that has been performing best, as evidenced by its highest head of 586.65 m with moderate pressure, and this node 71, which is situated at the greatest height, is therefore able to meet its demand satisfactorily. However, the J8 junction, even though it is at a mid-elevation point, is characterized by a high demand (55 m^3/s) and relatively low pressure, which may lead to it being a constraint at a peak performance situation. The pressure of the lower-elevation nodes like Ju 23, Junc n2 and Junc J4 varies with each other as Ju 23 has the highest and Junc n2 the lowest pressure, thus showing the occurrence of local imbalances. These findings highlight the influence of the terrain and the demand at each node on the hydraulic system performance. All in all, Node 71 is the most suitable node, as far as the distribution of heads is concerned, whereas other nodes can also be improved by adjusting the pump or resizing pipes. The combination of the GIS analysis also defines the key nodes and the locations of high demand, which outlines the effective planning and optimization of the network.

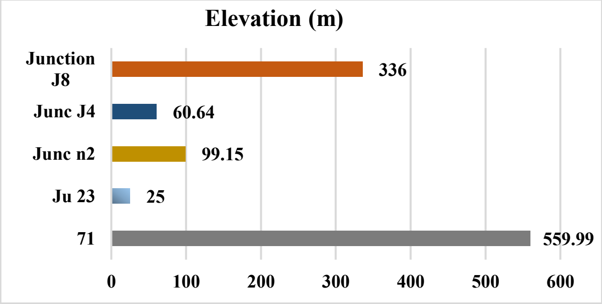

Fig. 8. Elevation of Selected Junctions in the Irrigation Network

VI. CONCLUSION AND FUTURE DIRECTIONS

Sustainability of agriculture relies heavily on effective management of water especially in places where there is increasing water scarcity, population, and climatic change. This paper has provided an elaborate model for solving and optimization of piped water distribution systems of Irrigation by incorporating hydraulic simulation, spatial analysis using GIS and operational evaluation. The findings showed that there were high differences in the hydraulic head, pressure, and flow among the nodes with Node 71 having the tallest elevation and being the best in the hydraulic head and moderate pressure with good performance in satisfying its water demand. Critical nodes were found with low or high pressure and it is important to provide specific interventions like pump adjustments, pipe sizing and flow control points to enhance the efficiency of water delivery as a whole and decrease non-revenue water. GIS visualization and hydraulic modeling were found useful in the detection of the high-demand areas and bottlenecks of operation to support the development of sustainable irrigation management based on data. Further research will be done on real-time monitoring and decision-support systems based on IoT-enabled sensors and SCADA-based platforms to dynamically control the pressure, flow, and water distribution. Adding predictive models based on machine learning and scaling the framework to include the seasonal changes, as well as multiple crop irrigation needs, will improve the resilience of the systems, their efficiency, and long-term agricultural productivity.

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