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Designing Resilient Water Distribution Systems Under Demand Uncertainty: A Kohat City Case Study

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Abstract: This study explores the impact of accurate water demand forecasting and the integration of diurnal consumption patterns on the design and efficiency of water distribution systems, particularly in Pakistan. Due to the lack of a comprehensive metering infrastructure, water demand patterns remain poorly understood, complicating optimal system design. In response, a hypothetical diurnal pattern based on Iranian water usage behaviours was adopted to simulate and assess the performance of water supply systems under varying demand scenarios. The study compares two models: one based on instantaneous peak demand and the other incorporating realistic diurnal fluctuations over a 24-hour period. Simulations revealed that designing systems based on instantaneous peak demand leads to overdesign, resulting in excessive pressure during low-demand periods, thus increasing operational costs, risking pipeline damage, and reducing system lifespan. In contrast, designing with a diurnal pattern proved to be more cost-effective, sustainable, and reliable, as it better matched actual consumption patterns. The findings emphasize the necessity of integrating dynamic pressure management, seasonal and peak demand considerations, and advanced flow regulation techniques in future infrastructure projects. These recommendations aim to enhance the sustainability and efficiency of water distribution systems, ensuring adequate water supply and equitable distribution, while minimizing resource wastage and operational inefficiencies.

I. INTRODUCTION

Water supply planning in rapidly urbanizing and population-growing regions, like Pakistan, presents significant challenges, particularly due to the uncertainty of water demand. Accurate water demand forecasting is crucial for efficient resource allocation and infrastructure development. However, in the absence of comprehensive daily consumption patterns, predicting water demand remains uncertain. This research proposes a solution to this issue by integrating statistical analysis, hydraulic modelling, and optimization techniques to design a robust water supply system that accounts for fluctuating and uncertain demand in Pakistan.

The proposed approach begins with statistical analysis of historical water consumption data to identify trends, seasonality, and potential demand fluctuations. Hydraulic modelling is then employed to simulate water distribution networks, considering factors such as pipe diameter, elevation, and network topology to optimize system design. Lastly, optimization techniques are applied to determine the most efficient allocation of resources, minimizing costs while ensuring reliable supply. By combining these methodologies, this study offers a comprehensive framework for designing flexible, resilient, and sustainable water supply systems capable of adapting to uncertain demand scenarios in Pakistan’s context, providing valuable insights for infrastructure planning and resource management.

II. LITERATURE REVIEW

Accurate evaluation of water demand and consumption patterns is vital for effective water management amid global water scarcity. Worldwide studies have explored this using methods like surveys, water metering, Smart Pulse metering, interviews, observations, and IoT-based technologies.

This literature review provides a comprehensive overview of research efforts, highlighting the critical role of water demand and diurnal patterns in designing efficient water supply systems.

The growing global demand for reliable water delivery systems is driven by urbanization, population growth, and infrastructure expansion. Ensuring a sustainable water supply is crucial, particularly in rapidly developing cities, as water remains essential for industrial, residential, agricultural growth, and the survival of all living beings [1].

Water scarcity is a major challenge in arid and semi-arid regions, where economic growth heavily relies on a stable water supply. To secure resources for future generations, stakeholders are increasingly focused on conserving and managing water consumption effectively [2]. With the growing importance of clean water, both its demand and usage are steadily rising. Water remains essential for sustaining life on Earth and plays a crucial role in supporting both environmental balance and human survival [3]. Accurate forecasting of water demand is vital for planning reliable supply systems, and over the past three decades, extensive efforts have focused on refining prediction methods [4]. Precise calculation of customer water demand is crucial for effective hydraulic management across the water supply network [5].

Sustainable water use requires forecasting future demand, planning treatment and supply systems, securing resources, and managing wastewater. Per capita daily consumption is the key metric for residential water use, guiding municipalities in estimating future supply needs based on population projections [6]. Water demand forecasting is crucial for designing, managing, pricing, and planning water supply systems. It informs decisions on new system designs, upgrades, reservoir sizing, pump station planning, and determining pipe sizes and capacities [7]. Water distribution systems are responsible for delivering clean water at acceptable pressure. Effective management requires accurate demand forecasting for system design, pricing, and operational planning. Ensuring equitable water distribution is crucial to minimize the supply-demand gap, making precise prediction of water demand and consumption patterns essential for efficient resource management [8].

In Peshawar, the average daily water usage per person is 30 gallons, with peak demand often 1.5 times higher. Factors such as climate, income, and supply availability influence water demand. A study by the Japan International Cooperation Agency projects a decrease in per capita water use in Peshawar from 327 LPCD in 2009 to 205 LPCD by 2035. In India, the National Institute of Urban Affairs sets minimum water supply standards, with low-income villages requiring 40 LPCD, non-sewered areas needing 70 LPCD, and those with piped systems requiring 135-150 LPCD [9].

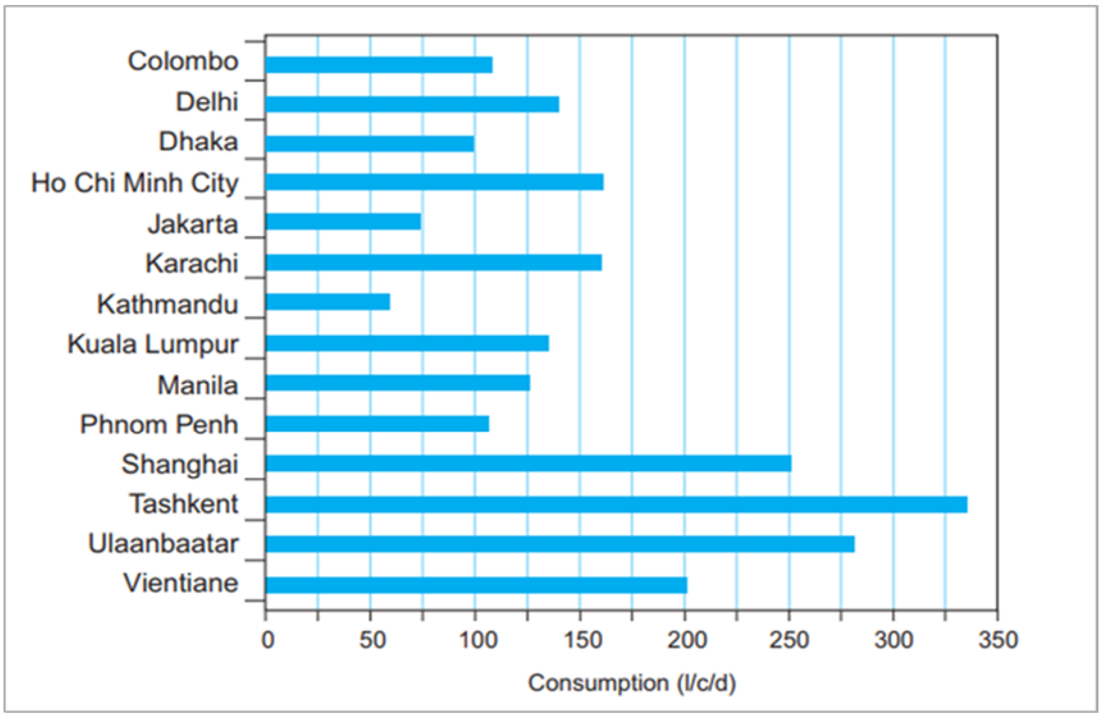

Figure 1.1 Shows the water consumption in different cities of the world

Towns depend on central water supply systems, as building individual networks is not economically feasible. To ensure adequate water quality, quantity, and pressure, the design and management of these systems must consider water demand and usage trends. Accurate water demand forecasting is essential for the effective operation and maintenance of distribution systems.

Kuala Lumpur's average daily water usage is 288 liters per person, falling within the typical range of 200 to 300 liters per day [10]. Rapid urbanization and population growth in Pakistan significantly impact water use, with per capita consumption ranging from 30 to 350 liters per day.

This variation is influenced by factors such as location, socioeconomic status, and climate conditions [11]. The projected water requirement for urban dwellings in Peshawar is 246 LPCD, as per USAID standards.

However, a National Development Consultants (NDC) study indicates actual residential usage of 164 LPCD, including 25% for non-domestic use, 20% for unreported water losses, and 5% for fire safety [9]. In Peshawar, water requirements for planning and maintaining supply systems vary across businesses and organizations. The Peshawar Development Authority (PDA) applies different values based on living standards, while the Public Health Engineering Department (PHED) uses a standard of 15 GPCD for water system development.

- Elegant Modern Town: minimum 300 LPCD
- Affordable lifestyle: 200–250 LPCD
- Basic low level: 70–120 LPCD

The lack of a standardized water demand value complicates effective planning. Designing a water supply system requires considering a region's population, daily water demand (LPCD), and 24-hour usage pattern, which vary based on climate, culture, and lifestyle. While Pakistan has used the instantaneous model for system design, this approach incurs higher costs compared to a diurnal pattern-based design. In this study, I used a hypothetical diurnal schedule to explore potential variations.

III. METHODOLOGY

To assess design uncertainty in Kohat’s water distribution system, model two demand scenarios. First, we apply a uniform, instantaneous demand at each node to establish baseline performance. Then, we impose a realistic diurnal demand curve over 24 hours, without changing the system's physical layout. Comparing pressures, flows, and service levels between the constant and time-varying simulations will reveal whether infrastructure designed for steady demand can handle real-world consumption fluctuations.

A. Population Projections

Table 1.1 summarizes population forecasts derived from past growth rates extended across the study horizon. By projecting each urban council’s historical trend forward, we identify which areas will remain the most and least populous, information that guides equitable urban planning and infrastructure investment.

Table 1.1 Kohat Projected population for the years 2022, 2025, 2030, 2035, 2040 & 2045

S.No	Union Council	2022 Pop	2025 Pop	2030 Pop	2035 Pop	2040 Pop	2045 Pop
1	Cantt	39,841	41,451	44,056	46,459	48,659	50,660
2	Urban 1	27,555	27,702	27,929	28,128	28,302	28,454
3	Urban 2	69,493	74,082	81,746	89,076	96,003	102,480
4	Urban 3	19,839	20,458	21,448	22,349	23,165	23,899
5	Urban 4	61,645	65,154	70,948	76,419	81,532	86,267
6	Urban 5	33,115	35,567	39,701	43,699	47,514	51,112
7	Urban 6	53,211	59,733	71,386	83,422	95,589	107,656
Total		**304,699**	**324,147**	**357,214**	**389,552**	**420,764**	**450,528**

B. Base Demand for Nodes

Base demand was set by first dividing the design horizon population evenly across network nodes, yielding a population per node. Each node’s figure was multiplied by the per capita consumption rate uniform across domestic, commercial, and industrial users because detailed data were lacking to obtain a constant base demand. These values were imported into EPANET via the Demand Pattern Editor, and a final check confirmed that the sum of all node demands matched total water availability and system capacity, preserving model realism.

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Table 1.2 Shows the base demand at each node

Parameter	Value	Notes/Explanation
Population per Node	9,023	Population per node = Total Population ÷ Nodes (38)
Base Demand per Node (L/s)	Population per Node × Daily Water Demand÷86,400	Use this formula to calculate demand per node in EPANET

Because the design assumes 100 L per capita per day and an even population split among nodes, every node receives the same base demand, keeping hydraulic loads uniform and simplifying network analysis.
Equal population at every node means equal demand, so under the 100 Lpcd assumption each node draws 10.44 L/s streamlining pipeline design and ensuring uniform service across the network.

C. *Instantaneous Water Supply*

Simulations of the Kohat water supply network were conducted for 100 LPCD models, adjusting base demand across nine scenarios. The system was optimized to ensure minimum pressure at all nodes remained above 14 meters, with varying pipe diameters to meet pressure requirements efficiently. Designed for gravity flow, the network minimizes reliance on mechanical pumping, reducing operational costs and enhancing sustainability. A peaking factor of 2.7 was applied to account for demand volatility, including weekly and seasonal spikes. The iterative design balanced base demand, peak factors, and gravitational constraints, ensuring robust hydraulic performance. This approach supports efficient infrastructure planning, future growth, and reliable water delivery for Kohat. The final output here in the Figure 1.2.

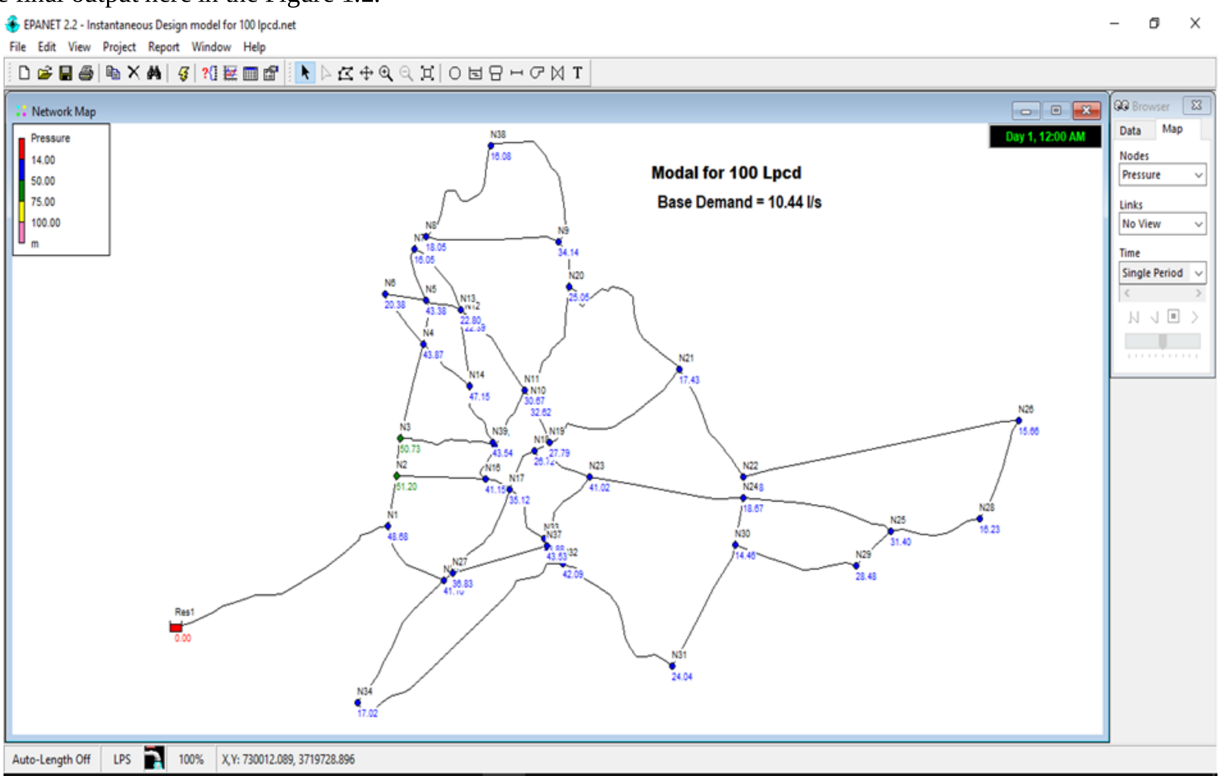

Figure 1..2 Shows the Distribution network with nodal pressure

D. *Continuous Water Supply with Diurnal Pattern*

Running the 100 lpcd model with a diurnal pattern and a peaking factor of 1.54 showed that the system, originally sized for instantaneous supply, was overdesigned leading to oversized pipes, reservoirs, and pumps. This highlighted inefficiencies and unnecessary costs, emphasizing the need for a 24-hour consumption pattern to accurately size infrastructure for real-world demand, ensuring a more cost-effective, sustainable, and reliable water supply system.

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E. Adoption of an Specific Hypothetical Diurnal Pattern

A hypothetical diurnal demand pattern based on Iranian water use habits was applied to reflect realistic daily fluctuations tied to local culture. This pattern, featuring morning and evening peaks with midday and night-time lows, was modelled in EPANET to assess system performance under variable demand. Simulations identified peak periods, informing design decisions on reservoir sizing, flow regulation, and pipe dimensions. The analysis ensured the network met demand efficiently, validating the diurnal pattern's role in achieving reliable, sustainable water delivery.

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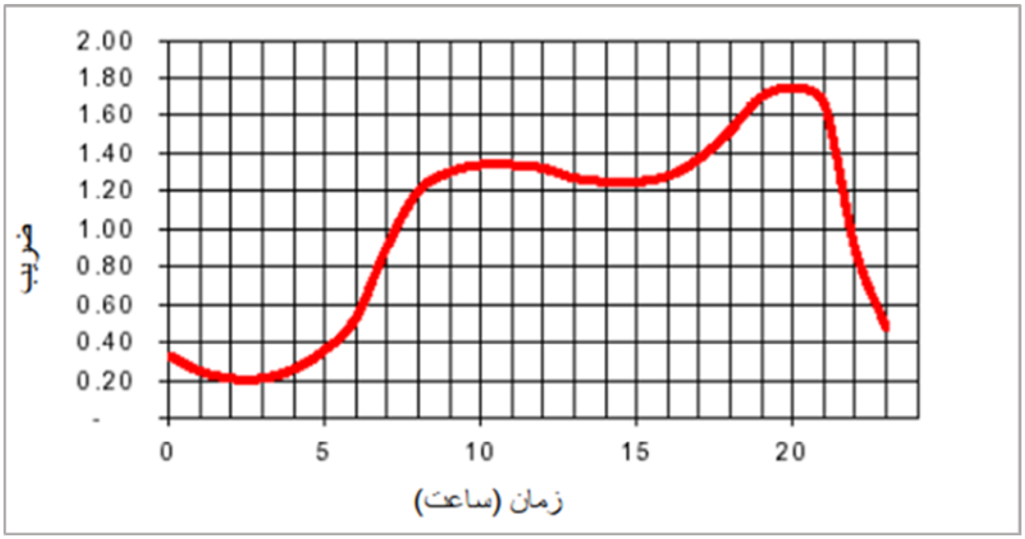

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Figure 1.3 Show the diurnal pattern used in Iran

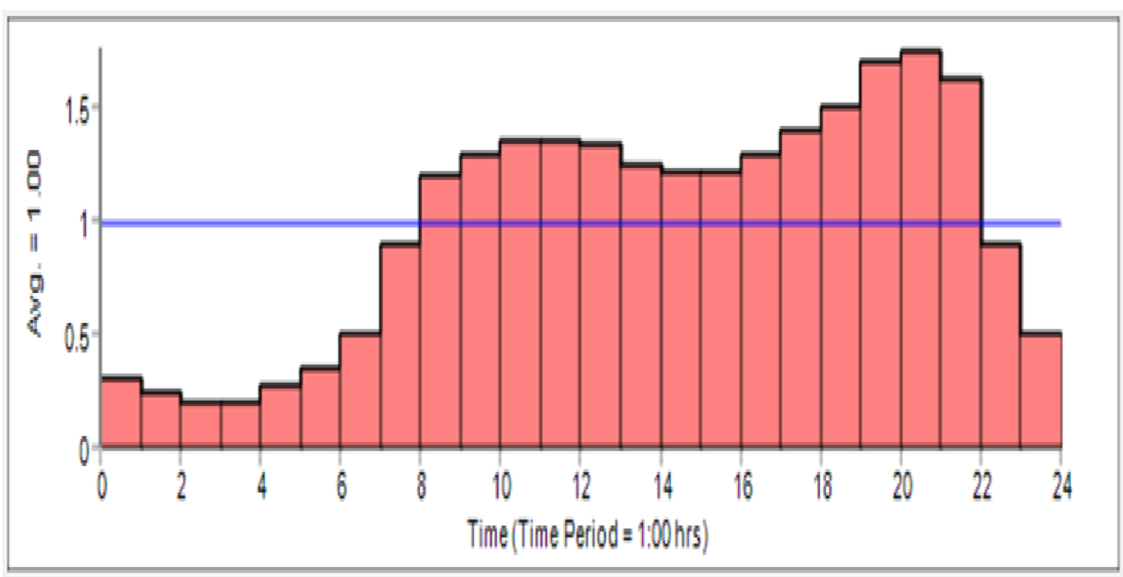

Figure 1.4 Diurnal pattern imported to EPANET

This study explores the uncertainty in assumed water demand during system design. After sizing the network for instantaneous peak demand, it was tested under a diurnal pattern without altering design parameters. The system functioned over 24 hours, but pressures spiked during low-demand periods, as shown in the comparative graph, highlighting the impact of demand assumptions on system performance.

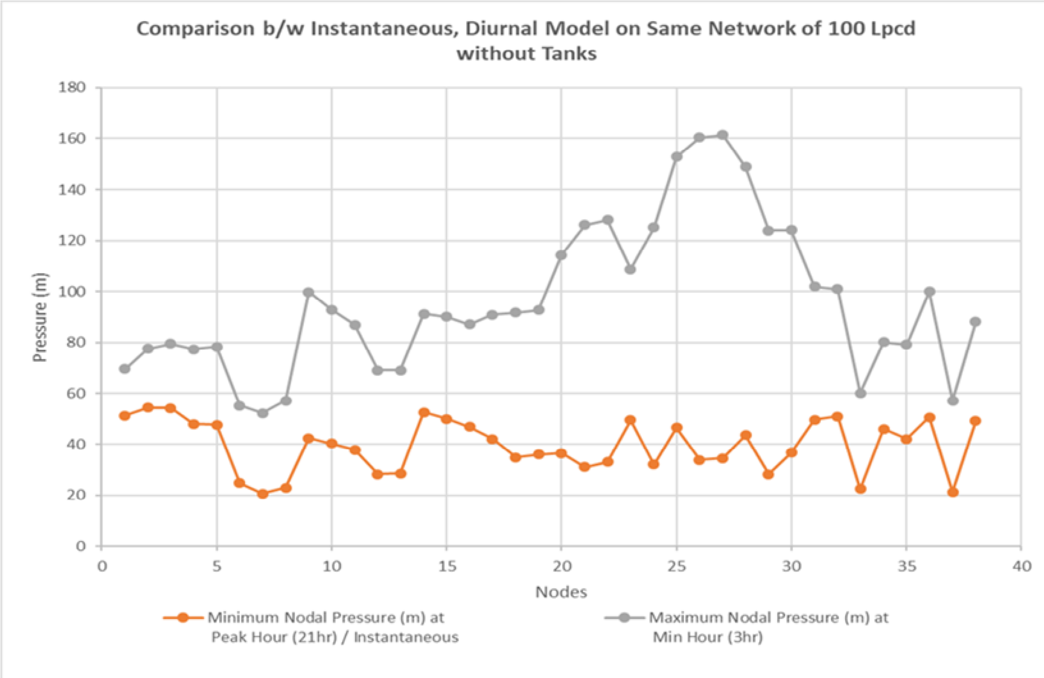

Figure 1.5 Shows the comparison of Instantaneous & Diurnal water supply design

The graph clearly shows that applying a diurnal pattern to the instantaneous design model, without parameter changes, allowed successful operation but resulted in excessively high pressures, reaching 160 m during low-demand periods.
The graph below compares flow in the transmission main for both models, highlighting that the instantaneous design targets a single daily peak, while the diurnal model adjusts flow hourly to match actual community demand throughout the day.

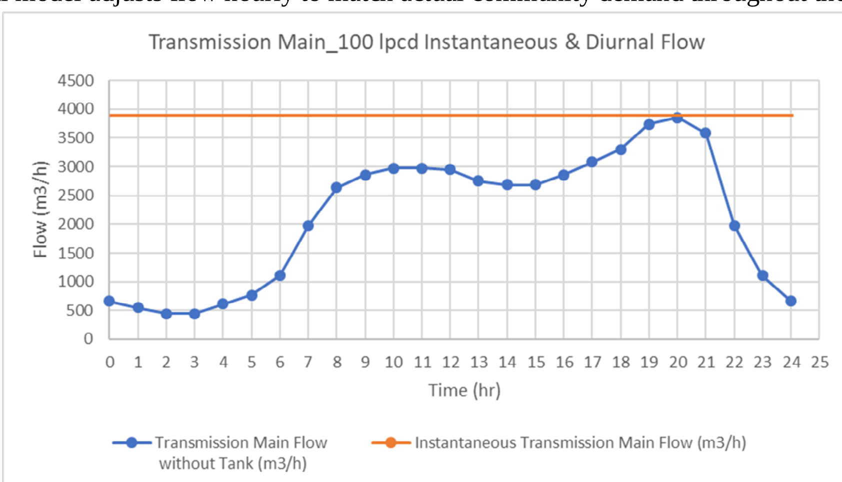

Figure 1.6 Shows the flow of water in Instantaneous & Diurnal pattern water supply design

So, from the above discussion the conclusion calls for designing the system based on the diurnal rhythm to achieve an economical design and avoid overdesign. The following are the descriptions of all the nine instantaneous network models that fulfill the diurnal pattern criteria. For this network, taken a peaking factor of 1.54 for the diurnal pattern and 2.7 for the instantaneous model, respectively, on the same network.

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IV. DISCUSSION

From the this research study I conclude that the overall networking like pipe sizing, layout and behaviour of the system is approximately the same but the effect only shows in terms of the cost of the system. The whole details are step by step given below.

The initial model, though fully developed, caused excessive pressures beyond user needs, risking pipeline damage and reducing system lifespan. To address this, the system was first tested under instantaneous peak demand, then with a diurnal pattern to reflect real daily fluctuations. The model performed well under the diurnal pattern, highlighting the importance of realistic demand modeling. Due to the lack of metering data in Pakistan, an Iranian consumption pattern closely matching local behavior was used. This analysis revealed major flaws in traditional designs and stressed the need for realistic demand patterns to enhance system performance, protect infrastructure, and ensure long-term reliability.

This Fig. 1.5 illustrates pressure distribution when applying a diurnal pattern to an instantaneous model. The gray line represents pressure under the instantaneous design, closely matching peak-time pressures in the diurnal model. However, even during low-demand periods, like around 3:00 AM, system pressure remains high, highlighting inefficiencies.

This indicates the system is overdesigned for low-demand periods. In an efficient network, pressure should adjust with demand to reduce stress on infrastructure, but here, consistently high pressures during low-use hours reveal a lack of dynamic response.

This overdesign leads to higher operational costs, increased risk of leaks and pipe damage, reduced system lifespan, greater water loss, and overall inefficiency. This study highlights the need for dynamic pressure management that adjusts to real-time demand. With Pakistan lacking metering data, using consumption patterns from similar regions like Iran provides a practical solution for optimizing system design and performance.

In conclusion, this research underscores the importance of designing water distribution systems that efficiently handle peak demand while dynamically adjusting pressure during low-demand periods to enhance sustainability, reduce costs, and extend infrastructure lifespan.

V. CONCLUSION

This study assessed Kohat's water supply scheme, highlighting that designing for instantaneous water supply without demand data results in overdesign and higher costs. In contrast, a system designed with a diurnal pattern is more reliable, sustainable, and cost-effective, reflecting real-life usage. It also ensures long-term effectiveness by keeping pressure within acceptable limits at each node. Designing an optimal water distribution network in Pakistan is challenging due to the lack of a metering system and accurate diurnal usage patterns. This study adopted a diurnal consumption pattern from Iran, reflecting local water use behaviors. The findings highlight the importance of incorporating a diurnal pattern in system design to improve efficiency, reduce costs, and extend infrastructure lifespan. While instantaneous demand design may seem cost-effective initially, it is unsustainable in the long term. Future infrastructure projects should focus on dynamic pressure management, reservoir integration, and advanced flow regulation for reliable, efficient, and cost-effective water systems.

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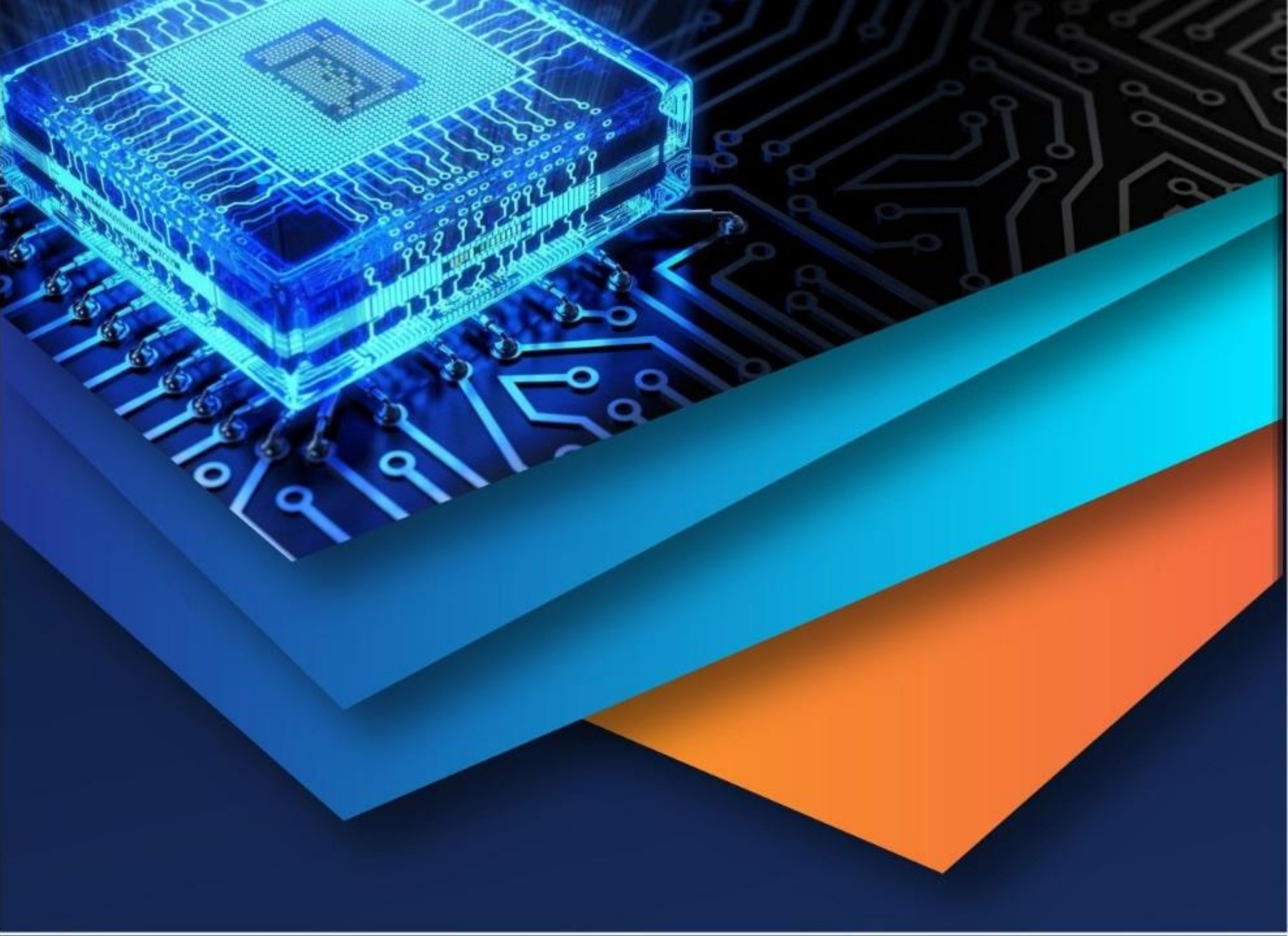

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