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Sensitivity Analysis of Alternate Technologies of Hardness Removal from Drinking Water: A Case Study of Lamki Water Supply Project Lamki Chuha Municipality, Kailali, Nepal

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Abstract

This study examines the urgent problem of water hardness in the context of Nepal's "1st Small Town Water Supply and Sanitation Project, Lamki, Kailali," a project that is having operational difficulties because of ineffective hardness removal technology and related expenses. This study attempts to determine the most appropriate and economically viable solution for the project by conducting a detailed comparative analysis of several hardness removal procedures, including Lime-Soda Ash Treatment and Sodium Zeolite Treatment. An effective water supply system's design, which includes decisions on pipeline sizing and pump capacity, is guided by population projections and water demand calculations. Sensitivity analyses are carried out to evaluate the financial effects of various treatment strategies, accounting for changes in power costs as well as withdrawal rates from a different source, the Karnali River. The results highlight the financial benefits of direct withdrawal from the alternative source, particularly in light of fluctuating electrical rates, and also highlight the need for additional research, including laboratory tests, transmission line surveys, and social assessments, to ensure the project's success. In order to fulfill the increasing water demand sustainably, this study offers useful insights into addressing water hardness concerns in the project region, taking into account both economic and operational factors.

Keywords

Hardness, Sodium Zeolite, Lime-Soda Ash, Population Projection, Pipelines, Pumps

1. Introduction

The presence of hard water is observed at a rate higher than 85%, when water absorbs ions of calcium and magnesium from rocks and soil. Ground water contains more minerals than surface water, so it is harder than surface water [1]. The temporary hardness of water arises from the presence of dissolved divalent metallic bicarbonates, notably Calcium (Ca) and Magnesium (Mg). Conversely, the permanent hardness of water results from the presence of dissolved divalent metallic sulfates and chlorides. Elevated water hardness levels (Total Hardness $\geq$ 500mg/L; NDWQS, Nepal) have recently raised health concerns, with cardiovascular diseases being linked to excessive consumption of hard water [2]. In boiler and heat transfer equipment pipelines, the presence of calcium and magnesium, minerals commonly found in hard water, leads to problems such as scaling and equipment failures [3]. The occurrence of hard water within water supply projects can lead to the accumulation of lime deposits in the distribution pipeline, thereby diminishing the pipes' discharge capacity.

Numerous methods, such as lime-soda ash treatment, electro membrane processes, reverse osmosis, ion exchange, and adsorption, are available to mitigate water hardness arising from calcium and magnesium ions. Among these methods, ion exchange and adsorption stand out as effective options, especially when utilizing cost-effective natural sorbents like clay, zeolite, biomass, perlite, and the like [4].

The existing project, “1st Small Town Water Supply and Sanitation Project, Lamki, Kailali,” which serves the inhabitants of Lamkichuwa Municipality in Kailali, Sudurpaschim Province, Nepal, has encountered technical complications and financial limitations that hinder its sustained operation. The primary challenge confronting this water supply project pertains to the inefficiency of the employed hardness removal technology and its associated operational expenses.

Hence, the purpose of this work is to provide a comparative analysis of various hardness removal technologies for the Water Supply and Sanitation Project, with the goal of identifying the most suitable technology from both economic and technical perspectives.

2. Literature Review

2.1 Existing Situation

The existing water supply project serves wards 1 and 3 of Lamki Chuha Municipality through existing ground water from three boring wells. Notably, the Overhead Tank, WUSC office, and associated structures (Table 1) are located within ward-3 of the municipality, marked by the following coordinates: Latitude 28°38’5.71"N and Longitude 81°9’51.71"E.

The existing structures of municipality are shown in Table 1. These structures were built as part of the Lamki Small Town Water Supply Project. At present, these structures are in operational condition and continue to supply drinking water to the households connected to the service lines.

Table 1: Existing structures

Structure	Numbers	Functionality
Over Head Tank (360 cum)	1	Functional
Pressure Filter	4	Functional
Zeolite Filter with NaCl regenerator	4	Functional
Boring	3	Functional
Reservoir Tank (660 cum)	1	Functional

2.2 Treatment Methods

Numerous techniques, including electro dionization [5], electro membrane processes, lime-soda method, reverse osmosis, ion exchange process, and adsorption, can be used to lessen the hardness of water caused by calcium and magnesium ions. All types of water sources can be softened and filtered with lime. Ground water sources are typically treated using electrodialysis, electro membrane, and green sand filtering techniques. Adsorption and reverse osmosis are both helpful for sources of surface water [6].

Synthesis Zeolites are used extensively as a filler in subsurface reactive bed reactors intended to extract hard water minerals from the ground and surface for industrial purposes [7]. Since synthetic zeolite has a high SiO2 content, it is an effective substance for removing hardness. At pH 6.5, Ca+2 and Mg+2 ions can be adsorbed most effectively. The percentage of calcium removed rose from 37.2% to 94.1% and that of magnesium rose sfrom 22.5% to 81.4% [8]. $Ca^{+2} > Mg^{+2}$ is the order of ion exchange capability in the elimination of hardness by synthetic zeolite.

The lime-soda ash method, also known as the Clark's method, is a time-honored and frequently applied technique for the elimination of temporary hardness in water, which is principally brought on by the presence of calcium (Ca^{+2}) and magnesium (Mg^{+2}) ions. In order to precipitate the calcium and magnesium ions as insoluble compounds, this approach requires adding lime (calcium hydroxide, Ca(OH)2) and soda ash (sodium carbonate, Na2CO3) to hard water. For the purpose of eliminating hardness and dissolved salts (measured as conductivity) from groundwater, many lime soda ash-containing techniques are examined, including electrocoagulation (EC), soda ash process, and lime softening. The hardness removal efficiencies by lime softening, soda ash process, and their combinations are 70.7, 33.3, and 86.7% respectively with the corresponding electrical energy required per unit mass (EEM) of hardness are 0.23, 3.08, and 0.78 kWh/kg [9].

3. Methodology

3.1 Population Projection

In 2022, based on satellite imagery, the total number of existing households was determined to be 4,739, and the average household size was 6 individuals. For the purposes of project design, an annual growth rate of 3.00% was employed. The population projection utilized the geometrical progression method (Eqn. 1) with a base period of 2 years and a design period spanning 20 years.

$$P = Po(1+r)^2 \tag{1}$$

Where,
P = Projected population at any time n
Po = Present population
r = annual growth rate (%)

A 5% of the projected population is added to the total projected population as floating population.

3.2 Water Demand

Since the service area is categorized as an urban area, the daily water demand per capita is set at 100 liters per day. Additionally, 10% of the total domestic demand has been considered for leakage/wastage in the conveyance system. No consideration has been made for institutional demand and fire demand in the calculation of total demand.

3.3 Lime-Soda Ash Treatment

The proposed dosing unit comprises of a Mixing Tank where the chemicals are mixed with mechanical agitator and a storage tank with dosing pump with 60% efficiency of the system being adopted. Lime is employed to eliminate temporary hardness, while Soda Ash is utilized to address permanent hardness in the water as given by Equations 2, 3 and 4.

$$CaO + H_2O \rightarrow Ca(OH)_2 \tag{2}$$

$$Ca(OH)_2 + Ca(HCO_3)_2 \rightarrow 2CaCO_3 + 2H_2O \tag{3}$$

$$Na_2CO_3 + M^{++} \rightarrow MCO_3 + 2Na^+ \tag{4}$$

3.4 Sodium Zeolite Treatment

Sodium zeolite (average density = 0.40 to 0.80 mg/L) plays a pivotal role in water treatment by serving as an effective agent for the removal of water hardness through an ion-exchange mechanism (Equations 5 and 6).

$$Na_2Al_2Si_2O_8.xH_2O + M^{++} \rightarrow 2Na^+ + CaAl_2Si_2.O_8.xH_2O \tag{5}$$

$$Na_2Z + M^{++} \rightarrow 2Na^+ + CaZ \tag{6}$$

The sodium zeolite can be regenerated by application of concentrated common salt/sodium chloride (Eqn.. vii).

$$CaZ + 2NaCl \rightarrow Na_2Z + CaCl_2 \tag{7}$$

The overall efficiency of the hardness removal using zeolite is adopted as 60%.

3.5 Transmission Line and Pump Design

The alignment of transmission line is fixed by the use of Google Earth and the Ground Profile Elevation is created using STRM 90 DEM. Calculation of the headloss is done by using Darcy–Weisbach equation (Equation 8).

$$hL = \frac{fLv^2}{2gd} \tag{8}$$

Where,
f = frictional factor which is calculated from the Empirical Formula (Equation 9),

$$\frac{1}{\sqrt{f}} = 1.14 - 2\log\left[\frac{K^s}{D} + \frac{21.25}{Re^{0.9}}\right] \tag{9}$$

Where,
Re = Reynolds number
K = 0.001 (for DI)

The efficiency of the pump is taken as 70% and 17.5hr of pump operation hour is adopted. The required power of the pump is calculated using Equation 10.

$$P = \frac{g\,H\,Q}{\eta \times 0.746} \tag{10}$$

Where,
P = Required Pump Power (HP)
η = efficiency of pump
H = Total head against which the pump has to work (m)
g = acceleration due to gravity (m^2/s)
Q = pumping discharge (m^3/s)

3.6 Sensitivity Analysis

Sensitivity analysis of the cost for treatment at design period using both proposed treatment method along with blending of the existing source ground water with water pumped from alternative source (Karnali River) is carried out. The proposed intakes lies 8.25km east on the right bank of the Karnali River at an elevation of 201m amsl with a maximum rise in elevation of 215m amsl along the alignment as shown in Figure 1.

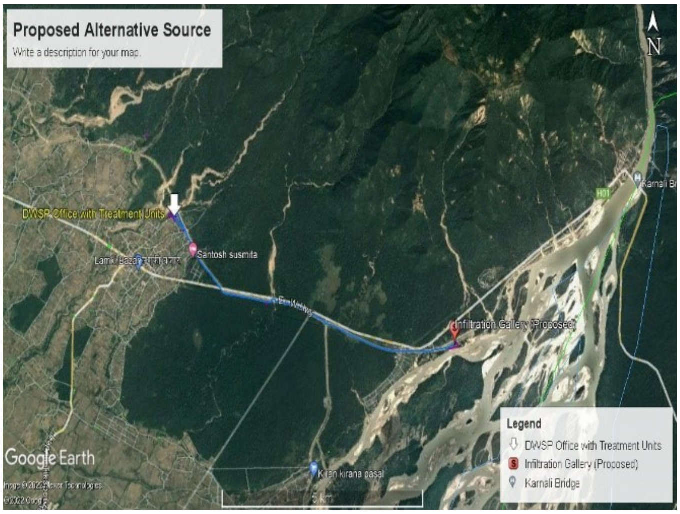

Figure 1: Alignment of Transmission Line from alternative source

The total hardness of the source is assumed to be 500mg/L with 40% temporary hardness and 60% permanent hardness with reduction in both type of hardness to 100mg/L each after treatment.

The cost of materials adopted is based on the 2078/79 district rate of Kathmandu and the available market rate as provided in Table 2.

Table 2: Adopted rates

Particular	Unit	Rate
Submersible Pump		
100 HP	No	1,683,769
70 HP	No	1,245,949
60 HP	No	1,100,000
15 HP	No	443,277
Chemical Cost		
Sodium Zeolite	kg	300
Lime	kg	60
Soda Ash	kg	75
Sodium Chloride	kg	20
D.I. Pipe		
350 mm	Rm	8,390
250 mm	Rm	5,760
200 mm	Rm	4,140
150 mm	Rm	3,010

An initial average of NRs. 11.00 per Unit of electricity consumed is taken for calculation with sensitivity analysis carried out with changes in electricity price by i) 10

4. Results and Discussions

4.1 Population Projection and Water Demand

The population projections for the study area are significant indicators of the future water demand. In the study, it was observed that the projected population for the base year stood at 30,003, and for the design year, it was estimated to reach 54,188, with an additional 2,710 floating population.

Considering these population figures, we conducted a thorough water demand calculation to better understand the requirements for the design period. Our results indicate a grand total water demand of 625,878 liters per day (lpd), which translates to a pumping design discharge rate of 100 liters per second (lps). These values serve as crucial benchmarks for planning water supply infrastructure. The detailed water demand calculation is provided in Table 3.

Table 3: Water Demand calculation

S.N.	Demand Type	Quantity	Unit
1	Total Domestic demand	5,689,800	lpd
2	Assume 10% leakage/wastage	568,980	lpd
3	Grand total demand	6,258,780	lpd
		72.44	lps
	Adopt	73.00	lps
4	Pumping Discharge	99.36	lps
5	Adopted Pumping Discharge	100	lps

These findings provide valuable insights into the water demand dynamics of the study area, underscoring the importance of precise population projections and demand calculations for the effective planning and operation of water supply infrastructure.

4.2 Pipeline Sizing and Pump Capacity

To optimize the water supply system based on the calculated water demand and transmission main details, the specific selected pipeline diameters and corresponding pump capacities as outlined in Table 4.

Table 4: Pipeline and Pump summary

Discharge (lps)	Pipe Dia (mm)	Pump Capacity (HP)	Total Pump Capacity (HP)
100	350	100	100
34	200	60	60
12	150	15	15
50	250	70	70

Furthermore, to ensure the maximum withdrawal of water from an alternative source, it is determined that a 350mm Ductile Iron (D.I.) pipe is required. This pipe is coupled with a submersible pump with a capacity of 100 HP. This configuration is designed to meet the anticipated demand for water from this alternative source effectively.

These pipeline and pump selections are critical components of our water supply system planning, ensuring that the system is capable of delivering the required water flow rates to meet the demands of the population and maintain reliable and efficient water distribution.

4.3 Sensitivity Analysis

Initially, without the dilution for the design period, to reduce the total hardness from 500 mg/L to 200 mg/L, an average of 10,080 kg of Sodium Zeolite is needed. This process requires 10 Zeolite filter units, each with dimensions of 3.00 meters in height and 1.50 meters in diameter (H x D). For the regeneration of the Zeolite at the same efficiency, a total of 6,142.5 kg of Sodium Chloride (NaCl) is required per day. Meanwhile, to reduce the temporary hardness from 200 mg/L to 100 mg/L, a total of 588 kg of Lime is needed per day. Additionally, to lower the permanent hardness from 300 mg/L to 100 mg/L, a daily amount of 2,226 kg of Soda Ash is required for the treatment process.

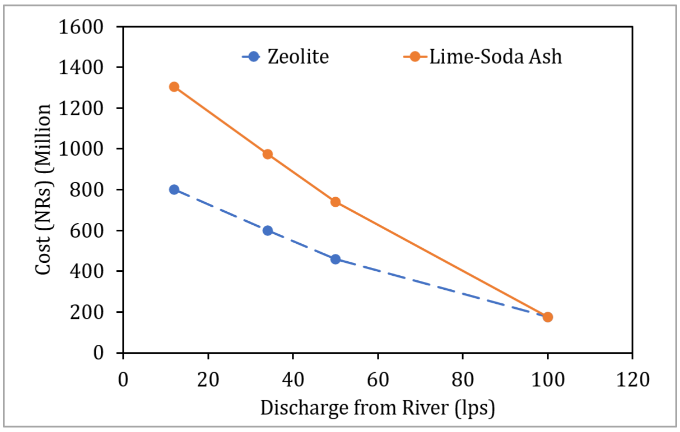

Figure 2: Variation in cost for different rate of withdrawal from alternative source

From Figure 2, it is evident that the cost of supplying the total water demand directly from the alternative source is considerably lower, at approximately NRs 175.70 million. In contrast, the cost of implementing the dilution method is higher, totaling around NRs 460.62 million for Zeolite Treatment at a rate of 50 liters per second. Moreover, the Lime-Soda Treatment for the same rate of 50 liters per second incurs a higher total cost of NRs. 741.61 million.

Furthermore, the sensitivity analysis, as illustrated in Figure 3, explores the impact of electrical prices on the operational costs of these alternatives. Notably, it becomes apparent that the operational cost will experience significant increases with higher electrical rates when opting for full water withdrawal from the river as compared to partial dilution of water from both the river and a borehole.

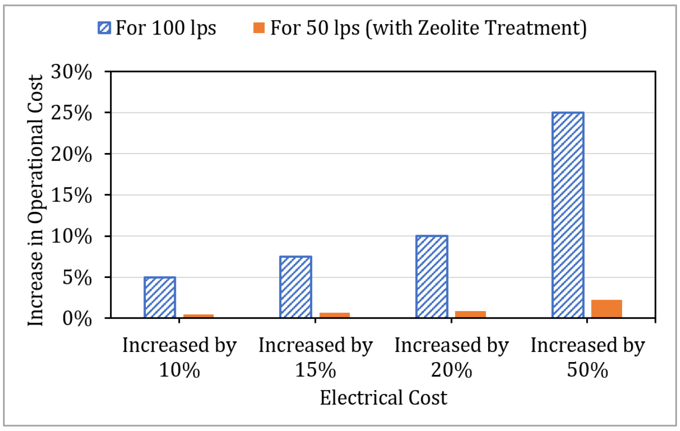

Figure 3: Variation in operational cost with electrical cost alternative source

It is determined that a 350mm Ductile Iron (D.I.) pipe is required. This pipe is coupled with a submersible pump with a capacity of 100 HP. This configuration is designed to meet the anticipated demand for water from this alternative source effectively.

5. Conclusions and Recommendations

In conclusion, the study of water treatment and supply strategies for the design period has yielded valuable insights into the challenges and opportunities associated with ensuring a sustainable and cost-effective water supply. Two key approaches were examined: direct withdrawal from an alternative source and a dilution method involving Zeolite Treatment and Lime-Soda Treatment.

The findings demonstrate that direct withdrawal from the alternative source is the more economically favorable option in electricity price. Furthermore, the sensitivity analysis highlights the impact of electrical prices on daily operational costs. Notably, opting for full water withdrawal from the river can lead to substantial cost increases in the face of rising electrical rates.

As the study is carried out based on the secondary sources of data and assumptions of some critical parameters following recommendation of further study have been made:

1. While calculating total water demand, include institutional and fire demands also.

2. As electrical prices can significantly influence operational costs, it is advisable to closely monitor and strategize for potential fluctuations in electrical rates.

3. Evaluate the environmental footprint of chosen strategies and explore eco-friendly alternatives where feasible.

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