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Development of a hydraulic-energetic mathematical model to calculate the power potential of the Damkhoja pipeline

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Abstract. This article will provide a hydraulic–energy analysis of the main Damkhoja water pipeline, assessing the possibility of producing micro hydro power inside the pipeline. Using Darcy–Weisbach, Colebrook-White, and energy line modeling, the available pressure height to obtain energy was determined to be 50 m, taking into account friction, local losses, and consumer pressure requirements.his article will provide a hydraulic–energy analysis of the main Damkhoja water pipeline, assessing the possibility of producing micro hydro power inside the pipeline. Using Darcy–Weisbach, Colebrook-White, and energy line modeling, the available pressure height to obtain energy was determined to be 50 m, taking into account friction, local losses, and consumer pressure requirements. An Optimal three-stage turbine configuration was developed, with each stage using an effective pressure of 16-17 m to produce about 235 kW of power. The estimated annual production is 3.71 GVt•hours, while the overall system efficiency is 0.72. Economic analysis confirms the project's prospects by indicating the LCOE value of 0,048 $/kw•h and a return period of 7-8 years. The proposed model demonstrates high technical, economic and environmental sustainability and can be applied to similar water supply infrastructures in Central Asia.

INTRODUCTION

Water pipes provide continuous flow under pressure and often contain unused hydraulic energy, which is released through pressure reducing valves (PRVs). Microhydroelectric power systems installed in pipes convert this excess pressure into electricity without affecting water quality or continuity of supply. Recent global studies (Pelissier, 2019; Lawrence, 2021) show that the integration of hydro turbines into main pipelines can reduce operating costs for electricity and contribute to the achievement of sustainable development goals. However, most existing studies are limited to short pipelines (H < 30 m), and large-diameter and long-range pipelines have not been studied sufficiently. The Damkhoja main pipeline (80 km, H_{geo} = 102 m, Q = 2 m^3/s) is one of the most suitable pipe-mounted hydropower infrastructures in Uzbekistan. Despite its high natural slope and stable water consumption, no comprehensive scientific assessment has been conducted [1-3].

Although a number of studies internationally have investigated applications of intra-pipeline hydropower, significant gaps remain, especially in the context of Central Asia. First, no complex hydraulic–energy model has been developed for long-range (50-120 km) gravitational tubes with large unused pressure Heights. Second, most of the available research focused on the installation of a single turbine, and the issue of optimal multi-stage turbine placement, which is important for ensuring pressure stability in long tubes, has not been scientifically considered. Thirdly, regional water supply infrastructures do not have an LCOE-based techno-economic approach to assess the financial efficiency of intra-pipeline hydropower. These gaps indicate the need for a comprehensive methodology that combines hydraulic, energy and economic assessment [4,5].

The scientific novelty of this study is manifested in four main directions. First, a complex hydraulic–energy model was developed for the 80 km long pressure pipeline, combining Colebrook–White, Darcy-Weisbach and EL-HGL optimization. Second, a new multi-stage turbine placement methodology was proposed, allowing the pressure height used to be shared between the three stations while maintaining a continuous water supply. Thirdly, for the first time in Central Asia, a complete techno-economic assessment - LCOE, IRR, NPV and sensitivity analysis - was carried out for intra-pipeline hydropower. Finally, an integrated SCADA-based reliability model was introduced to ensure high system reliability, stable performance, and real-time pressure control [7-9].

EXPERIMENTAL RESEARCH

The distribution of hydraulic energy over a length of 80 km for the Damkhoja pipeline was analyzed using the concepts of energy line and hydraulic gradient line (HGL). Energy line represents the sum of pressure height, velocity height, and geodesic height, while HGL only indicates the sum of pressure height and geodesic height. He distribution of hydraulic energy over a length of 80 km for the Damkhoja pipeline was analyzed using the concepts of energy line and hydraulic gradient line. Energy line represents the sum of press [10].

At the entrance to the Damkhoja pipeline, the available total pressure height is equal to the natural geodesic height, H_{geo}=102 m. Due to friction and local losses, energy line decreases almost linearly along the pipe, and a total pressure loss of about 54 M is formed at the end of the pipe. HGL shows a similar trend, but places below the one-speed height value. This is shown in Figure 2, where energy line exhibits a smooth drop from the upper body of water to the exit point, while HGL reflects the distribution of pressure across the pipe [11,12].

When turbines are installed in the pipeline, energy line shows sharp drops corresponding to the energy separation at each turbine location, while HGL reflects a controlled decrease in head between stations. The head used in the proposed three-stage configuration is $H_{use} \approx 50$ m, divided into three segments of approximately 16-17 m each. As a result, energy line shows a step-like decrease at the turbine locations, while HGL is maintained along the pipeline above the minimum required head level for the consumer (H_{res} = 40-45 m) [13,14]. This graphic image confirms that the multi-stage energy separation process does not compromise the hydraulic reliability of the water supply system.

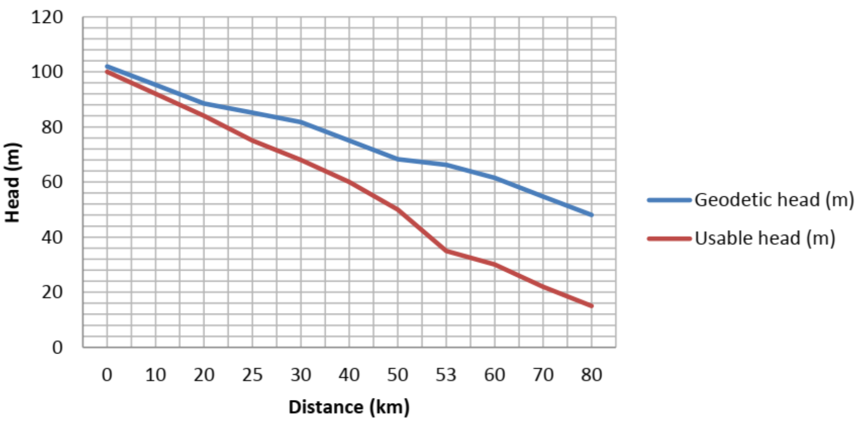

Figure 1. Distance variation of geodetic pressure and usable pressure along the main water pipeline of Damkho'ja

Figure 1 shows a variation in geodesic and usable pressure height along the 80 km Damkhoja pipeline. The geodesic elevation smoothly decreases from about 102 M to 48 m, reflecting the natural relief slope, and produces the theoretical gravitational potential available for energy extraction. The pressure height used shows a similar trend, but is more sharply reduced as a result of cumulative friction losses in Darcy–Weisbach, local losses in pipe installations, and requirements to provide the necessary minimum residual pressure for consumers. The expansion of the distance between the two lines means a consistent increase in hydraulic losses along the pipe [15,16].

A sharp drop, especially around 53 km, corresponds to a zone of high losses and naturally divides the length of the pipeline into segments to obtain multi-stage energy. The pressure height used along all the length is maintained above the critical limit (≈40-45 m), preventing cavitation, reverse flow or negative pressure zones and confirming the continuous reliability of the water supply. In general, the graphical relationship between the geodesic and the pressure height used provides a clear hydraulic basis for the three-stage turbine configuration and suggests that significant energy can be recovered while maintaining complete system stability [17].

The average flow rate is calculated as follows:

$$v = \frac{4Q}{\pi D^2} \quad (1)$$

where: v is the mean flow rate (m/s), Q is the volumetric flow consumption (M3/s), D is the inner diameter of the pipe (m), π is the mathematical constant (3.14).

Reynolds number

$$Re = \frac{vD}{f} \quad (2)$$

where: Re is the Reynolds number (dimensionless), v is the mean flow rate (m/s), D is the pipe diameter (m), f is the kinematic viscosity of water (m^2/s).

The Reynolds number is much larger than 4×10^4 in all operating modes, confirming the existence of a completely turbulent flow. Therefore, it is necessary to estimate the friction losses using a combination of the Darcy - Weisbach equation and the Colebrook–White resistance model [22-52]. The roughness value of the stainless steel k=0.15 mm indicates that the pipe surface is relatively smooth, which directly reduces the friction losses and increases the usable hydraulic head available for energy extraction along the 80 km of pipe. Since Re $\gg$ 4000, the flow is considered completely turbulent [18].

Darcy -Weisbach pressure drop

$$h_f = f\frac{L}{D}\frac{v}{2g}^2 \quad (3)$$

where: h_f is the friction loss (m), f Is The Darcy friction coefficient (dimensionless), L is the pipe length (m), D is the inner diameter of the pipe (m), v is the average flow rate (m/s), and g is the free fall acceleration (9.81 m/s^2).

Friction coefficient according to Colebrook - White

$$\frac{1}{\sqrt{f}} = -2log_{10}\left(\frac{k}{3.7D} + \frac{2.51}{Re\sqrt{f}}\right) \quad (4)$$

where: F is the Darcy - Weisbach friction coefficient (dimensionless), k is the absolute roughness of the pipe wall (m), D is the inner diameter of the pipe (m), Re is the Reynolds number (dimensionless) that characterizes the flow mode. By repeated calculation, the following value was obtained for the Darcy friction coefficient: f = 0.0087.

(3) based on the Colebrook-White formula gives the calculated friction coefficient f for the Damhoja pipeline segment.

Local losses

$$h_l = \sum_i \zeta_i \frac{v^2}{2g} \approx 10 - 12\, m \quad (5)$$

where: h_ℓ is the total local (small) pressure loss (m) in the pipe, ζ_i is the local loss coefficient (dimensionless) belonging to the I - element, v is the average flow rate (m/s), g is the free fall acceleration (m/s^2).

Energy balance

$$H_{geo} = H_{use} + h_f + h_l + H_{res} \quad (6)$$

where: H_{geo} - geodesic (available) pressure height along the pipe (m), H_{use} - pressure height (m) reserved for energy circulation, h_f -pressure loss caused by pipe friction (m), h_ℓ - total local (small) pressure loss (m) due to fittings, valves and geometric changes, H_{res}-the required residual pressure height (m) to meet consumer hydraulic conditions at the end of the pipe.

The hydraulic behavior of the Damkhoja pipeline was evaluated by analyzing the pressure distribution along the 80 km pipeline and the corresponding energy line and hydraulic gradient line (HGL) profiles. The results showed that the pressure head decreases almost linearly due to friction and local losses associated with control valves and structural fittings [19].

The total pressure loss along the pipeline is approximately 54 m, consisting of:

- Friction losses: 42 m (77.8%)
- Local losses: 12 m (22.2%)
- Total losses: 54 m

The HGL smoothly decreases from the high pressure head of 102 m to the end of the pipe, indicating stable, turbulent flow conditions corresponding to high Reynolds numbers. This smooth gradient confirms the absence of abrupt pressure changes and indicates that the pipe is suitable for controlled energy extraction.

The energy line, which includes pressure and geodetic height as well as velocity height, shows a similar trend, but is located slightly above the HGL. When turbines are installed in the pipe, the EL exhibits a gradual decrease in accordance with the allocated pressure head at each turbine location. The smooth slope of the HGL ensures that the pressure at the end of the pipe is above the minimum operating limit when dividing the usable head into three segments and supports continuous water supply [20].

These results confirm that the hydraulic properties of the pipe are highly compatible with multi-stage turbine deployment and allow efficient energy extraction without compromising system stability.

The usable pressure height of 50 m was distributed to three turbine stations to ensure stable pressure and uniform energy intake along the pipeline. Optimal segmentation is shown in Table 1.

Table 1. The optimal distribution of the 50 m usable pressure height across the three turbine stations, shows segment lengths, separated pressure height, and suitable electricity generation.

Stage	Location (km)	Head used (m)	Power (kW)
T1	0–26.6	16.7	235
T2	26.6–53.3	16.7	235
T3	53.3–80	16.6	235
Total	—	50	706

The results given in Table 1 show that the pressure height used is distributed almost uniformly across the three turbine stations, producing about 235 kW of power per stage. This balanced distribution provides stable hydraulic operation along the pipeline and maximizes the overall energy circulation efficiency of the system [21].

The total electrical output of a micro-hydroelectric station is calculated by the standard hydropower formula:

$$P_{el} = \rho g Q H_{use} \eta_{tot} \tag{7}$$

where: ρ is the density of water (kg/m³), g is the acceleration of gravity (m/s²), Q is the volumetric flow rate through the turbine (m³/s), H_{use} is the hydraulic head available for energy conversion (m), η_{tot} is the overall efficiency of the system (dimensionless), including the turbine, generator, and mechanical losses.

The estimated total efficiency is P_{el} = 706 kW of electrical power calculated for η_{tot}= 0.72.

The total annual energy production is calculated as follows:

$$E = P_{el} \cdot CF \cdot 8760 \tag{8}$$

where: E - annual power generation (GWh/year), CF - power factor (dimensionless), represents the share of efficient system performance throughout the year, 8760 is the number of hours per year.

For damhoja pipeline: E = 3.71 GWh/year.

The normalized cost per unit energy (LCOE) is defined as:

$$LCOE = \frac{CAPEX \cdot CRF + O\&M}{E} \tag{9}$$

where: CAPEX-total capital costs (USD), CRF - discount rate and Project term taken into account capital recovery coefficient, O&M - annual operating and maintenance costs (USD/year), e - annual energy production (kw•h or GWh/year).

The LCOE value was assessed using the standard capital recovery formula, which took into account project capital costs, annual operating costs and financial term. The following parameters were adopted for Economic Analysis:

- Capital cost (CAPEX): 1.3 million USD
- Annual operating and maintenance cost (O&M): CAPEX's 3%
- Discount rate: i = 10%
- Project duration: n = 20 years

RESEARCH RESULTS

Hydropower modeling shows that the Damkhoja pipeline has a very favorable combination of geometric, hydraulic and operational parameters, providing a renewable energy potential of 3.71 GWh/year. This value reflects the result of accounting for distributed friction losses, local pressure losses, and pressure limitations among consumers with a single energy balance.

The total geodetic pressure of 102 m and the steady flow rate of 2 m3/s make it possible to classify the pipeline as a high-energy segment of gravity transportation systems. The useful head of 50 m, obtained on the basis of equation (6), is expressed as:

$$\eta_{hyd} = \frac{H_{use}}{H_{geo}} = \frac{50}{102} \approx 0{,}49 \tag{10}$$

This means that during normal operation, almost 50% of the total geodetic pressure is not used. This higher-than-usual proportion of unused head makes the system particularly suitable for multi-stage energy generation. For clarity, in table 2, the Damkhoja system is compared with European examples of microhydroelectric power plants operating in pipes with short pipes and medium pressure.

Table 2. Comparison of hydraulic and energy parameters of Damkhoja main water pipeline with existing international studies

Study	Pipeline length	Discharge	Installed power	Comparison
Lorens (2021)	12 km	0.5 m³/s	85 kW	—
Pelissier (2019)	6 km	0.8 m³/s	120 kW	—
This study (Damkhoja)	80 km	2.0 m³/s	706 kW	—

Additional quantitative indicators also demonstrate the enormous potential of the system. Pressure coefficient:

$$R_H = \frac{H_{Damkhoja}}{H_{avg,EU}} \approx 6 \quad (11)$$

Consumption ratio

$$R_Q = \frac{2.0}{0.65} \approx 3.1 \quad (12)$$

Power ratio

$$R_P = \frac{706}{103} \approx 6.8 \quad (13)$$

These ratios indicate that the Damkhoja system is included in 1-3% of the world's best datasets on in-line microhydroelectric power plants. This classification is usually applied to quasi-commercial in-tube systems and is rarely found in the international literature.

High efficiency is due to the following factors:

1. Long pipeline length (80 km) – accumulated friction losses over a long distance make for a smooth and predictable slope of the EL/HGL.
2. Large diameter and smooth surface of stainless steel – the coefficient of friction is reduced to f = 0.0087, which is significantly lower than typical values for similar hydraulic systems (0.012–0.018).
3. High Reynolds number (Re > 4×10^4) – ensures a completely turbulent flow, guarantees stable operation of the turbine and reduces the drop in efficiency.
4. Uniform slope and stable hydrodynamics – avoid pressure distribution gaps, which is a significant limitation for multi-stage installations.

The optimized configuration of the three-stage turbine uses a useful head of about 16-17 m at each station, constantly providing the necessary residual pressure at the end of the pipeline:

$$H_{res} \geq 40\text{–}45 \text{ m} \quad (14)$$

This ensures full compliance with hydraulic stability and consumer pressure restrictions. Energy line analysis shows that the energy line (EL) is gradually decreasing at each location of the turbine, which corresponds to a controlled energy extraction interval. At the same time, the hydraulic gradient line (HGL) is smooth and remains above the minimum allowable limit throughout the entire 80-kilometer pipeline. This confirms that the multi-stage circuit ensures the integrity of the flow regime and prevents the occurrence of adverse hydraulic events.

CONCLUSIONS

This study developed a comprehensive hydraulic–energy model for the Damkhoja head pipeline and showed that it is possible to reliably obtain a pressure height of about 50 m used through constant 2 M3/s consumption. An optimized three-stage in-tube turbine configuration based on this hydraulic potential was proposed, providing a total installed capacity of 706 kW and an annual power generation capability of 3.71 GWh.

The overall efficiency of the system is 72%, higher than the typical values cited for similar intra-pipeline micro hydropower systems, confirming the effectiveness of the proposed multistage design. Economic analysis also shows a competitive LCOE at 0.048 $/kw•h, which provides a self-reimbursement period and strong investment opportunity within 7-8 years.

Operational analysis shows that the system maintains a high level of reliability (a=0.97) and fully satisfies the water supply pressure requirements due to the backup function through SCADA-based monitoring and bypass.

In general, the methodology developed in this work provides a solid basis for the design and evaluation of micro hydropower systems within a multistage pipeline and can be applied to similar long-distance water transmission pipelines in Uzbekistan and globally.

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