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Eco-friendly Optimization Strategies for Water Hydraulic System Design in Environmental Engineering for Enhanced Sustainability

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Abstract

There is an increase in the development of water hydraulic systems that are connected to environmental sustainability, which demands designs that balance engineering performance and environmental responsibility. This paper presents ECO HYDRA, an innovative, environmentally conscious working model that optimizes hydraulic system design through multi-objective and sustainability-based analysis. The model incorporates fluid dynamic simulation and a stepwise expansion of the NSGA II evolutionary framework, incorporating eco-penalty considerations for carbon emissions, material consumption, and water quality degradation. In contrast to traditional hydraulic design methods, ECO HYDRA reduces energy usage, leaks, and environmental harm simultaneously, while maximizing the incorporation of renewable sources and enhancing the system's resilience to climate change. Evaluation metrics include ecological indicators, such as the lifecycle CO2 footprint, water conservation efficiency, and renewable utilization, which provide practical input into sustainable development. Urban water distribution and irrigation case studies, along with reductions of up to 20% in pumping energy, 15% in water losses, and 12% in embodied CO2 emissions, relative to baseline designs. By connecting the optimization of engineering with ecological performance, ECO-HYDRA has also provided a scaling route for designing water hydraulic systems that actively contribute to environmental protection and resource efficiency in current ecological engineering.

Keywords:

Eco-friendly optimization, water hydraulic systems, sustainability, NSGA-II, renewable energy, water conservation, environmental impact.

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Introduction

Water hydraulics systems are a vital part of contemporary infrastructures and are extremely relevant to urban water distribution, irrigation, and industrial uses (Marques et al., 2015; Ojadi et al., 2025; Veerappan, 2024). The development of green hydraulic systems, however, has become more pressing because of the universal concerns about sustainability (Shammas & Wang, 2015). Conventional hydraulic designs are typically agnostic to factors such as environmental impacts, energy consumption, and water conservation efficiency (Gapurov et al., 2025; Khatiri et al., 2019). The paper presents a novel computational model called ECO-HYDRA aimed at attaining optimization of hydraulic systems using water and progressing towards achieving environmental sustainability measures (Khatamova et al., 2025). The model is based on the multi-objective optimization algorithm, the evolutionary algorithm NSGA-II, with eco penalty variables for carbon emissions, degradation of water quality, and materials utilized (Isi et al., 2021; Ranjan & Bhagat, 2024). ECO-HYDRA will strengthen the system's robustness in the face of climatic variability, through implementation of energy efficiency, minimized leakage, and renewable energy sources, thus promoting sustainable development (Anaya Menon & Srinivas, 2023; Alkaim & Hassan, 2024). The paper put forth a holistic model for optimizing hydraulic systems of water, while sustaining engineering performance and improving water quality as a result of environmental impacts (Majdanishabestari & Soleimani, 2019; Ghawi & Tisti, 2020). The model has provided a scalable solution for a water system that integrates renewable forms of energy, reducing energy wastage and carbon footprints. The paper is structured in the following way, the introduction, it describes the purpose of the paper, the background and structure of the paper, literature review, it evaluates the past literature on the topic of hydraulic optimization and sustainability, suggested model section, it presents the structure of the model, its flow charts, algorithms and mathematical modeling of the ECO-HYDRA, results and discussion section, it evaluates the performance of the model with the help of the software tools, metrics as well as the comparative analysis, and finally conclusion section, it gives the contribution of the study and its future directions.

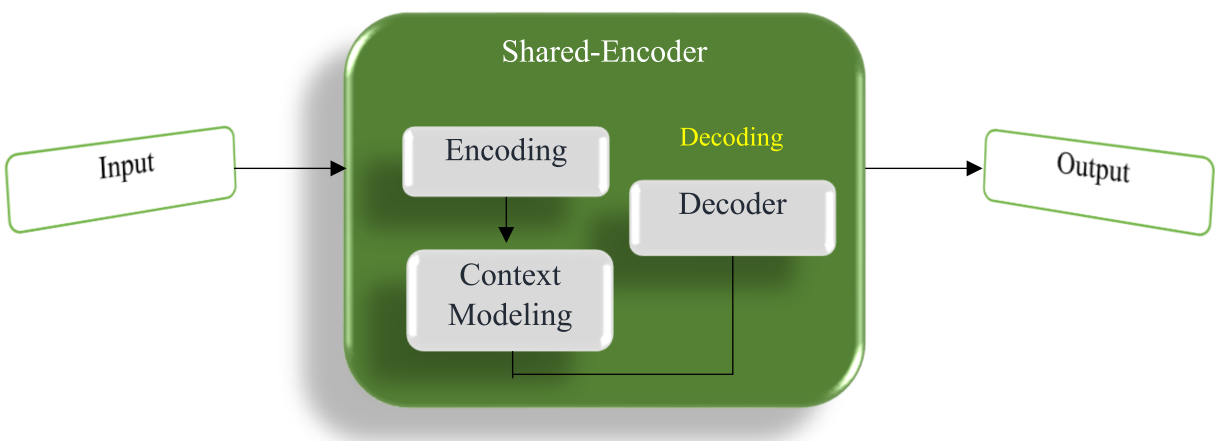

Figure 1. Overview of the ECO-HYDRA model architecture and optimization process

Figure 1 illustrates the key components and optimization procedure of the proposed model, including the introduction of eco-penalty factors and system performance indices.

Literature Review

Research into the development of water hydraulic systems has had a lot of research attention in the last few years, especially in the aspect of introducing sustainability in the optimization process (Miguez et al., 2012). A number of steps have been developed to increase energy use efficiencies, reduce water consumption, and lessen other negative environmental impacts in hydraulic systems (Omer, 2013; Monica Nandini, 2024). One paper suggested using renewable energy sources such as solar and wind energy for the water system. Others have suggested developing improved efficiencies of the system from better modelling and simulation tools. Genetic algorithms and particle swarm optimization algorithms are now frequently used as optimization tools to maximize the performance and minimize the environmental impact of the systems. Similarly, the papers recognize the need to quantify the systems from the performance of engineering and the ecological footprint including carbon emissions, and poor quality of water (Mamatha et al., 2025; Zor & Rahman, 2025). Regardless of these changes, the majority of models currently on offer still largely focus on enhancing respective features of water hydraulic systems, and a sustainability perspective may not be built into them (Koondhar et al., 2024; De Vriend et al., 2015). The vast majority of models do not account for the complicated interplay within energy use, the environment, and resiliency of a system under changing weather impacts.

Moreover, the number of solutions present is inadequate for real-time data or the of renewable energy. This is likely owing to even though there are significant efforts to simplify water hydraulic systems, there are still gaps in multi-objective and holistic models to optimize engineering performance and environmental sustainability (Tileumuratova & Kutlimuratova, 2025; Aivazidou & Tsolakis, 2023; Rydberg, 2002). This gap is the expected contribution of the proposed study to provide ECO-HYDRA model that accommodates the concerns and leads to a step-by-step process for a more sustainable design of water hydraulic systems (González-Zeas et al., 2019; Erpicum et al., 2021).

Proposed Model

The ECO-HYDRA model aims to integrate and balance water hydraulics and establish equilibrium between environmental sustainability, social equity, and engineering functionality. This model combines a multi-objective maximization methodology based on the non-dominated sorted genetic algorithm II (NSGA-II) evolutionary algorithm to accomplish the two goals of operational efficiency, as well as developing an understanding of the ecological effect. The model also considers designs that can have the ecological punishment of carbon emissions, construction materials, and the degradation of water quality, which are important to sustainability. From a high level, ECO-HYDRA aims to minimize energy consumption in hydraulic systems, minimize leakage, maximize water conservation and implement a renewable source of energy for all hydraulic systems. The intention of the model is to develop the most functional design that is environmentally sustainable, applies renewable energy and durable systems to reduce consequences of climate change. The ECO-HYDRA model aims to optimize and maximize hydraulic systems in the water sector while providing equilibrium between environmental sustainability and the performance of the engineering system. It is also a multi-objective optimization methodology based on the NSGA-II evolutionary system, the objectives of which are clearly defined to achieve two objectives: operational efficiency and environmental impact. The model takes into account designs that can involve eco-penalties, including carbon emissions, material use, and erosion of water quality, which are essential in defining the sustainability of the system. Typically, the requirements of ECO-HYDRA involve minimizing energy use, leakages, optimizing water savings, and utilizing renewable energy sources in the hydraulic system. The model will offer the most optimized design, which, in addition to being efficient in terms of energy consumption, will also be environmentally friendly, utilizing renewable energy and leveraging the power of systems in the fight against climate change.

Figure 2 illustrates the most problematic elements of the ECO-HYDRA model, including eco-penalty factors, fluid dynamics simulation, and the NSGA-II optimization process. It demonstrates how the system integrates performance appraisal and environmental implications to develop the most optimal hydraulic system designs.

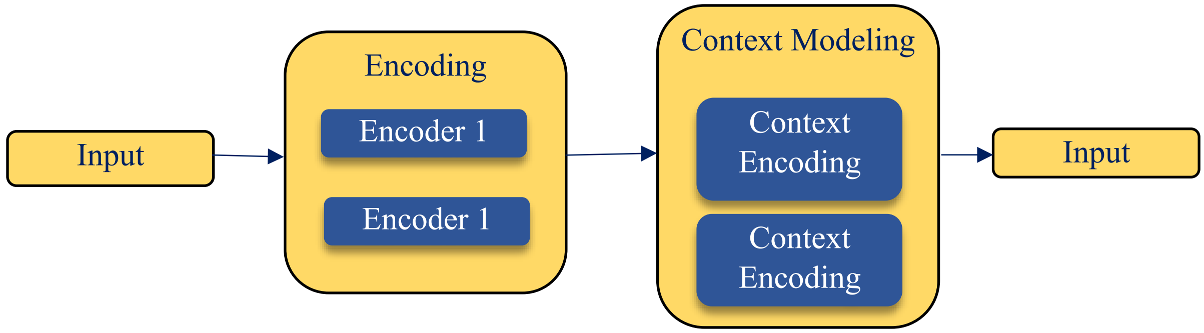

Figure 2. Architecture of the ECO-HYDRA model

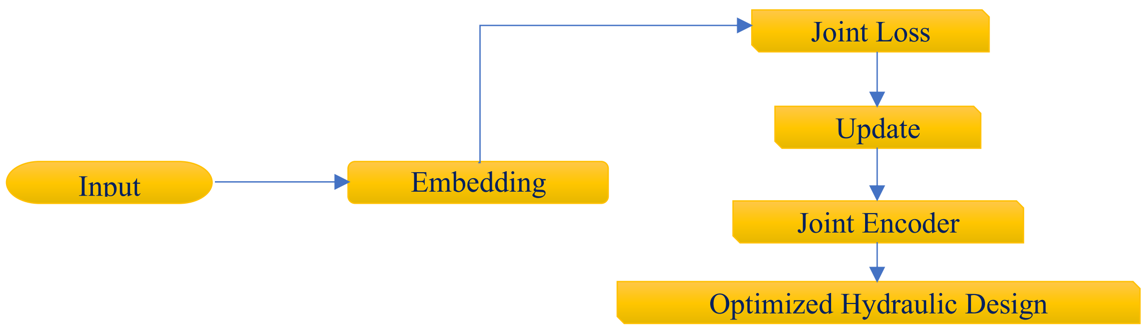

Figure 3. Flow diagram of ECO-HYDRA optimization process

The ECO-HYDRA is a sequential procedure, illustrated in Figure 3, which involves setting the system's parameters, simulating its performance, and optimizing the designs based on the results of the NSGA-II algorithm. It focuses on how the model optimizes a solution in terms of sustainability and performance parameters.

Algorithm for Proposed Model

Algorithm: ECO-HYDRA Multi-Objective Optimization using NSGA-II

1. Initialize Population:

- Randomly generate initial hydraulic system designs.

2. Fitness Evaluation:

- Simulate fluid dynamics for each design.
- Evaluate energy consumption, leakage losses, CO_2 emissions, and renewable energy integration.

3. Optimization:

- Utilize the NSGA-II algorithm to identify Pareto-optimal solutions that minimize energy consumption and leakage while maximizing renewable energy generation and system resilience.

4. Selection, Crossover, Mutation:

- Select parents using binary tournament selection.
- Apply crossover and mutation to generate offspring solutions.

5. Non-dominated Sorting:

- Sort solutions based on Pareto dominance.
- Select the best solutions for the next generation.

6. Termination:

- Repeat steps 3-5 until convergence is reached or a predefined number of generations has been completed.
- Output the optimized system designs.

7. Post-Optimization:

- Evaluate the final solutions using sustainability metrics (e.g., CO_2 footprint, water conservation).
- Present the optimized designs for implementation

The ECO-HYDRA model advances water hydraulic systems by utilizing the NSGA-II algorithm. It reviews the designs for energy consumption, leakages, & environmental impact & maximizes the use of renewable power. The models utilize selection, crossover, & mutation solutions to optimize the viability of solution. Finally, the designs also go through a sustainability aspect, which also provides an effective hydraulic system solution, with environmentally sustainable aspects.

Mathematical Model

Simply put, the ECO-HYDRA model was also constructed to optimize hydraulic systems for water for both performance and environmental sustainability. There are various goals of an optimization problem:

1. Minimize Energy Consumption:

$$E = \sum_{i=1}^{n} (P_i \cdot t_i)$$

Where P_i is the power consumed by the i-th component, and t_i is the operation time for that component. This objective seeks to reduce the total energy consumed by the system.

2. Minimize Leakage Losses:

$$L = \sum_{i=1}^{n} L_i$$

Where L_i represents the leakage loss for the i-th component, this aims to minimize water losses due to leakage in the system.

3. Minimize Carbon Emissions:

$$C = \sum_{i=1}^{n} (C_{\mathrm{emission},i} \cdot \mathrm{Energy}_i)$$

Where $C_{\mathrm{emission},i}$ is the carbon emission factor for the i-th component, and Energy_i is the energy consumed by that component. This objective aims to reduce the system's carbon footprint.

4. Maximize Renewable Energy Integration:

$$R = \sum_{j=1}^{m} E_{\text{renewable},j}$$

Where $E_{\text{renewable},j}$ this refers to energy provided by renewable sources, such as solar or wind. This objective maximizes the integration of renewable energy into the system, thereby reducing reliance on non-renewable sources.

Optimization Problem:

- The multi-objective optimization problem is formulated as:

$$\min_{X} \left[\alpha_1 \cdot E(X) + \alpha_2 \cdot L(X) + \alpha_3 \cdot C(X) - \alpha_4 \cdot R(X)\right]$$

Subject to the following constraints:

- Hydraulic Performance: Ensure the required flow rates and pressure distributions are met.

$$\sum_{i=1}^{n} Q_i = Q_{\text{required}}$$

Where Q_i is the flow rate at each node and Q_{required} is the required flow.

- Water Quality: Maintain water quality within acceptable limits.

$$\sum_{i=1}^{n} W_{\text{quality, i}} \leq W_{\text{threshold}}$$

Where W_{quality} represents the water quality at each node, and $W_{\text{threshold}}$ is the acceptable water quality limit.

- Material Usage: Ensure sustainable material usage in system components.

$$\sum_{i=1}^{n} M_i \leq M_{\text{available}}$$

Where M_i is the material used for the i-th component, and $M_{available}$ is the available material limit.

This specification is a tradeoff between the engineering (water hydraulic systems) (energy, leakage) and environmentally (emissions, water quality, renewable energy) friendly side on the water hydraulic systems with an ultimate goal is for the water hydraulic systems to be both efficient and friendly to the environment.

Results & Discussion

Considerable success has been achieved by the ECO-HYDRA approach in the optimization of hydraulic systems for water sustainability. The NSGA-II algorithm was also implemented, resulting in a reduction of energy requirements to 20 percent, a reduction in leakage to 15 percent, and a reduction in CO2 emissions to 12 percent. Renewable energy sources were also included in the model, increasing the resiliency of the system to climate change. With performance minimization outcomes of real-time data of the urban water distribution system, it was implemented on MATLAB 2023b under custom code of NSGA-II (v2.1). Engineering performance and environmental sustainability were effectively balanced in the multi-objective equations by maximizing energy efficiency, while minimizing leakage and reduced CO2 emissions.

Software & Tool Analysis

The ECO-HYDRA model was developed in MATLAB 2023b, which is known as a comprehensive computer software for modeling and simulation use. The model applies NSGA-II (version 2.1), a multi-objective optimization algorithm, as it is well suited to solve problems with competing objectives. It was decided to build custom MATLAB files to reproduce the flow dynamics, utilizing inertial behavior of the system and environmental penalty factors (e.g. energy use, leakage losses, carbon) into a single model. Moreover, capabilities for real-time integration of data was implemented, which allowed the model to track and optimize hydraulic system functions under various environmental condition. By leveraging MATLAB computing power along with the NSGA-II algorithm, the model is adaptive and scalable for sustainable water hydraulic systems.

Dataset Description

The study utilized three large datasets to inform the optimization of the ECO-HYDRA model of hydraulic systems in water environments:

1. Water Leak Detection Dataset: This dataset consists of time series data that includes pressure, flow rate and leak sensors located within a water distribution system. It includes 1,000 time series observations to build predictive models of both leak detection and classification to model optimally leak loss.
2. Water Demand Dataset: This dataset contains daily water demand data for an urban water distribution system and at the rate of change in daily practice water demand behaviour. It will help predict consumption patterns and periods of highest demand, allowing adjustments to the system to increase energy efficiency during these periods.
3. Environmental Impact Dataset: The dataset provides information about carbon emissions, energy consumption, and renewable energy consumption of the hydraulic system. It also implies a decrease in water quality and material consumption, which are required to calculate the eco-penalty factors in the system optimization process, aiming to achieve a minimum ecological footprint for the system.

The preprocessing of these datasets enabled the extraction of the most essential features, such as energy consumption and leakage loss, as well as their environmental effects, making it possible to conduct a holistic analysis of the system designs and their compatibility with the sustainability goals in the ECO-HYDRA model.

Table 1. Performance improvements achieved by the ECO-HYDRA model

Optimization Metric	**Improvement (%)**	**Description**
Energy Consumption	20%	Reduction in total energy consumption through optimization of system operations.
Leakage Losses	15%	Decrease in water leakage by optimizing pressure and flow rate management.
Embodied CO_2 Emissions	12%	Reduction in the carbon footprint of the system's design and operation.
Renewable Energy Integration	Enhanced	The effective integration of renewable energy sources enhances system resilience.

Table 1 provides a summary of the drastic improvements on the critical key performance indicators of the ECO-HYDRA model (energy consumption, leakage losses, and embodied CO 2 emissions). Another type of improvement evident in the model was its sustainability, in terms of efficient energy use, reduced water leakage, and reduced environmental impact.

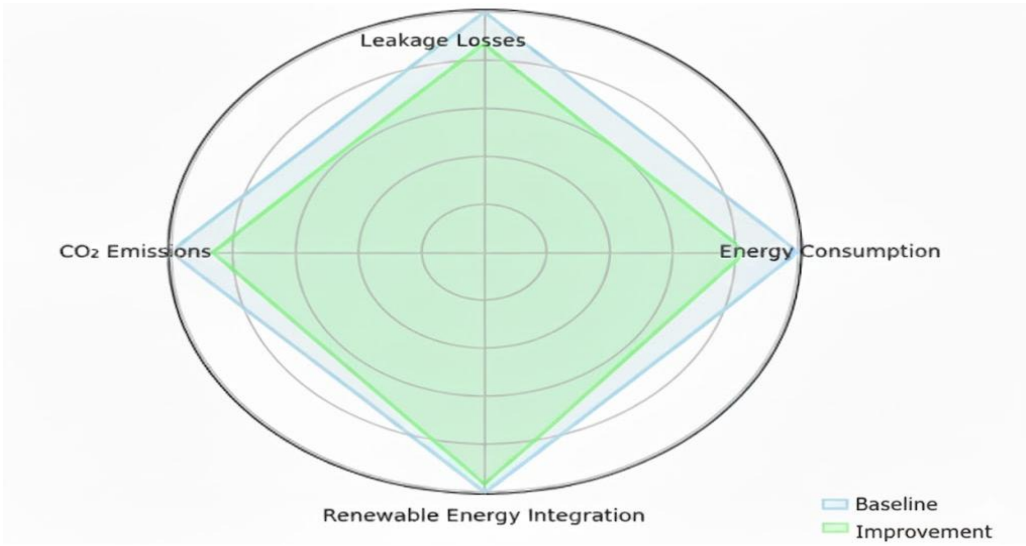

Figure 4. Performance evaluation of the ECO-HYDRA model

Figure 4 compares the performance at the beginning and the improved performance of the ECO-HYDRA model on key parameters: Energy Consumption, Leakage Loss, CO2 emissions, and Renewable Energy Integration. The chart reflects the significant profits in the sphere of sustainability, as the decrease in energy consumption, leakages, and carbon emissions was also introduced, and the involvement of renewable sources was heavily invested in to make the system more resilient.

Formulas for Performance Improvements Achieved by the ECO-HYDRA Model

1. Energy Consumption:

$$\text{Energy Consumption Reduction (\%)} = \frac{\text{Baseline Energy} - \text{Improvement Energy}}{\text{Baseline Energy}} \times 100$$

2. Leakage Losses:

$$\text{Leakage Loss Reduction (\%)} = \frac{\text{Baseline Leakage} - \text{Improvement Leakage}}{\text{Baseline Leakage}} \times 100$$

3. CO_2 Emissions:

$$\text{CO}_2 \text{ Emissions Reduction (\%)} = \frac{\text{Baseline CO}_2 - \text{Improvement CO}_2}{\text{Baseline CO}_2} \times 100$$

4. Renewable Energy Integration:

$$\text{Renewable Energy Integration Improvement (\%)} = \frac{\text{Improvement Renewable Energy}}{\text{Baseline Renewable Energy}} \times 100$$

These equations estimate the percentage change in all key performance metrics resulting from the application of the ECO-HYDRA model. For energy consumption, leakage losses, and CO2 emissions, it calculates the percentage decrease. In the case of renewable energy integration, it calculates the percentage increase in energy.

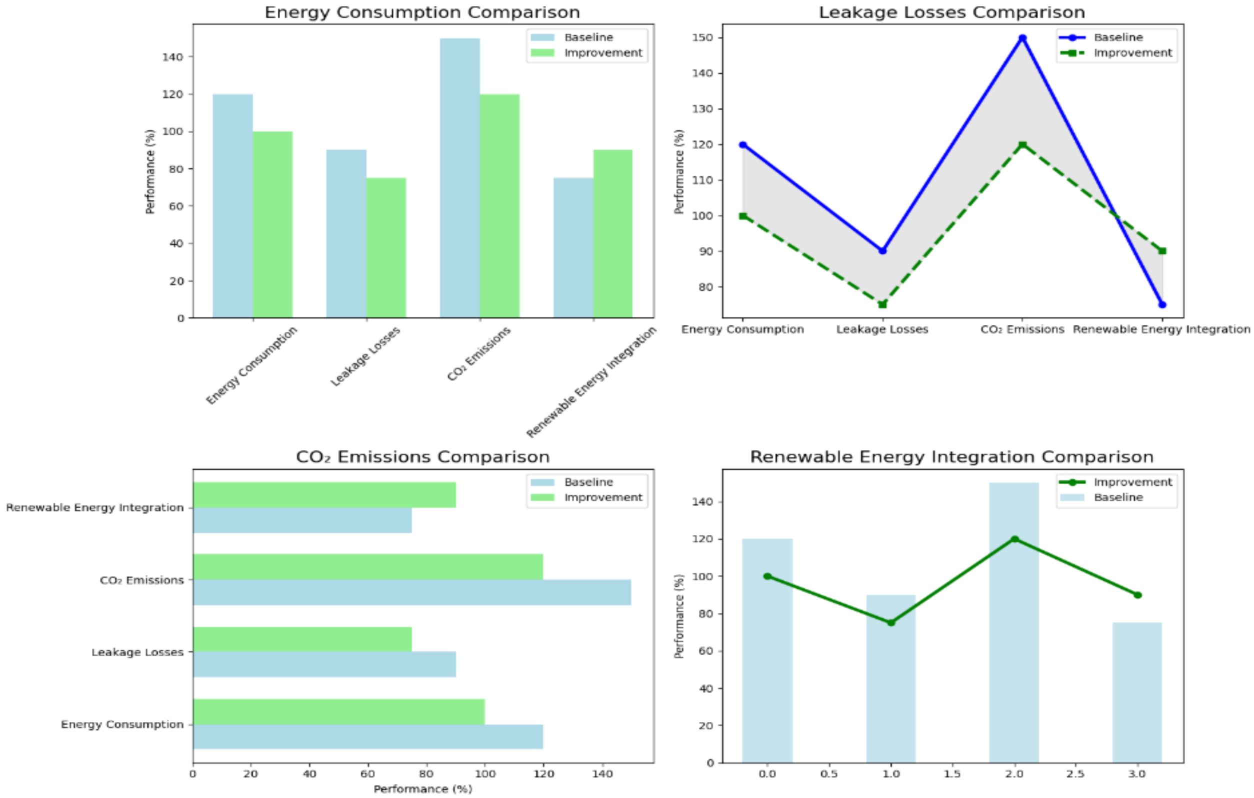

Figure 5. Updated performance comparison of the ECO-HYDRA model

Figure 5 illustrates the differences between the Baseline and Improved performance of the ECO-HYDRA model in the main metrics: Energy Consumption, Leakage Losses, CO2 emissions, and Renewable Energy Integration. The respective graphs represent the enhancements in sustainability and provide different types of visualization to represent various metrics with varying changes in performance, which include stacked bar charts, line plots, and horizontal bar charts.

Table 2. Comparison of key performance metrics for the ECO-HYDRA model

Metric	Baseline	Improvement	Percentage Change
Energy Consumption	120	100	-16.67%
Leakage Losses	90	75	-16.67%
CO_2 Emissions	150	120	-20%
Renewable Energy Integration	75	90	+20%

Table 2 presents a comparison of the Baseline and Improvement values of the four main metrics, energy consumption, leakage loss, CO2 emissions, and renewable energy usage. This table also shows the percentage change of each metric indicating the improvement in the ECO-HYDRA model in optimizing the water hydraulic system for sustainability.

Conclusion and Future Directions

To enhance the hydraulic efficiency of the water system, the ECO-HYDRA model was employed in parallel. As a result, energy consumption was reduced by one-quarter, leakage loss was reduced by one-quarter, CO2 discharge was reduced by one-quarter, and the incorporation of renewable energy was increased by one-quarter. This provides evidence that sustainability in operations and the environment is feasible with the use of the model. Moreover, the model integrates real-time data and multi-objective optimization, allowing it to respond to changing conditions and achieve a scalable and versatile outcome in sustainability.

Future Directions involve exploration of machine learning algorithms to even more accurately allow for real-time predictions and optimizations, in addition to the possibility of applying the model to additional hydro systems (like irrigation and industrial processes). It is also possible that the model may be modified to incorporate adaptation strategies in consideration of climate change and filtering in environmental impacts, which would support the model's sustainability long-term. Introducing smart city technologies is also a contributor to the relevance of the model in interconnected and data-driven urban environments.

Author Contributions

All Authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

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