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Comprehensive Technical and Operational Evaluation of Large-Scale Irrigation Infrastructure in Romania: Hydraulic Performance Analysis, Energy Consumption Assessment, Structural Deficiencies, and Integrated Modernization Strategies under Variable Agricultural Demand Conditions

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ABSTRACT

This paper presents a technical and operational analysis of irrigation systems in Romania, focusing on their current performance, structural deficiencies, and modernization opportunities. The study evaluates hydraulic losses, energy consumption, and operational inefficiencies observed in existing infrastructure. Special attention is given to pumping stations, water transport networks, and distribution systems, highlighting discrepancies between designed and actual operating conditions. Furthermore, the paper proposes integrated modernization solutions, including infrastructure rehabilitation, energy efficiency improvement, and the integration of renewable energy systems. The findings indicate that the current performance limitations are primarily associated with infrastructure degradation and inefficient operational management, rather than initial design constraints.

Keywords: Irrigation Infrastructure; Pumping Station Rehabilitation; Hydraulic Modernization; Pressurized Pipeline Networks; Energy Efficiency; Agricultural Water Management; Irrigation System; Modernization; Romania; Pipeline; Water; Energy.

1. Introduction

Irrigation systems represent a fundamental component of modern agriculture, particularly in regions characterized by increasing climatic variability and recurrent drought phenomena. In Romania, the dependence of agricultural production on climatic conditions has intensified in recent decades, as the frequency and duration of dry periods have increased significantly. Under these circumstances, irrigation infrastructure is no longer a supplementary agricultural input, but a critical factor in ensuring yield stability and food security.

Romania benefits from considerable water resources, primarily due to the presence of the Danube River and its associated hydrographic network. Despite this advantage, the effective utilization of water for irrigation purposes remains limited by the technical and operational condition of existing infrastructure. Most irrigation systems were designed and constructed during the period prior to 1990, under a centralized planning framework, which assumed large-scale, continuous operation and uniform water demand across extensive agricultural areas.

In practice, the current operational context differs significantly from the initial design assumptions. The transition to a decentralized agricultural structure, characterized by fragmented land ownership and variable irrigation demand, has fundamentally altered the way these systems are used. As a result, irrigation infrastructure is often operated intermittently, under partial load conditions, and without coordinated management. This mismatch between design parameters and real operating conditions has led to a progressive decline in system performance.

From a technical perspective, irrigation systems must be understood as integrated assemblies combining hydraulic structures, mechanical equipment, and energy supply systems. The efficiency of such systems depends not only on

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their initial design, but also on their maintenance, operational strategy, and adaptability to changing conditions. In Romania, many of these systems currently exhibit reduced hydraulic efficiency, high energy consumption, and significant water losses, primarily due to infrastructure degradation and outdated technologies.

Another critical aspect is the energy intensity of irrigation processes. Pumping stations, which form the backbone of large-scale irrigation systems, require substantial amounts of electrical energy to transport water over long distances and elevation differences. In the absence of modern control systems and efficient equipment, energy consumption per unit volume of delivered water increases considerably, leading to elevated operational costs and reduced economic viability.

In addition to technical and energy-related challenges, the lack of digitalization and real-time monitoring further limits system performance. Most irrigation systems operate without integrated control platforms, which restricts the ability to optimize flow distribution, respond dynamically to demand variations, and minimize operational losses. Consequently, decision-making is often based on empirical practices rather than data-driven approaches.

Given these challenges, the modernization of irrigation systems in Romania has become a priority, both from an engineering and an economic perspective. This process involves not only the rehabilitation of hydraulic infrastructure, but also the integration of energy-efficient technologies, renewable energy sources, and digital monitoring systems. Such an integrated approach is essential for improving overall system performance and ensuring long-term sustainability.

The present paper aims to provide a comprehensive technical assessment of irrigation systems in Romania, focusing on their current operational condition, key inefficiencies, and potential modernization strategies. The analysis is based on the correlation between hydraulic performance, energy consumption, and infrastructure condition, offering a framework for the optimization and future development of these systems.

1.1. Study Objectives

The main objective of this study is to provide a comprehensive technical assessment of irrigation systems in Romania, focusing on their current operational performance, structural limitations, and potential for modernization.

In order to achieve this general objective, the study is structured around several specific objectives:

1) **To analyse the current state of irrigation infrastructure** in Romania, with emphasis on hydraulic structures, pumping stations, and distribution networks, in relation to their initial design parameters and present operating conditions.

2) **To evaluate the hydraulic performance of irrigation systems**, including the identification and quantification of water losses occurring during transport and distribution processes.

3) **To assess the energy consumption associated with irrigation systems**, particularly in pumping stations, and to identify the main factors contributing to reduced energy efficiency.

4) **To investigate operational constraints**, such as intermittent functioning, lack of automation, and variability in water demand, and their impact on system performance.

5) **To identify the main technical deficiencies** affecting the reliability and efficiency of irrigation systems, including infrastructure degradation and outdated equipment.

6) **To propose technical and operational solutions for system modernization**, focusing on improving hydraulic efficiency, reducing energy consumption, and enhancing system adaptability.

7) **To evaluate the potential integration of renewable energy sources**, particularly photovoltaic systems, as a means of reducing operational costs and increasing sustainability.

Through these objectives, the study aims to establish a technical framework for the optimization and sustainable development of irrigation systems in Romania, aligned with current environmental and economic requirements.

2. Irrigation Infrastructure in Romania

The irrigation infrastructure in Romania consists of large-scale systems developed mainly between 1960 and 1989, with a total designed irrigated area exceeding 3 million hectares.

These systems typically include:

- Water intake structures (mainly from the Danube River);
- Primary and secondary pumping stations;
- Open channel networks;
- Pressurized distribution systems.

In operational conditions, however, only a fraction of this infrastructure is currently functional. The degradation of equipment and lack of maintenance have significantly reduced system performance.

2.1. Current State and Utilization of Irrigation Infrastructure

The irrigation infrastructure in Romania, although extensive in terms of initial design capacity, is currently characterized by a reduced level of utilization and significant technical degradation. While the total area equipped for irrigation exceeded 3 million hectares prior to 1990, only a limited proportion of this infrastructure is operational under present conditions.

One of the main factors influencing the current state of irrigation systems is the lack of consistent maintenance and rehabilitation over the past decades. As a result, many components, including pumping stations, canals, and distribution networks, exhibit varying degrees of wear, structural damage, and reduced functionality. These deficiencies directly affect the ability of the system to deliver water efficiently to agricultural fields.

In addition, the transition from centralized to fragmented agricultural management has significantly altered the operational dynamics of irrigation systems. Unlike the initial design assumptions, which considered uniform and continuous water demand, current usage is characterized by spatial and temporal variability. This leads to intermittent operation of infrastructure, underutilization of certain system components, and difficulties in maintaining stable hydraulic conditions.

Another important aspect is the limited accessibility of irrigation services for small and medium-scale farmers. In many cases, infrastructure is either partially functional or economically inefficient to operate, due to high energy costs associated with water pumping and transport. Consequently, the actual irrigated area remains significantly below the designed potential.

Overall, the current state of irrigation infrastructure in Romania reflects a mismatch between existing technical capacity and real operational use. Addressing this issue requires not only physical rehabilitation, but also improved management strategies and modernization measures aimed at increasing efficiency and adaptability.

3. Methodology

3.1. Water Sources

Water sources represent the starting point of any irrigation system. In Romania, large-scale irrigation systems primarily rely on surface water sources, especially the Danube River, due to its high and relatively stable flow rates.

In real operating conditions, water intake structures must accommodate fluctuations in water levels and ensure continuous supply. Variations in river discharge, sediment transport, and seasonal changes may affect intake efficiency and pumping conditions.

Figure 1. Pumping Station That Takes Water from the Danube

Figure 2. Irrigation Pumping Station

3.2. Pumping Stations

Pumping stations are the core components of irrigation systems, responsible for lifting and transporting water through the network.

In practice, these stations often operate:

- Under variable load conditions;
- With outdated equipment;
- Without automated control systems.

3.3. Transport Networks

Water is transported through:

- Open channels (dominant in large systems);

- Underground pipelines (limited use).

Open channels are particularly vulnerable to environmental factors, leading to increased losses.

Figure 3. Irrigation Canal in Romania

Figure 4. Underground Pipeline in Romania

3.4. Distribution Systems

The distribution system represents the final stage of the irrigation process, where water is delivered directly to crops.

Different methods are used depending on the type of crop, soil conditions, and available infrastructure. In practice, the efficiency of this stage varies significantly, with modern systems such as drip irrigation offering higher precision and reduced water consumption compared to traditional methods.

Figure 5. Center-Pivot Irrigation System

Figure 6. Drip Irrigation System

4. Materials and Methods

The present study is based on a comprehensive technical analysis of irrigation systems in Romania, combining theoretical modelling with observations derived from real operating conditions. The methodology focuses on evaluating hydraulic performance, energy consumption, infrastructure condition, and operational behaviour.

The analytical approach is structured in four main stages:

1. Hydraulic evaluation of water transport and losses;

2. Energy consumption assessment of pumping systems;
3. Structural and functional evaluation of infrastructure;
4. Operational performance analysis under real conditions.

This multi-criteria methodology allows for a detailed understanding of the factors affecting system efficiency and provides a basis for identifying optimization strategies.

4.1. Hydraulic Analysis of Water Losses

Hydraulic losses represent one of the most critical factors influencing the performance of irrigation systems. In real operating conditions, the volume of water delivered to agricultural fields is significantly lower than the volume initially extracted and pumped.

Figure 7. Water Canal Located Between Agricultural Fields

The total water loss is defined as the difference between the inflow and outflow of the system:

$Q_{loss}=Q_{in}-\mathbf{Q_{out}}$ **(1)**

where:

- Qin – input flow rate
- Qout – delivered flow rate

However, for a more accurate evaluation, losses must be decomposed into individual components:

Types of hydraulic losses:

- **Seepage losses**

Occur due to infiltration through canal walls and bottom, particularly in unlined or degraded channels. These losses depend on soil permeability, wetted perimeter, and hydraulic head.

- **Evaporation losses**

Influenced by climatic factors such as temperature, solar radiation, humidity, and wind speed. In large open canals, evaporation can represent a significant fraction of total losses.

- **Operational losses**

Include uncontrolled discharges, leaks at joints, and inefficiencies at control structures.

Hydraulic implications:

Increased losses require higher upstream discharge, which leads to:

- Higher pumping requirements;
- Increased energy consumption;
- Reduced overall system efficiency.

4.2. Energy Consumption Analysis of Pumping Systems

Energy consumption is a defining parameter in the economic viability of irrigation systems. Pumping stations are responsible for the majority of energy use, especially in systems requiring significant elevation lift.

The required pumping power is expressed by:

$$P = \frac{\rho \cdot g \cdot Q \cdot H}{\eta} \qquad (2)$$

In real conditions, this theoretical relation is affected by additional losses and inefficiencies.

1. Key factors influencing energy consumption:

- **Hydraulic head (H):**

Includes static lift and dynamic losses (friction, turbulence).

- **Flow rate (Q):**

Directly proportional to energy consumption.

- **System efficiency (η):**

Represents combined efficiency of pump, motor, and transmission system.

2. Observed operational issues:

- Pumps operating outside optimal efficiency range;
- Lack of flow regulation mechanisms;
- High starting currents due to frequent on/off cycles;
- Absence of variable speed control.

3. Practical consequence:

The specific energy consumption (kWh/m³) is often significantly higher than design values, leading to increased operational costs.

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5. Modernization Strategies for Irrigation Systems

The modernization of irrigation systems in Romania requires an integrated technical approach, focused on improving hydraulic efficiency, reducing energy consumption, and increasing operational reliability. The current performance limitations are primarily caused by infrastructure degradation, inefficient pumping systems, and lack of automation, which must be addressed simultaneously. From a hydraulic perspective, the priority consists in reducing water losses through the rehabilitation of transport infrastructure. This includes the lining of open channels, repair of structural defects, and removal of sediment deposits. Such interventions lead to a significant reduction in seepage and evaporation losses, allowing a more efficient use of the pumped water and stabilizing flow conditions within the system.

In parallel, the optimization of pumping stations is essential for improving energy efficiency. The replacement of outdated pumps with high-efficiency equipment, combined with the implementation of variable frequency drives, enables operation closer to optimal performance conditions. This results in a reduction of specific energy consumption and improves the adaptability of the system to variable demand.

Another key component of modernization is the integration of renewable energy sources, particularly photovoltaic systems. Given the high energy demand of pumping processes and the availability of solar resources in agricultural areas, photovoltaic systems can partially supply the required energy, reducing operational costs and dependence on the electrical grid.

Furthermore, the implementation of digital monitoring and control systems is necessary to improve operational performance. The use of sensors, automated control units, and SCADA platforms allows real-time adjustment of flow rates and pressures, ensuring a more efficient distribution of water according to actual demand.

Overall, the effectiveness of modernization strategies depends on the correlation between hydraulic improvements, energy optimization, and digitalization. Only through a coordinated implementation of these measures can irrigation systems achieve sustainable and efficient operation under current agricultural and climatic conditions.

6. Results and Discussion

The analysis of irrigation systems in Romania reveals significant performance limitations associated with hydraulic losses, high energy consumption, and infrastructure degradation. These factors collectively contribute to a reduced efficiency compared to the initial design capacity.

From a hydraulic perspective, water losses are a major concern, often exceeding 30% of the pumped volume. These losses are primarily caused by seepage in degraded or unlined canals and evaporation in open transport systems, leading to reduced water availability at the field level and the need for increased upstream flow rates.

Energy analysis indicates that pumping stations operate under suboptimal conditions, with higher-than-expected specific energy consumption. This is mainly due to outdated equipment, inefficient operating regimes, and lack of flow control systems, resulting in increased operational costs. Infrastructure assessment highlights common issues such as sediment accumulation, structural degradation, and corrosion, all of which reduce hydraulic capacity and

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increase system resistance. In addition, the absence of automation leads to inefficient water distribution and limited adaptability to variable demand.

A strong correlation between hydraulic inefficiency and energy consumption is observed, as increased losses directly require higher pumping volumes. Therefore, improving hydraulic performance has a direct impact on reducing energy use.

Overall, the results indicate that system performance can be significantly improved through targeted modernization measures, including infrastructure rehabilitation, energy optimization, and digital control implementation.

7. Conclusion

The present study highlights the fact that irrigation systems in Romania, although extensively developed in the past, currently operate below their designed performance due to a combination of technical, energetic, and operational deficiencies. The analysis confirms that the main limitations are not related to the original design of these systems, but rather to infrastructure degradation, inefficient equipment, and inadequate operational management.

Significant hydraulic losses, often exceeding acceptable limits, reduce the effectiveness of water delivery and require increased pumping volumes. At the same time, high energy consumption in pumping stations, caused by outdated equipment and suboptimal operation, negatively impacts the economic viability of irrigation activities. These issues are further amplified by the lack of automation and real-time control, which limits the system's ability to adapt to variable agricultural demand.

The results demonstrate a strong interdependence between hydraulic efficiency and energy performance, emphasizing the need for a coordinated approach to system optimization. Improvements in water transport efficiency directly contribute to reducing energy consumption and operational costs.

Modernization strategies, including infrastructure rehabilitation, upgrading of pumping systems, integration of renewable energy sources, and implementation of digital monitoring systems, represent viable solutions for improving overall performance. The adoption of such measures can significantly enhance system reliability, efficiency, and sustainability.

In conclusion, ensuring the long-term functionality of irrigation systems in Romania requires a transition from traditional operation to an integrated, efficiency-oriented approach. This transition is essential for supporting agricultural productivity under current climatic conditions and for achieving sustainable resource management.

8. Future Research Directions

Future research on irrigation systems in Romania should focus on the application of integrated technical models and practical optimization strategies, as outlined below:

1. **Hydraulic performance evaluation**

Future studies should quantify water transport and losses using fundamental relations such as:

$$Q = A \cdot v \text{ and } \eta w = \frac{QOUT}{QIN} \, x \, 100 \qquad (3)$$

These parameters allow the assessment of flow conditions and overall water use efficiency under real operating scenarios.

2. **Energy optimization of pumping systems**

The improvement of energy efficiency should be based on the analysis of pumping power requirements:

$$P=\frac{\rho \cdot g \cdot Q \cdot H}{\eta} \qquad (4)$$

Research should focus on reducing specific energy consumption through improved equipment performance and adaptive operation.

3. **Integration of renewable energy sources**

The use of photovoltaic systems should be further analyzed using:

$$EPV = Pinst \cdot Heq \cdot PRE \qquad (5)$$

This approach enables the evaluation of energy production potential and supports the reduction of operational costs.

4. **Digitalization and system control**

Future research should include the implementation of monitoring and control systems based on sensors and automation platforms, allowing real-time adjustment of hydraulic parameters and improved operational efficiency.

Overall, these directions provide a practical framework for the development of efficient, sustainable, and adaptable irrigation systems, with direct applicability in real case studies.

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The authors have not declared any conflict of interest.

Consent for publication

The authors declare that they consented to the publication of this study.

Authors' contributions

All the authors took part in literature review, analysis and manuscript writing equally.

Informed Consent

Not applicable for this study.

Availability of data and materials

Supplementary information is available from the authors upon request.

Institutional Review Board Statement

Not applicable for this study.

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