

Optimising Water Allocation for Combined Irrigation and Hydropower Systems [†]

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[†] Presented at the 3rd International Joint Conference on Water Distribution Systems Analysis & Computing and Control for the Water Industry (WDSA/CCWI 2024), Ferrara, Italy, 1–4 July 2024.

Abstract: The allocation of water resources among different sectors is often driven by distinct objectives, as exemplified by the divergence between hydropower production and irrigation. This study aims to optimise the water–energy nexus of an irrigation system abstracting water directly from a hydroelectric plant by minimising the pumping costs for irrigation, ensuring necessary water needs for crops and maximising revenue from hydropower generation. The optimisation procedure was implemented using a methodology based on a particle swarm optimisation algorithm and applied to a real case study located in northern Italy. The findings offer facility operators a management tool to optimise water resources efficiently for different needs.

Keywords: irrigation; hydropower; water allocation; particle swarm optimisation; pumping costs

1. Introduction

The relationship between water and energy has become more significant, especially in recent years, due to the impact of climate change on water availability [1]. The energy crisis has increased the focus on efficient systems and the transition from fossil fuels to renewable fuels to reduce energy consumption and costs. Additionally, the awareness of water scarcity has highlighted the fact that water is a limited resource that may need to be shared among different sectors.

Water requires energy for collection, treatment, distribution, and delivery. Additionally, water can be used to generate energy in hydropower plants. Conflicts may arise when the source of water is contested between multiple sectors with differing objectives [2]. For instance, the hydropower sector seeks to maximise energy production and profit, while the agricultural sector aims to meet water demand while minimising operational costs.

Optimising energy consumption of irrigation pumps involves allocating water to ensure the pump operates efficiently during periods of low electricity prices. Methodologies have been developed to identify plant sectors with similar energy requirements, reducing overall energy consumption [3,4]. The energy produced by a hydropower plant can be maximised by allowing the operation to follow the production plan during hours with higher electricity costs [5]. For this purpose, optimisation algorithms are widely used in research because they can find the optimal configuration from a wide range of possibilities.

This study aims to optimise water allocation by incorporating irrigation and hydropower production in a unique system to be optimised, with the objective to minimise pumping costs for irrigation, ensuring necessary water needs for crops and maximising revenue from hydropower generation. The methodology used employs hydraulic modelling to simulate irrigation demand at the farm level, to obtain pump behaviour and production data. An optimisation procedure is then applied using the Speed-constrained Multi-objective Particle Swarm Optimisation algorithm (SMPSO). Two different weeks



Citation: Peretti, F.; Menapace, A.; Righetti, M. Optimising Water Allocation for Combined Irrigation and Hydropower Systems. *Eng. Proc.* **2024**, *69*, 66. <https://doi.org/10.3390/engproc2024069066>

Academic Editors: Stefano Alvisi, Marco Franchini, Valentina Marsili and Filippo Mazzoni

Published: 4 September 2024



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with varying irrigation demands are considered and compared to a reference schedule to evaluate the effectiveness of the methodology.

2. Material and Methods

The methodology was applied to a real case study in northern Italy that integrates an upstream hydropower plant and a downstream pressurised irrigation network, covering approximately 197 ha. The irrigation intake is linked to the hydropower expansion tank, allowing for a maximum concession of 96 L/s for irrigation. Four pumps, with capacities ranging from 7.5 kW to 22 kW, support approximately 16 ha of land by powering the highest irrigation areas. The system is designed to accommodate four nodes at a time. Therefore, the weekly schedule of the entire plant must be defined to meet this requirement. The aim of this work is to find the optimal water allocation for both irrigation and hydropower production, with the goal of minimising costs and maximising revenue. The optimisation variable is the combination of a pattern of four nodes in a weekly schedule, which is then evaluated by the objective function. Irrigation time was calculated for each crop using the FAO methodology [6].

The irrigation water distribution network's hydraulic model was created in QEPANET [7], including all features of the plant. The optimisation methodology was implemented in Python using the SMP SO [8]. As a solution to the problem, a single objective function can be considered since it can satisfy the objective simultaneously. Pump consumption should be allocated during hours with lower electricity prices, while production should be maximised during hours with higher prices.

The objective function considers two contributions: the cost of pumping consumption due to irrigation and the revenue from hydropower production. To ensure equal weighting of contributions, a coefficient is applied to irrigation consumption, taking into account the significantly higher production of hydropower. The coefficient is calculated by dividing the energy consumed by the pumps by the energy produced by the hydropower plant during the first simulation. This is due to slight variations caused by different loss conditions. This approach does not consider the variation due to cost and revenue optimisation resulting from the simulation. Instead, it only takes into account the order of magnitude of the energy consumed and produced, giving equal weight to both contributions. To obtain the function that minimises costs and maximises production, the two contributions, one pumping costs and the other production revenue, are subtracted. This allows us to consider the solution that minimises the objective function.

The objective function is reported in Equation (1):

$$f_{min} = w_1 \cdot \sum_{t=1}^{168} \sum_{p=1}^4 \frac{\gamma \cdot q_p(t) \cdot \Delta h_p(t)}{\eta_p(q_p(t))} \cdot \Delta t \cdot pr(t) + \sum_{t=1}^{168} \frac{\gamma \cdot q_{hp}(t) \cdot \Delta h_{hp}(t)}{\eta_{hp}(q_{hp}(t))} \cdot \Delta t \cdot pr(t) \quad (1)$$

where the first contribution is the sum of the energy produced by each pump p over the course of a week (168 h). In the equation, γ is the specific weight of the water [N/m³], $q_p(t)$ is the pumped flow at time step t [L/s], $\Delta h_p(t)$ is the hydraulic head supplied by the pump [m], $\eta_p(q_p(t))$ is the efficiency of the pump [-], which is taken from the pump's characteristics curves, Δt is the time step of the simulation [h], $pr(t)$ represents the electricity price (PUN), which varies depending on the hour of the day throughout the year [Euro/MWh], and w_1 is the coefficient weight, which is multiplied by the costs of pumping consumption to ensure that the two contributions are on the same order of magnitude. The second contribution of the formula involves the production of the hydropower plant, in which $q_{hp}(t)$ is the remaining flow not used for irrigation at time step t [L/s], $\Delta h_{hp}(t)$ is the head available on the hydropower plant to produce energy [m], and η_{hp} is the efficiency considered for the Francis turbine [-].

The economic objective function is evaluated on the results of the hydraulic simulation of the irrigation distribution network, which was performed using the dedicated Python package WNTR [9]. To evaluate the simulation results, a reference schedule was defined

manually for four nodes at a time, without any optimisation criteria, simply assigning the irrigation time slot in sequence.

The analysis focused on two representative weeks during the irrigation season of a particularly dry year, which were characterised by varying agricultural water demands.

3. Results and Discussion

The methodology first generates a simulation of the network, which provides values for pressures and flows in the reference and optimised schedule. These results can be used to estimate the consumption of pumping stations and the potential production of the hydropower plant.

Table 1 presents the optimisation outcomes for the week with low demand. It is evident that pump consumption is low because of the low irrigation demand, while the hydropower plant utilises almost the entire available flow. When comparing the two contributions with the same weight, hydropower production has a relatively low variability among the simulations, while pump consumption, despite being very low, shows a small difference that becomes significant when comparing the two orders of magnitude. Therefore, the solution with lower pumping costs tends to yield better results. This is why hydropower production is lower in the optimised solution. Consequently, during weeks of low irrigation demand, the approach prioritises pumping consumption over hydropower production.

Table 1. Optimisation results for the week with low irrigation demand.

	Reference Schedule [Euro/Week]	Optimised Schedule [Euro/Week]
Pump 1	92.6	87.5
Pump 2	19.0	18.5
Pump 3	56.4	55.7
Pump 4	13.6	14.5
Hydropower production	12,448.0	12,323.7

Table 2 shows the results for the week with high irrigation demand. Pumping consumption was highest during this period, resulting in the lowest hydropower production. Pump 3 demonstrated significant optimisation, while pump 2 showed similar results between the optimised and reference schedules. Overall, pumping costs were reduced by 14% and production increased by 11%.

Table 2. Optimisation results for the week with high irrigation demand.

	Reference Schedule [Euro/Week]	Optimised Schedule [Euro/Week]
Pump 1	683.9	548.0
Pump 2	135.3	136.4
Pump 3	179.2	189.5
Pump 4	90.8	61.0
Hydropower production	3831.7	4299.0

4. Conclusions

The methodology applied shows that optimisation criteria can reduce consumption by 14% during high-irrigation-demand weeks, while also increasing revenue by 11% from hydropower production. However, the total savings and revenue for weeks with low irrigation demand are not significant when comparing the two contributions of similar magnitudes. In this situation, it is possible to adjust the ratio between the two contributions to consider the optimal configuration.

The interactions among objectives become complex and divergent, especially in the context of increasing irrigation water demand in the face of climate change. In such

scenarios, optimisation criteria may be a suitable approach to reduce energy costs for irrigation and increase revenue from hydropower production.

Author Contributions: Conceptualisation, methodology, software, validation, formal analysis, investigation, data curation, writing—original draft preparation, writing—review and editing, visualisation, F.P. and A.M.; project administration, A.M.; funding acquisition, M.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Free University of Bozen-Bolzano (Italy) under the projects “Extreme Events in Mountain Environments (EXTREME)” grant number [TN202R] and “Data Driven Anomaly Detection for Sustainable Water and Energy Smart Grids Management (DIADEM)” grant number [TN202O].

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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