INTEGRATED WATER-ENERGY-FOOD MANAGEMENT IN A CHANGING CLIMATE: A HYBRID STOCHASTIC-EVOLUTIONARY APPROACH FOR ADAPTIVE INFRASTRUCTURE PLANNING

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Keywords – Water management, infrastructure planning, Multiobjective optimization.

INTRODUCTION

Climate change is increasing the frequency of hydrological extremes, threatening both food and energy security (IPCC 2023). Expanding irrigation through small-scale reservoirs (SR) helps increase water reliability for agriculture but may reduce inflows to large reservoirs, affecting hydropower generation (Bof et al. 2021). These trade-offs are often overlooked in current models, which rarely integrate irrigation, energy, and storage infrastructure in a unified framework (Schmitt et al. 2022). While SR offer benefits to food production and resilience, their impact on downstream users under uncertain climate conditions must be better understood. Integrated models are needed to balance competing uses and inform compensation policies or adaptive investments. This study addresses these gaps by proposing a framework combining Stochastic Dual Dynamic Programming (SDDP) with a Multi-Objective Evolutionary Algorithm (MOEA) to explore trade-offs under hydrological uncertainty. The approach enables multi-objective planning in basins with agricultural and energy demands. Results offer insights to improve policy decisions on SR expansion, energy reliability, and adaptive water management under climate change.

METHODOLOGY

The São Marcos River Basin, located in the Paraná Hydrographic Region hosts two hydropower plants (Batalha and Serra do Facão, with installed capacities of 265.08 MW and active storage of 4,798.56 hm^3) and 458 small reservoirs for consumptive uses. The basin supports significant irrigated agricultural production, with 1,271 center-pivot irrigation systems, particularly in the headwaters upstream of the Batalha Hydropower Plant creating water balance impacts and generating water-use conflicts between agriculture and energy generation. In the São Marcos Basin, irrigated areas are projected to increase linearly until 2040, potentially doubling current coverage. These characteristics make the São Marcos Basin an ideal system to demonstrate our integrated modeling approach. The proposed methodology framework combines a hydroeconomic model SDDP with a Multi-Objective Evolutionary Algorithm Borg-MOEA. The SDDP model represents system objectives of food

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production through irrigated agriculture and hydropower generation, optimizing water allocation and large-scale reservoir operating policies over time to maximize economic returns. Borg-MOEA complements this approach by explicitly representing two objectives (maximize energy production and water withdrawals).

RESULTS

Future climate scenarios reveal distinct impacts on water use and energy production. Under baseline conditions, dry climates reduce hydropower generation while increasing irrigation demands due to higher evapotranspiration. Wet climates, conversely, support both higher water withdrawals and increased energy production. When irrigation expansion and small-scale storage are introduced, results trade-offs: increasing irrigation often decreases energy output. These trade-offs are more pronounced in drier futures, where gains in agricultural supply require greater compromises in energy generation. Under historical and wet conditions, moderate storage expansion can improve both objectives. However, expanding beyond certain irrigation thresholds leads to nonlinear increases in energy loss. Water withdrawals above 433 hm^3/year, for example, trigger steeper declines in energy production, indicating less favorable trade-offs. Seasonal analyses also show that climate variability intensifies uncertainty, especially during dry months, affecting water availability.

CONCLUSION

Agricultural production can expand, especially under historical climate, but it depends nonlinearly on local water storage capacity. Increased irrigation reduces hydropower generation, mainly in dry scenarios, while impacts are smaller in wet conditions. Small-scale reservoirs improve reliability in historical and wet conditions but are insufficient to mitigate deficits in dry climates, making such investments riskier. Irrigation expansion relying solely on small reservoirs may increase vulnerability to prolonged droughts. Therefore, it is essential to combine these investments with other adaptive measures like drought-resistant crops, water use efficiency, and flexible agreements between irrigation and hydropower.

ACKNOWLEDGMENTS

The authors thank the Organization for Women in Science for the Developing World (OWSD) and the Swedish International Development Cooperation Agency (SIDA) for Ph.D. scholarship through Fund 3240314460, and the National Council for Scientific Technological Development (CNPQ) Grants 404187/2021-8 and 311263/2023-2 for research funding.

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