How does optimizing water-environment-energy nexus affect river-aquifer exchanges in an alpine river basin ?

Comment l'optimisation du lien eau-environnement-alimentation affecte-t-elle les échanges rivière-aquifère dans un bassin fluvial alpin ?

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RÉSUMÉ

L'interaction entre les rivières et les aquifères, connue sous le nom d'échanges rivière-aquifère (R-A), est vitale pour le maintien des systèmes d'eaux de surface et souterraines. Ces échanges régulent l'écoulement des cours d'eau, rechargent les aquifères et influencent la qualité de l'eau, mais sont de plus en plus sous pression en raison de la demande croissante en eau et du changement climatique. Cette étude examine les impacts de l'optimisation du lien eau-énergie-environnement (WEE) sur les échanges R-A dans le bassin inférieur de la rivière Ain, en France. Un cadre de simulation-optimisation intègre MODFLOW pour l'écoulement des eaux souterraines et MT3DMS pour la modélisation du transport des nitrates. À l'aide de l'optimisation multi-objectif par essaim de particules (MOPSO), les objectifs de maximisation de l'extraction des eaux souterraines, de minimisation des concentrations de nitrates et de réduction de la demande énergétique sont analysés parallèlement aux paramètres d'échange R-A. Les compromis entre les objectifs ont été visualisés via des fronts de Pareto et les préférences des parties prenantes ont éclairé la prise de décision via TOPSIS pondéré. Les résultats révèlent des interdépendances critiques, telles que les relations inverses entre le prélèvement d'eau et la remontée naturelle des eaux, et des risques accrus de nitrates dans les zones de descente des eaux. Cet ouvrage fournit des informations exploitables sur la gestion durable des bassins fluviaux alpins, en équilibrant les besoins humains et la préservation écologique tout en relevant les défis liés au lien WEE.

ABSTRACT

The interaction between rivers and aquifers, known as river-aquifer (R-A) exchanges, is vital for sustaining both surface and groundwater systems. These exchanges regulate streamflow, recharge aquifers, and influence water quality, yet are increasingly pressured by rising water demands and climate change. This study investigates the impacts of Water-Energy-Environment (WEE) nexus optimization on R-A exchanges in the lower Ain River Basin, France. A simulation-optimization framework integrates MODFLOW for groundwater flow and MT3DMS for nitrate transport modeling. Using multi-objective particle swarm optimization (MOPSO), objectives of maximizing groundwater extraction, minimizing nitrate concentrations, and reducing energy demand are analyzed alongside R-A exchange parameters. Trade-offs among objectives were visualized through Pareto fronts, and stakeholder preferences informed decision-making via weighted TOPSIS. Results reveal critical interdependencies, such as inverse relationships between water withdrawal and natural upwelling, and heightened nitrate risks in downwelling zones. This work provides actionable insights into managing alpine river basins sustainably, balancing human needs and ecological preservation while addressing WEE nexus challenges.

KEYWORDS

English: Groundwater management, multi-objective optimization, river-aquifer exchanges, Water-Energy-Environment nexus

French: Gestion des eaux souterraines, optimisation multi-objectifs, échanges rivière-aquifère, nexus Eau-Énergie-Environnement

1 INTRODUCTION

Alpine river basins are critical freshwater sources, supporting various ecological, economic, and social functions. The interaction between rivers and aquifers, commonly called river-aquifer (R-A) exchanges, plays a fundamental role in sustaining surface and subsurface water resources. These exchanges regulate streamflow during dry periods, recharge aquifers during wet periods, and influence water quality through nutrient transport (Dole Olivier et al., 2019). However, increasing water demands driven by agriculture, energy production, and urbanization, coupled with the impacts of climate change, have put significant pressure on the delicate balance of these interactions in alpine regions. The water-energy-environment (WEE) nexus captures the intricate interrelationship among water resources, energy use, and environmental impact on rivers, all essential for human well-being and sustainable development. Thus, a systematic WEE nexus optimization approach must be adopted to evaluate the synergies or trade-offs of different management plans.

Simulation-optimization (SO) methods are crucial in addressing practical challenges related to single and multi-objective optimization problems. It has been applied to various management goals relating to the nexus management. For instance, to optimize the sharing of physical and virtual water for different water users while considering the environmental impact (Stamou et al. 2018) and to maximize wastewater reuse by considering reuse supply and demands, costs, and profits while reducing pollutants (Zhang et al. 2017).

This study investigates the effects of WEE nexus optimization on R-A exchanges in a case study applied to the lower Ain River basin in France. Using a coupled simulation-optimization framework, we examine how different optimization strategies influence streamflow, aquifer recharge, and water quality. The study incorporates numerical models, namely MODLFOW for simulating the groundwater head and R-A exchanges and MT3DMS for simulating the total nitrate load in the river. Further, an integrated many-objective optimization model was set up to optimize competing objectives of maximizing groundwater extraction, minimizing nitrate concentration, and minimizing the energy demand for water supply. Mulit-objective particle swarm optimizer was used to obtain non-dominated solutions, and further, the trade-offs among the objectives were analyzed. Apart from the three objectives, R-A exchange parameters such as leakage out and leakage in were calculated to determine the correlation between the WEE nexus and R-A exchanges. Finally, management scenarios are chosen based on the weighted TOPSIS method, which incorporates stakeholder's preferences by assigning weights to the objective values.

2 METHODS

2.1 Integrated simulation-optimization model

In this study, numerical modelling is organized in two phases. MODFLOW first simulates transient grid-based groundwater flow to identify the region's hydrological flow patterns and upwelling/downwelling behaviours. The groundwater flow field is then coupled to a reactive transport model based on MT3DMS to simulate nitrate contamination and its transportation to the nearest river reach, reflecting the impacts of agricultural practices on alluvial groundwater and the stream.

2.1.1 MODFLOW and MT3DMS model

Based on the conceptual model approach, the groundwater flow modelling was performed using MODFLOW 2005 (GMS) 10.7. It was adopted to create different geospatial data-based input layers for defining the area's surface recharge, boundary conditions, discharge wells, observation wells, and hydraulic conductivity. The Ain River, a significant surface water feature in the study area, is modelled to capture the dynamic exchanges between the river and the underlying aquifers using the stream (STR) package in MODFLOW 2005. The GW flow model derived initial conditions, aquifer parameters, and sources/sinks in the model. A transient concentration levels are defined based on the data available at ADES portal (https://ades.eaufrance.fr/Recherche). In the calibration processes, the groundwater head values computed by the model and observed head at the four observation wells were analyzed at a 95% confidence level. Metrics such as RMSE and R^2 were calculated for four observation wells to quantify the discrepancy between the observed and simulated groundwater heads over the twenty-three stress periods. The coupling of MODFLOW-MT3DMS allows for for simultaneous qualitative-quantitative simulation to calculate response variables.

2.1.2 WEE nexus management model

The management goals include maximizing net groundwater extraction, reducing nitrate concentrations, and minimizing the energy required for groundwater withdrawal. The planning horizon spans 7 years, taking into account water and food security as well as land use constraints. The decision variables were 319 pumping wells and nitrate concentration levels in 4 irrigation zones. The specific objectives include :

The minimization of energy costs for meeting water requirements was estimated as follows:

$$E_h = \sum_{d=1}^{D} \frac{\gamma \times F_{d,h} \times H_{d,t} \times t_{d,h}}{\mu} \times C_e$$

Where, γ(9.8 kN m^{-3}) is the water-specific weight; $F_{d,h}$ is the demand discharge in the corresponding commune (m^3 d^{-1}) in LARB; $H_{d,t}$ is the simulated head difference through the MODFLOW model corresponding to time step t. C_e is unit energy cost (€ kWh^{-1}) (here 0.26 was considered as the unit price); $t_{d,h}$ hours running time of the GW pump.

The objective function included maximization of the "leakage out" component of the flow budget from MODFLOW as well as the pumping extraction from the aquifer. The leakage-out component determines the exchanges between the aquifer and the stream. The objective function can be mathematically described as:

$$\text{Maximise} \begin{cases} \sum_{i \in R} L_{out} - P \\ \sum_{i=1}^{n_z} N_i * Q_i - P \end{cases}$$

where L_{out} denotes the leakage rate from the aquifer to the river; Q_i represents the discharge rate of the i^{th} pumping well zone; R comprises the river grid cells associated with the leakage component. n_z represents the total count of well zones; N_i denotes the number of wells in the i^{th} zone.

This objective emphasizes reducing nitrate pollution impacts on ecological systems and human health by promoting sustainable agricultural practices and efficient resource use. The mathematical formulation for this objective is:

$$Minimize\ A_{affected} = \sum_{i=1}^{n_c} A_i \times \delta(N_i - N_{threshold})$$

Where, $A_{affected}$ is the total area affected (ha), n_c is the total number of land cells in the study area, A_i is the area of i^{th} cell, $N_i$is simulated nitrate concentration in the i^{th} cell (mg/L), $N_{threshold}$ is the permissible nitrate concentration threshold (mg/L) and δ is binary indicator function at the end of simulation period, where $\delta = 1\ if\ N_i > N_{threshold}, and\ \delta = 0$ otherwise.

3 RESULTS

A total of 776 Pareto-optimal solutions were identified as equally good unless decision-makers preferences were identified. The generated Pareto front, depicted in the parallel plot in figure 1, effectively illustrates the trade-offs among the four key objectives. Higher concentrations of contaminants correlate with high leakage out values, indicating that increased water withdrawal and system losses are associated with higher pollutant migration. substantial challenges for groundwater quality management, particularly in agricultural zones where nutrient runoff is critical in the overall health of river-aquifer systems.

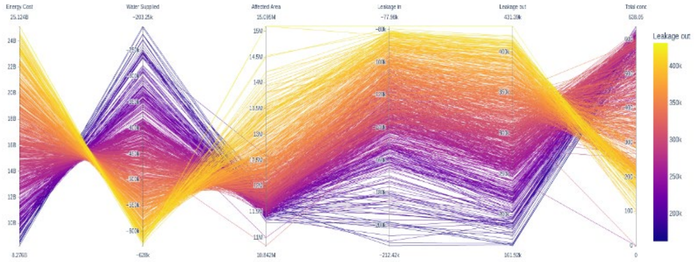

Figure 1 Parallel plot representing the non dominated pareto front solutions. Each verticle axis represensts the objective function while the colorbar represents the leakage from aquifer to the river.

The correlation heatmap in figure 2 illustrates the relationships between crucial WEFE nexus elements objectives and the R-A exchanges, specifically leakage in (downwelling) and out (upwelling). The data indicates significant correlations that highlight the interdependencies in this complex system. Leakage In represents water moving from the stream into the groundwater system, strongly correlating positively with energy cost (0.93) and affected area (0.74). This implies that higher energy costs are associated with increased downwelling rates, likely due to high pumping requirements or the need to maintain groundwater levels. Leakage out, which refers to water moving from the groundwater into the river, demonstrates even stronger correlations across multiple parameters. The most notable relationship is its negative correlation with water supplied (-0.99) and energy cost (0.98), suggesting that high extraction rates reduce the upwelling of groundwater, potentially diminishing the natural flow contributions to river systems. Additionally, leakage out shows a significant positive correlation with the affected area with nitrate (0.85), indicating that upwelling events will likely influence larger regions, affecting land use and agricultural productivity.

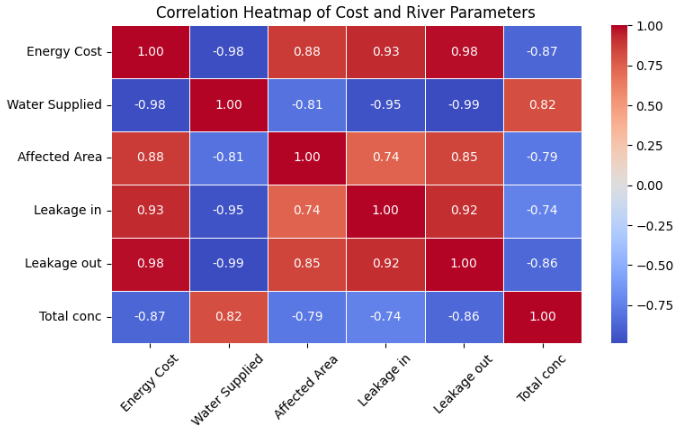

Figure 2 correlation heatmap of all three objectives and the R-A exchanges parameters (Leakage In and Leakage out)

4. Discussion and conclusions

Many objective S-O pave the way for solving the hidden synergies and trade-offs among the water availability, food, land security, socio-economic development, and ecosystem health nexus. Decision-makers could leverage the solutions obtained from a complex yet integrated element-wise simulation and its optimization for sustainable management goals. The framework used in the study could be helpful for concerned stakeholders who have different goals depending upon the sector they belong. For integrated water resources management and planning, scientists have been using S-O for managing water demand versus supply, quality and quantity, coastal management, and other areas. Considering only an elemental approach limits the interdependency among various other WEE sectors.

The findings of this study underscore the significant influence of WEE nexus optimization on river-aquifer exchanges in alpine river basins. Through the integration of advanced numerical models and optimization techniques, we demonstrated that trade-offs between groundwater extraction, energy demand, and nitrate pollution substantially affect R-A exchanges, particularly in terms of leakage dynamics. The results revealed critical interdependencies, such as the inverse relationship between water withdrawal and natural upwelling contributions, and the heightened risk of nitrate contamination in regions with intensified downwelling.

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