Chapter 8: MANY OBJECTIVE OPTIMIZATION FOR RIVER-AQUIFER EXCHANGES: PERCEPTIONS FROM WATER-ENERGY-FOOD-ENVIRONMENT NEXUS

8.1 Introduction

A river flows through different management goals whose developments are highly interlinked by combined demands and constraints. For example, a river may connect different stakeholders (hydropower, irrigation, and fishermen) with multiple actors (geomorphology, aquifer, and GW flow) (Döll and Zhang, 2010; Pagès et al., 2020). The excessive pumping of GW alters the river flow regime and further aggravates the variability in the other sectors. Hydropower at the upstream of the river impacts agricultural production via changing water availability for irrigation due to hydropeaking. This, in turn, affects microhabitat ecosystems (Daufresne and Boët, 2007). Maximizing sufficient R-A exchanges while meeting the GW extraction rate is a complex issue that involves regional hydrogeological conditions, climate, ecology, and, most critically, human activities (Cai et al., 2018). These human activities act as external factors within the system and are intricately linked to socio-economic benefits. Thus, managing GW along with R-A exchanges must focus on optimizing the scope of the nexus rather than individual water-energy-food-environment (WEFE) elements. GW, agriculture, and river health policies are connected to environmental regulations, and that degree of interdependency needs to be determined to ensure overall coherence. The above approach could provide more sustainable decisions due to the very nature of interconnections among WEFE objectives (Albrecht et al., 2018). A systematic WEFE nexus optimization approach must be adopted to evaluate the synergies or trade-offs of different management plans.

This chapter aims to develop a many-objective S-O framework tailored for the LARB for exploring sustainable GW extraction strategies in the context of R-A exchanges and WEFE elements. Specifically, the objectives include: (1) employing the MODFLOW-MT3DMS model to assess groundwater-surface water interactions and reactive nitrogen transport dynamics at the reach scale; (2) integrating a MOMEA, adaptive multi-objective particle swarm optimizer (AMOPSO) into the validated simulation model to optimize water use strategies with nexus objectives; and (3) identifying critical interdependencies and trade-off for better decision making in context to enhanced R-A exchanges and streamflow capture. The main research question addressed in this article is how the fulfillment or compromise of WEFE objectives affects the R-A exchanges in a connected riverbed. This S-O framework addresses the challenges of balancing socio-economic growth with environmental sustainability in the region. It offers a valuable tool for quantifying and forecasting hydrogeological changes, enabling decision-makers to balance the trade-offs between economic, energy, water, and environmental goals.

8.2 Methods

In this study, the AMOPSO algorithm proposed by (Huang and Zhang, 2021) is utilized to solve the conflicting objectives. The algorithm is modified based on energy conversion and explosive mutation, which makes it a better performer in large-scale many-objective optimizations. The main steps of the AMOPSO are parameter adaptor, global best selection, personal best selection, mutation operator, and external archive maintenance. The population is divided into three classes, and customized optimization strategies are formulated for the particles in different classes.

The key steps involved in the integrated MODFLOW-MT3DMS-AMOPSO S-O model are as follows: (1) initiating the process by generating random initial solutions using the coupled MODFLOW-MT3DMS simulation model; (2) reading the output data from the ".h5" file and generating new candidate solutions; (3) applying the adaptive Multi-Objective Particle Swarm Optimization (MOPSO) enhanced with an explosive mutation operator to improve the search process; (4) computing the objective functions and rewrite the ".h5" file with updated costs, and ; (5) evaluating all potential solutions stored in the archive through the numerical model to derive the final set of Pareto-optimal solutions. Subsequently, a visual analytics tool (Plotly) explores and analyzes the WEFE nexus management strategies within a four-dimensional objective space. This facilitates decision-making by providing insights into trade-offs, aiding multi-stakeholders and decision-makers across various sectors in selecting optimal strategies based on diverse criteria and concerns. The parameters used in the optimization algorithm are summarized in Table 8.1

Table 8.1 The control parameters of AMOPSO for the optimization process

Parameter	Value
Population size	50
Repository size	200
Maximum generations	800
Inertia weight	0.4
Individual confidence factor	2.0
Swarm confidence factor	2.1
Maximum velocity in percentage	5
Uniform mutation ratio	0.5
Division parameter (α, β)	10,40
Number of sparks	50

8.2.1 WEFE nexus management model

The management goals include maximizing net groundwater extraction, reducing nitrate concentrations, optimizing agricultural yield, and minimizing the energy required for groundwater withdrawal. The planning horizon spans 7 years, considering water and food security and land use constraints. The decision variables were 319 pumping wells and nitrate concentration levels in 4 irrigation zones. The methodology described by (Mishra et al., 2023) was adopted to reduce the pumping well decision variables for computational efficiency. The corresponding objective functions and constraints are detailed as follows:

8.2.1.1 The Energy Objective

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

$$E_h = \sum_{d=1}^{D} \frac{\gamma \times F_{d,h} \times H_{d,t} \times t_{d,h}}{\mu} \times C_e \qquad (8.1)$$

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. It was calculated as the ratio of total GW requirement during peak demand and design capacity of pumping wells and μ is the pumping system efficiency (in this work μ = 0.75 was considered).

8.2.1.2 Crop yield and Economic benefit objective

The objective function of the model is given as:

$$F = max \sum_{j=1}^{J}\sum_{i=1}^{I} \min ((Y_{max}(1 - b_{NP} \times e^{(-C_N N_{GC})}), Y_{max}(1 - b_{NP} \times e^{(-C_P P_{GC})}), Y_{max}(1 - b_k \times e^{(-C_k K_{GC})})(\times C_i A_{j,i} \quad (8.2)$$

In which j is the index for the irrigation zone, J= total number of irrigation zones in the study area. i = index for crop, I= total number of crops; Aj, i =area under crop i in the irrigation zone j (ha); Y_{max} is the maximum yield possible for the climate bin and land use; P_{GC}, N_{GC}, K_{GC} are the NPK application rate in the area (kg/ha); b_{NP}, b_k are the y-intercept of the yield response curve for each nutrient; C_N, C_P and C_k are response variables describing the percentage of max yield achieved at a given nutrient level. All the variables described above are summarized in Table 8.2 below. The dataset is derived from the InVEST model nutrient database available at (https://github.com/natcap/invest.users-guide/raw/main/data-sources/nutrient_db_0212.xlsx).

Table 8.2 Crop pattern in agricultural zones with constants

Crop	b_{NP}	b_k	C_N	C_P	C_k	max_yield (tonnes/ha)	Area (ha)	Agriculture zone
Wheat	0.81778	0.7216	0.02616	0.02511	0.02678	6.8317	18.5902	
Maize	0.8121	0.704	0.01	0.04457	0.01896	5.6681	20.0579	1
oilseeds	0.62583	0.41953	0.06530	0.11705	0.01531	2.5101	3.42452	
Wheat	0.81778	0.7216	0.02616	0.02511	0.02678	6.8317	21.812	
Maize	0.8121	0.704	0.01	0.04457	0.01896	5.6681	23.534	2
oilseeds	0.62583	0.41953	0.06530	0.11705	0.01531	2.5101	4.018	
Wheat	0.81778	0.7216	0.02616	0.02511	0.02678	6.8317	21.964	
Maize	0.86326	0.71263	0.04160	0.06896	0.02179	5.1773	23.698	3
oilseeds	0.68867	0.4808	0.06530	0.08719	0.01536	2.5101	4.046	
Wheat	0.81778	0.7216	0.02616	0.02511	0.02678	6.8317	15.238	
Maize	0.86326	0.71263	0.04160	0.06896	0.02179	5.1773	16.441	4
oilseeds	0.49756	0.37016	0.02416	0.08719	0.01085	2.5101	2.807	

8.2.1.3 Water Supply Objective

The objective function included maximization of the "leakage out" component of the flow budget from MODFLOW and 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:

$$\text{Maximise}\begin{cases}\sum_{i\in R} L_{out} - P \\ \sum_{i=1}^{n_z} N_i * Q_i - P\end{cases} \tag{8.3}$$

A dynamic Penalty is introduced as:

$$P = C_{model} \times d_{distance} \tag{8.4}$$

$$d_{dist} = \sqrt{\sum_{i\in W} (d_i - d_{threshold})^2} \tag{8.5}$$

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; P represents the penalty incurred by violating the drawdown constraint; $(Q_i)_{lb}$ denotes the lower limit of discharge for the i^{th} well zone; $(Q_i)_{ub}$ signifies the upper limit of discharge for the i^{th} well zone. d_i is the drawdown at the i^{th} well, W represents the set of well zones under examination, and $d_{threshold}$ is the permissible drawdown threshold, established at 2 meters as mandated by the Rhone Mediterranean water department. The term d_{dist} functions as a distance-based metric for drawdown, quantifying the difference of the actual drawdown from the threshold over all wells. The penalty P is calculated by multiplying this measure by a constant C_{model}, selected to ensure that the penalty aligns with the amount of the optimization cost. The expected value of d_{dist} is initially assessed by 500 random model iterations, after which C_{model} is established as the ratio of 1×10^5 (the cost order) to this expected value.

8.2.1.4 Environmental Objective

The environmental objective focuses on minimizing the land area affected by nitrate pollution to ensure sustainable water and soil quality management within the WEFE nexus. The affected area represents the total spatial extent where nitrate concentrations exceed permissible thresholds due to agricultural runoff or leaching. This objective emphasizes reducing nitrate pollution impacts on ecological systems and human health by promoting sustainable farming practices and efficient resource use. The mathematical formulation for this objective is:

$$Minimize\ A_{affected} = \sum_{i=1}^{n_c} A_i \times \delta(N_i - N_{threshold}) \tag{8.6}$$

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 a binary indicator function at the end of the simulation period, where $\delta = 1\ if\ N_i > N_{threshold}, and\ \delta = 0$ Otherwise.

8.2.1.5 Constraints

Water demand

To ensure water security, the optimization problem must account for the water demands of various sectors, including agriculture, industry, and households. The total groundwater abstraction in the communes must be constrained within feasible bounds, considering the cumulative demand from these sectors:

$$[W_{a,r} + W_{i,r} + W_{h,r} \leq G_r \leq G_{max,r} \quad \forall\, r = 1,2, \dots, R] \tag{8.7}$$

Where ($W_{a,r}$) is the water demand for agricultural use in the commune (r), ($W_{i,r}$) is the water demand for industrial use, ($W_{h,r}$) is the water demand for household use, (G_r) is the total groundwater abstraction capacity, and ($G_{max,r}$) is the maximum allowable groundwater abstraction in the commune. The maximum permissible extraction was limited to maintain a less than 2 m drawdown. The pumping decision variables were set between -500 and -2500 m3/d for the management period.

Land availability constraint

The total area allocated to the cultivation of wheat, maize, and oilseeds should not exceed the total available arable land in each commune:

$$Aw,r + Am,r + Ao,r \leq Atotal,r \quad \forall r = 1,2, \dots, R \tag{8.8}$$

Where:

Aw,r Am,r and Ao,r are the areas allocated to wheat, maize, and oilseeds in commune r, respectively. $Atotal,r$ is the total available arable land in commune r.

Minimum production requirements

The crop yield for each crop type must satisfy the minimum production demand to ensure food security:

$$Yw,r \cdot Aw,r + Ym,r \cdot Am,r + Yo,r \cdot Ao,r \geq Pmin,r \forall r = 1,2, \dots, R \tag{8.9}$$

Where, Yw,r , Ym,r and Yo,r are the per unit yield (ton/ha) of wheat, maize, and oilseeds in the agriculture zone r. $Pmin$ is the minimum production demand for the commune in which the agriculture zone is present.

8.3 Results

8.3.1 Pareto optimal solutions

A four-objective S-O framework is employed to address the WEFE nexus management model. The Pareto front provides an array of optimal solutions, where no single solution is superior across all objectives. One aim can only be improved by compromising performance in the other objectives due to the inherent trade-off inside the nexus. Thus, the collection of non-inferior decision variables is referred to as the non-dominated or Pareto-optimal set, illustrating the conflicts or trade-offs among food, energy, water, and nitrate contamination objectives. 776 Pareto-optimal solutions were identified as equally good unless the decision-maker's preferences were identified. The pareto solutions also reveal the delicate relations between nitrate leaching and R-A exchanges. The parallel coordinate plot in Figure 8.1 shows the behavior of total contaminant concentration compared to other 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. The plot shows many slope segments revealing significant trade-offs between these two objectives. This poses substantial challenges for groundwater quality management, particularly in agricultural zones where nutrient runoff is critical in the overall health of river-aquifer systems.

The generated Pareto front, depicted in the 3D scatter plot in Figure 8.2, effectively illustrates the trade-offs among the four key objectives. Specifically, the x-axis represents the total water supplied, the y-axis corresponds to the energy cost, and the z-axis denotes the affected area due to nitrate contamination. The color gradient encodes the fourth objective, total contaminant concentration loading in the river, providing a comprehensive view of many-objective optimization. The plot shows a clear upward trend between water supplied and energy cost. The total water supplied objective varied from 2×10^5 to 6.28×10^5 m^3/day while the energy cost objective had a range from 8.27×10^9 to 25.12×10^9 euros. This reflects an inherent trade-off in the GW extraction process, where increasing water supply demands an elevated energy input. As the groundwater withdrawal increases, energy consumption intensifies, reflecting the diminishing returns typically encountered due to increased pumping depths and system inefficiencies in groundwater nexus management. Furthermore, the color gradient across the Pareto solutions reveals that as more water is supplied, the total contaminant concentration initially decreases, but beyond a certain threshold, it starts to increase. This suggests that high levels of groundwater extraction can exacerbate nitrate leaching from agricultural zones, leading to contamination concerns. This aspect is critical when managing groundwater quality in regions with prevalent agriculture and nitrate inputs. On the other hand, the z-axis, representing the total affected area in ha, demonstrates a steep increase with higher water extraction levels. This indicates that more extensive areas are impacted as groundwater resources are drawn further. The affected area's increase correlates with broader environmental consequences such as soil degradation, aquifer depletion, and adverse effects on neighboring ecosystems.

Decision-makers must weigh the trade-offs between maximizing water supply, minimizing energy costs, reducing the affected area, and controlling contaminant concentrations. The visual clustering of points along a narrow band suggests zones where balanced compromises between objectives can be achieved, especially in the mid-range of water extraction levels, where energy costs remain moderate, and contaminant concentration is relatively controlled.

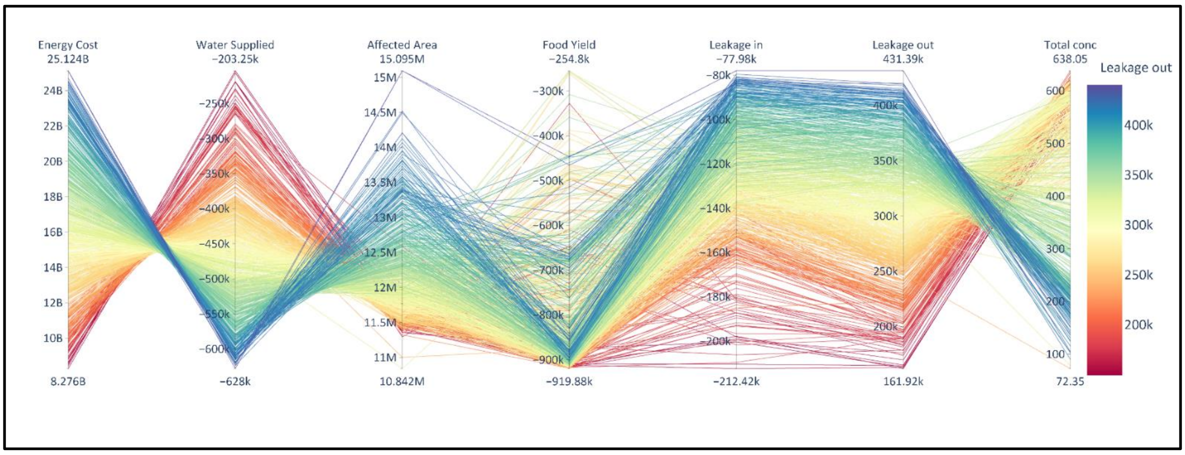

Figure 8.1 The parallel coordinate plot highlights conflicting objectives related to leakage in, leakage out, and total concentration, with solution color indicating downwelling in the LARB.

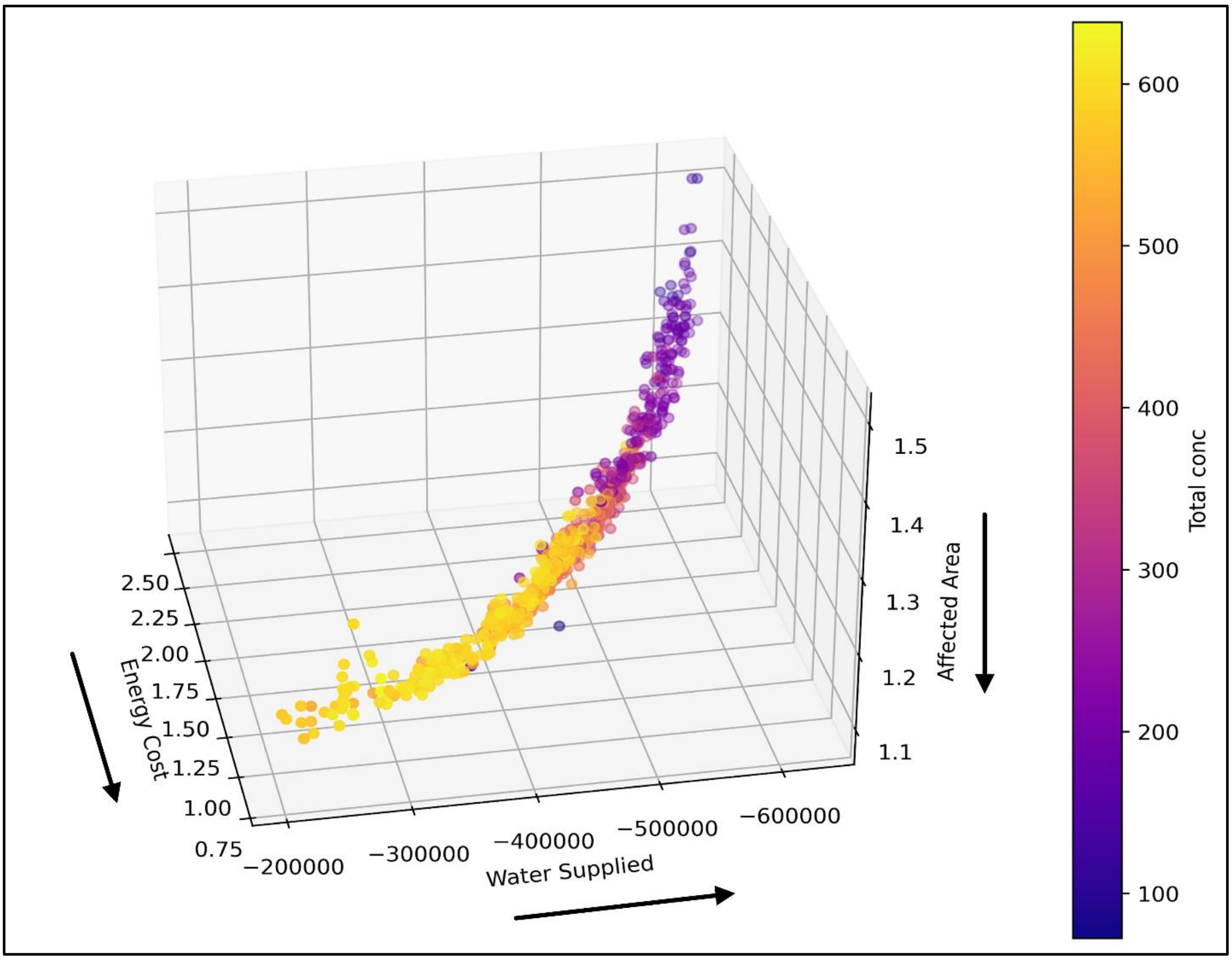

Figure 8.2 The scatterplot displays trade-offs among three WEFE nexus objectives, with total concentration loading shown by color. Pareto optimal solutions highlight synergies, and arrows indicate preferred directions.

The provided box plot in Figure 8.3 illustrates the variation of GW pumping values across 31 decision variables (Q1 to Q31) as part of the optimization process within the WEFE nexus. The distribution of values for each decision variable reflects the range and variability of groundwater extraction rates considered during the optimization. Decision variables Q1, Q2, and Q3 exhibit broader ranges with higher extraction values, suggesting a higher pumping potential in those regions. In contrast, variables such as Q6, Q14, and Q16 show more concentrated ranges, indicating limited variability and a more constrained pumping regime due to their presence near the river. Outliers in several decision variables, such as Q7 and Q25, highlight specific scenarios where extreme pumping rates were considered, potentially to balance the trade-offs between competing objectives.

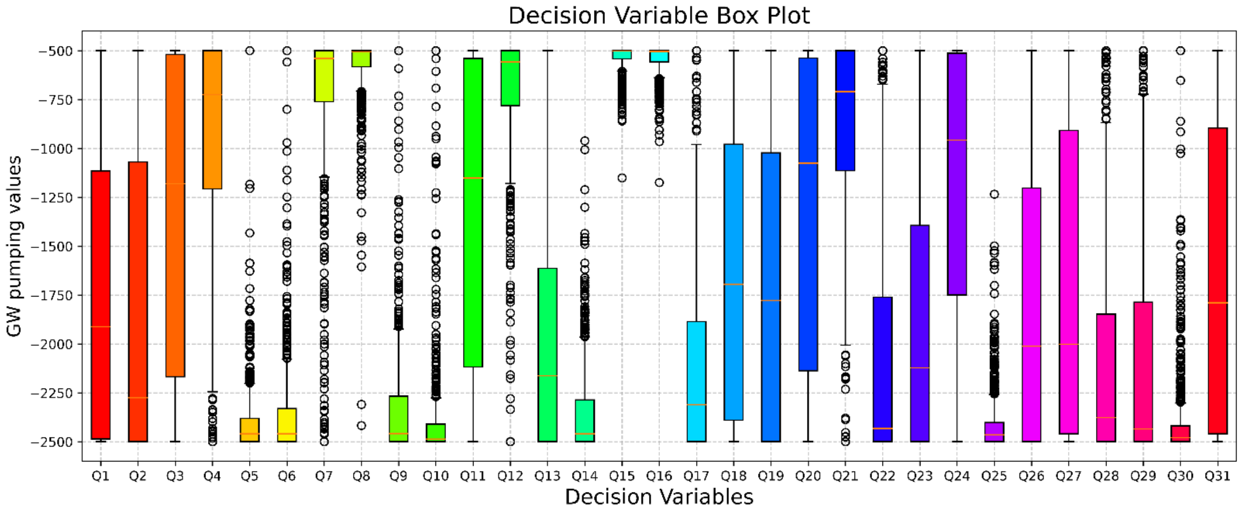

Figure 8.3 Variation of the decision variables. The pumping wells for each commune represent the corresponding discharge decision variables marked by a box. The colors are for representation purposes only.

8.3.2 Correlation between WEFE nexus elements and R-A exchanges

The correlation heatmap in Figure 8.4 illustrates the relationships between crucial WEFE nexus elements objectives and the R-A exchanges, specifically LeakageIn (downwelling) and out (upwelling). The data indicates significant correlations that highlight the interdependencies in this complex system. Both downwelling and upwelling are discussed below.

8.3.2.1 Leakage In (Downwelling)

LeakageIn 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. The affected area's correlation also suggests that more significant groundwater recharge (via downwelling) tends to impact a larger land area. However, LeakageIn exhibits a substantial negative correlation with water supplied (-0.95), indicating that increased water extraction from the aquifer reduces the net inflow from the river system, which may result in groundwater depletion under high withdrawal scenarios.

8.3.2.2 Leakage Out (Upwelling)

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. The correlation with total contaminant concentration (-0.86) highlights a critical environmental impact: lower upwelling rates are associated with higher contamination levels, potentially indicating the retention of pollutants within the groundwater when upwelling is restricted.

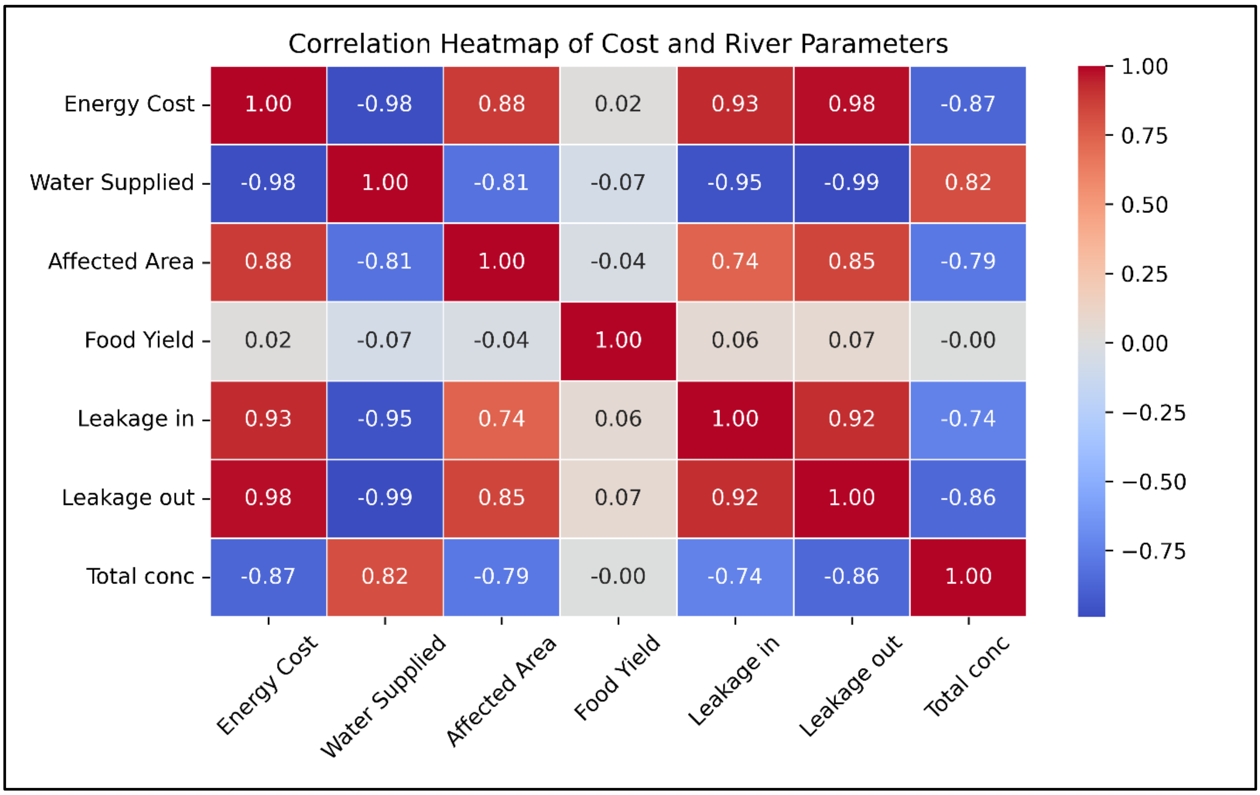

Figure 8.4 The correlation heatmap of all the objectives and the R-A exchanges parameters (LeakageIn and Leakage out)

The categorization of critical variables—' LeakageIn,' 'Leakage Out,' and 'Total Concentration'—based on their respective percentile distributions using quartiles (four equal-sized bins). Quartile-based categorization is a standard statistical approach for dividing continuous data into four equal-sized segments, effectively representing variability in data by assigning labels of "Low" to "High" (Song et al., 2020). This categorization is executed via pandas' "qcut" function, which enables assigning values into discrete intervals based on percentile ranks. The ranges are given in the below table 8.3.

Table 8.3 Different discretization of solutions for R-A exchanges and total nitrate concentration and their range

	LeakageIn category		Leakage out category		Total concentration	
	Min	Max	Min	Max	Min	Max
Low	-212420	-138300	161920	263740	72.354	298.08
Medium-low	-138190	-124550	264660	303160	298.400	484.90
Medium-high	-124470	-106780	303470	349020	485.100	587.71
High	-106560	-77977	349060	431390	588.190	638.05

The scatter plot in Figure 8.5 illustrates the relationship between energy cost and water supplied, categorized by ‘LeakageIn’ (faceted across four panels) and color-coded by ‘Leakage Out’ categories (Low, Medium-Low, Medium-High, High). The faceting by ‘leakageIn’ shows distinct variations in the impact of leakage on energy and water supply dynamics. In the high leakageIn category, scenarios with higher energy costs (approximately 15B to 25B euros) are still associated with significant reductions in water supply (around -500k m^3/d). However, these points also include a greater proportion of high leakage out scenarios, as shown by the shift in color distribution toward purple and red hues. This suggests that systems with high leakage rates, both in and out, require more substantial energy investments to maintain water supply, which can lead to operational challenges.

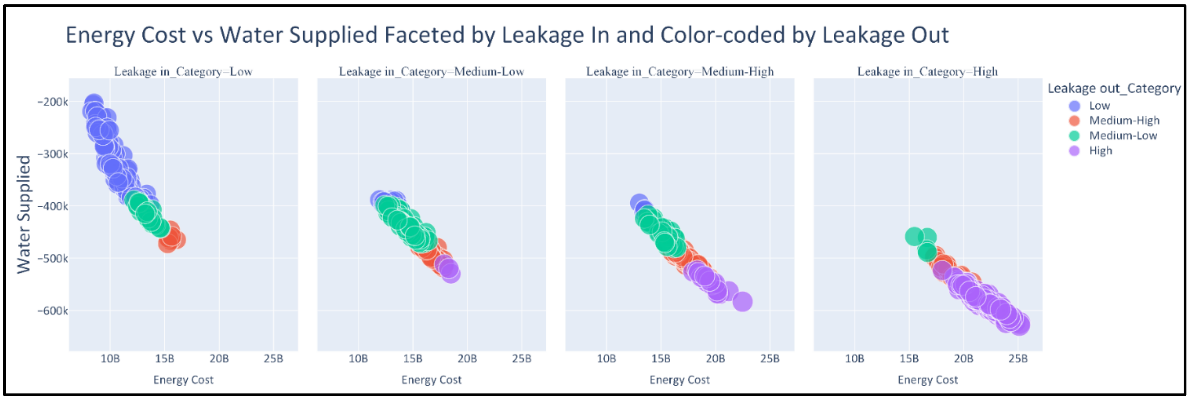

Figure 8.5 The scatterplot shows the relationship between energy costs and water supply, categorized by LeakageIn, with colors indicating Leakage out

8.3.3 Nitrate contamination and WEFE nexus

The influence of factors on river pollution, represented by the variable *Total Concentration,* was calculated to understand the dynamics between nitrate contamination and other nexus elements.

The presented parallel coordinates plot in Figure 8.6 illustrates. Lines representing high concentration levels generally align with moderate to high energy cost values, ranging between approximately 16 to 22 billion euros. This suggests that scenarios with elevated concentrations might be linked to higher operational costs, potentially due to increased efforts in managing contamination and maintaining water quality standards in river-aquifer systems.

Regarding total GW extraction (water supplied), cases with high concentration values tend to cluster in the lower range, typically between -250k to -500k m^3/d. This pattern indicates that high contaminant levels might be associated with reduced water supply, possibly due to restrictions or limitations on groundwater extraction from polluted sources to maintain ecological standards. The high concentration category appears more dispersed across the total affected area objective, ranging from 12M to 15M ha. This variation suggests that the impact of high contamination levels extends to broader regions, affecting more prominent areas of the watershed. However, there is a notable tendency for higher concentrations to coincide with regions where the affected area remains around the median to upper percentile range, indicating a more widespread influence of pollution.

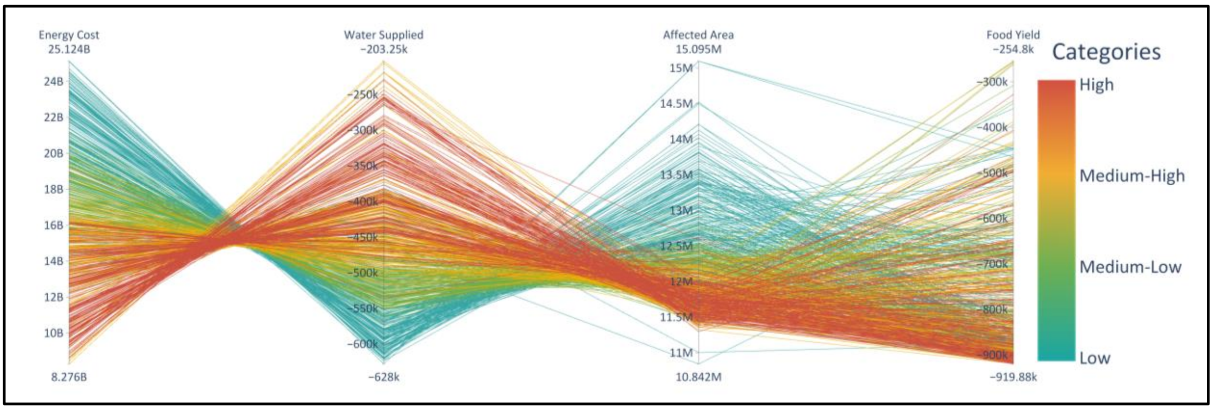

Figure 8.6 The parallel plot represents all four objectives of the WEFE nexus and their categorization based on the total concentration load.

These insights highlight the interconnected nature of water quality and resource management within the river-aquifer system. Elevated nitrate concentrations not only impose challenges for maintaining groundwater quality but also correlate with higher economic costs, constrained water supply, and reduced agricultural productivity. The current groundwater extraction and irrigation practices employed in the LARB are suboptimal and require modification to achieve synergies within the WEFE nexus.

8.3.4 Decision-making for optimized WEFE objective

Choosing a single or smaller number of optimal solutions becomes challenging, especially when the number of objectives is many with large-scale features. Many techniques are employed to get the reduced pareto front for the multi-stakeholders, such as clustering techniques, uniformly distributed sampling, and weighted sum methods such as TOPSIS, VIKOR, and ELECTRE (Mansour et al., 2024b; Wang et al., 2017). The 3-D pareto front was projected into lower 2-dimensional space for pairwise comparison and visualizing the trade-offs. 2-D contour plots are given in the Figure 8.7. The contours are defined by the density of the nondominated solutions obtained from the AMOPSO algorithm.

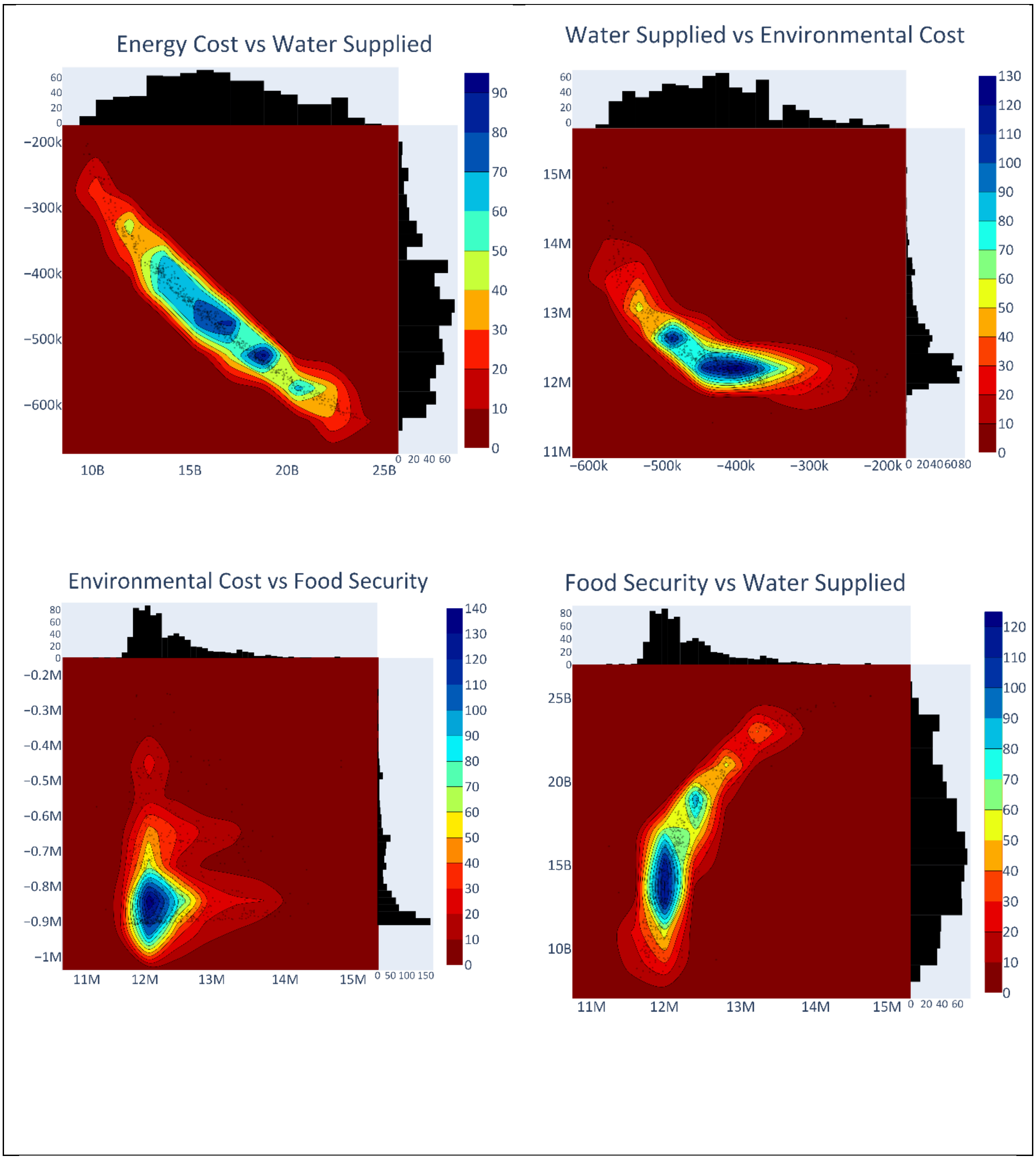

Figure 8.7 The 2D contour plot represents the density of a non-dominated solution for objective functions. The color bar represents the density of solutions obtained during the optimization problem.

In this study, we choose ten solutions from the pareto front to interpret the WEFE nexus elements and trade-offs. Solutions 1,4,6,8, and 10 are selected based on uniform sampling at equal intervals. The other five solutions, 2,3,5,7, and 9, were chosen with the TOPSIS technique. Furthermore, the ten solutions were categorized into three management scenarios based on the river's GW extraction, R-A exchanges, and total nitrate loading. Table 8.4 represents the objective values of the selected solutions.

Table 8.4 The table represents the 10 solutions by uniform sampling and weighted TOPSIS method

Selection method	Energy cost (10^9 euros)	Water supplied (m^3/d)	Total affected area (10^3 Ha)	Crop yield (tons)	Solution
Uniform sampling at equal intervals	8.27	-219270	11356	875.05	1
	13.04	-404210	11677	746.79	4
	15.85	-479780	11925	671.49	6
	18.97	-533220	1227	903.81	8
	25.12	-623740	15095	465.59	10
Weighted TOPSIS method	13.34	-409270	11564	887.20	5
	9.30	-255030	11597	881.79	2
	12.17	-388590	11656	483.09	3
	22.44	-598290	12794	675.45	9
	15.07	-456300	11889	844.33	7

The spatial distribution of decision variables across the study area for the selected solutions in the Figure 8.8 provides valuable insights into the variability of R-A exchanges and nitrate concentration loads. The solutions exhibit a gradual transition in the spatial patterns, capturing a range of exchanges between regions with relatively high infiltration (blue zones) and those dominated by discharge (red zones) (Cook et al., 2022). This clustering suggests that these solutions might be more tailored to optimize specific regions for maximizing recharge or reducing contamination risk (Uen et al., 2018).

8.3.5 Scenario comparison

8.3.5.1 Scenario 1 Low GW extraction with balanced R-A exchanges and nitrate load

This scenario is characterized by solutions prioritizing lower GW extraction rates while maintaining a balanced approach to R-A exchanges. The spatial distribution maps for solutions (1, 2, 3, and 4) show low values of discharge zones ranging from 500 to 1000 m^3/d, indicating favorable areas where water could infiltrate back into the aquifer and those where groundwater discharges into the river system. The nitrate levels are elevated with the first two solutions but decrease in the last two as evident in Figure 8.9. This scenario aligns with optimizing sustainable GW extraction while ensuring that the exchanges between the river and aquifer are not overly skewed towards depletion or recharge alone. However, the total nitrate loading in this scenario is moderate, suggesting that while groundwater withdrawal is low, efforts to control nitrate leaching into the rivers are to be prioritized.

8.3.5.2 Scenario 2 Moderate GW extraction with high R-A exchanges and high Nitrate load

Solutions 5, 6, and 7 fall into a scenario where pumping is moderate but with more pronounced R-A exchanges and higher total nitrate loads. These solutions depict scenarios where efforts are focused on sustaining the aquifer's connectivity with the river system, allowing for more significant water movement between the two. This enhances the recharge in some areas while supporting discharge zones in others. The spatial plots show more extensive zones of infiltration or discharge, reflecting a management focus on leveraging the ecological water demand and increasing the baseflow. However, this comes at the cost of increased nitrate loading into the river system, as the nitrate concentration levels in these solutions are notably higher than in others. This suggests that while maintaining water exchange is beneficial for sustaining river flow during dry periods, there is a need for additional measures to control nitrate contamination in this scenario.

8.3.5.3 Scenario 3 High GW extraction with emphasis on reducing Nitrate load

The third scenario includes solutions 8, 9, and 10, which focus on reducing the total nitrate load entering the rivers alongside lower levels of groundwater extraction. These solutions prioritize environmental health and water quality, aiming to minimize the impact of nitrate contamination on the river ecosystem. The total R-A exchanges in these solutions show that the interaction between the river and aquifer remains intense, allowing maximum recharge without exacerbating nitrate infiltration into the river system. The spatial maps reveal larger areas with reduced nitrate load, depicted by lighter shades in the corresponding figures, indicating high yield from the aquifer. This scenario represents a management approach where environmental conservation is prioritized, with higher economic gains from groundwater extraction and the advantage of sustaining the river's ecological integrity.

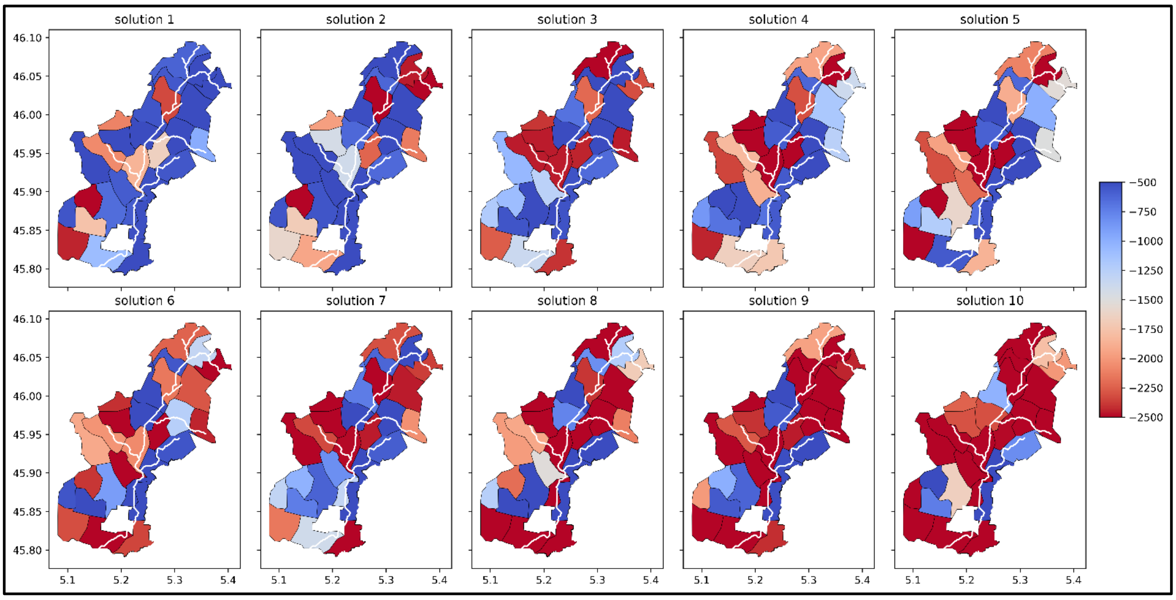

Figure 8.8 Spatial distribution of decision variables obtained from the 10 solutions within LARB

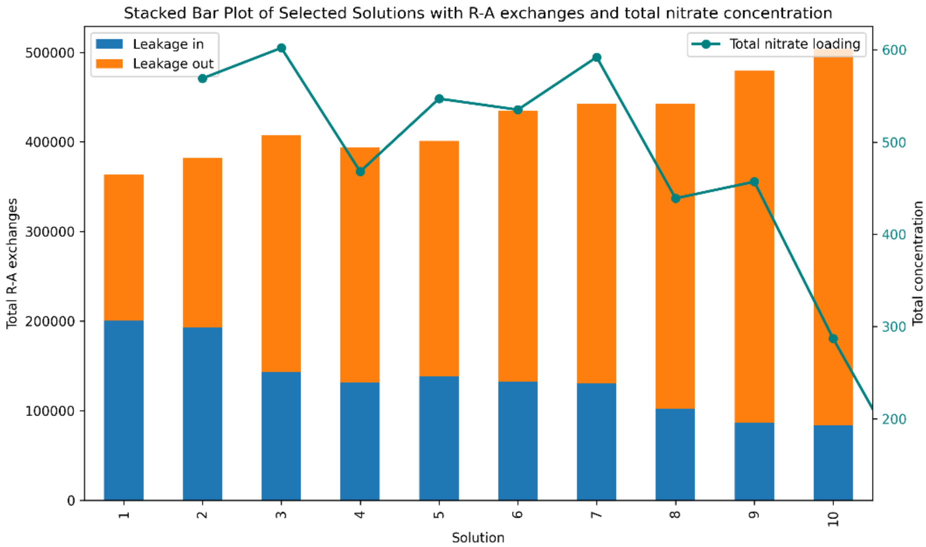

Figure 8.9 Stacked bar plot of selected solutions

8.4 Discussions

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 WEFE sectors. The trade-offs are generalized and not locally adaptable (Mendonça et al., 2023a). The solutions do not consider the co-participation and interplay of the nexus in the ecosystem. For the nexus management, these trade-offs need to be cooperatively managed. Thus, our work takes a step in connecting the GW to other nexus elements, focusing on the R-A exchanges that connect the surface and groundwater resources. This study will play a vital role in determining the effect of optimizing different nexus elements on the GW-connected river ecosystems qualitatively and quantitively.

In the context of ZRE, which are the areas characterized by a chronic insufficiency of water resources to the needs of users, the conflicts will increase with the rise in climate change, shortage of rainfall, shorter time of concentrations, and hydropeaking due to the dams situated on the upstream of the river. Currently, LARB does not fall into the ZRE classification, however, if not adequately managed cohesively, the GW could fail to meet all the demands. The proposed WEFE optimization model implements the GW abstraction strategies by setting the constraints and goals to meet the desired level of R-A exchanges and nitrate levels. The current LeakageIn and out is -3.59×10^5 m^3/d and 9.4×10^4 m^3/d, while the sum of concentration on all the river cells is 712 mg/L. After optimizing the WEFE objectives, there is a reduction in the leakage out term to the average of -1.34×10^5 m^3/d, which indicates a lessening water supply from the aquifer to the stream. This directly affects the ecological habitat of the Ain River. The sum of nitrate levels in all the stream cells is reduced to the average of 442 mg/L; in solution 10, it reaches up to 125 mg/L. However, the nitrogen mass accumulated over the past years could be better utilized as valuable nutrient resources for crops to improve water use efficiencies and reduce the application of chemical fertilizers (Y. Cai et al., 2021b; R. Li et al., 2017). Thus, policymakers could decide on better allocation for sustainable R-A exchanges while maximizing crop yield. To mitigate the increased energy demand, appropriate water allocation and non-conventional water resource management should be incorporated into the WEFE nexus, such as rainfall/stormwater runoff, cooling water, hydraulic fracturing wastewater, limited inter-basin water transfer, and domestic water circularity as discussed by (Chen et al., 2021). The nitrate concentration load is sensitive to the variation in the discharge fluctuation.

Moreover, after optimization, the nitrate concentration load is at 125mg//L, which is still higher than the threshold. It conveys that mitigating the nutrient contamination of the streams is a complex and challenging task that becomes more intricate while maintaining productive areas around the river catchment. To address nitrate leaching into rivers and align with the WEFE objectives, it is crucial to implement targeted management practices guided by Pareto-optimal solutions. For example, reducing fertilizer application by 20% and splitting the doses along with targeted reduction of mineral fertilizers can reduce nitrate leaching and nitrogen emissions by around 37% (Malagó et al., 2019). Further, to reduce high nitrate levels in urban stretches, special attention should be paid to wastewater treatment plants, non-point sources, and internal transformation processes (Jiang et al., 2021). Additionally, implementing efficient irrigation methods, such as drip and sprinkler systems, can help minimize vertical water movement and reduce nitrate leaching. However, the primary requirement from the agricultural stakeholders is often limited to crop yield and production. Changing the pattern of agriculture will require significant time and collaborative efforts (Y. Wang et al., 2022). The third scenario would be ideal for medium term future planning of managing existing infrastructure without changing the cropping pattern while increasing the socio-economic yield.

In resource management and governance, policies often fail to account for cross-sectoral interactions, leading to unwanted consequences such as water scarcity, food shortages, and environmental degradation. Developing policies within the WEFE nexus remains a complex challenge, emphasizing the need to bridge existing knowledge gaps. Key challenges include (1) the absence of a standard framework to address interactions among sectors, which are typically administered by separate stakeholders, markets, and infrastructures; (2) a lack of agreement on the extent to which the trade-offs and synergy occur; and how these dynamics vary across different spatial and temporal scales; and (3) the need for a standardized framework for effective decision making within the nexus, given the diverse governance structures globally.

This study develops an integrated many objective S-O for simultaneously optimizing different sectors within the WEFE nexus in the riparian zone of an alpine river basin. This framework can be applied to other areas for more realistic GW supply management and environmental degradation mitigation. The numerical model used to simulate the GW head and nutrient transport could be cohesively combined with different optimizers for robust decision-making. Corresponding objective functions and constraints can be added easily to the proposed framework, which makes it a flexible tool for additional goals. Nutrient transport and R-A exchanges are sensitive to variations in GW pumping rates, adding complexity to the decision-making process. Different visualization techniques are employed in the study to effectively navigate this complexity to illustrate the conflicts and trade-offs among the nexus elements across multiple objectives. These visual tools enhance the clarity of the interactions, helping to identify optimal solutions and support more informed management strategies. In practical terms, this approach offers a comprehensive framework for systematically analyzing the interactions between natural ecosystems and human activities. It enables a more holistic understanding of connected GW systems where managing the WEFE nexus should also focus on the interactions between streams and GW.

8.5 Summary

The R-A exchanges play a crucial role in groundwater sustainability, with strong correlations across the system's operational efficiency and environmental impacts. The rising GW demand must be managed across different WEFE sectors. Any degradation in one sector leads to dangers of food insecurity, high water prices, ecological degradation, and socio-economic divide. The trade-off and synergy must be studied at the nexus level rather than optimizing the individual sectors. To address this issue, this study develops many objective S-O models that combine MODFLOW-MT3DMS to simulate GW and nitrate transport with an optimization algorithm AMOPSO. The applied work combined the objectives of the WEFE nexus, precisely maximizing GW supply, minimizing the total area affected by nitrate contamination, energy prices for GW supply, and maximizing the crop yield in LARB. The simulation models were calibrated to provide a spatiotemporal variation of the R-A exchanges and nitrate contamination. The decision variables were decomposed to enhance the optimization process in a large search space, and AMOPSO was used to find solutions to many objective problems. Three variables, LeakageIn, leakage out, and total concentration load in the river, were calculated to study the effect of R-A exchange output. The observed trade-offs suggest that excessive extraction (high water supply) can severely impact the natural groundwater recharge-discharge cycles (LeakageIn and out). Implementing proposed scenarios could potentially increase the water abstraction from 2.1×10^5 to 6.2×10^5 m^3/day while the total crop yield is increased from 483 to 887 tons/year while satisfying the constraints for environmental sustainability and land use. These dynamics are critical for maintaining long-term groundwater balance, particularly in agricultural regions where upwelling supports river baseflows and contributes to preserving water quality through contaminant dilution.

The WEFE nexus is fraught with uncertainties related to climate change, socio-economic factors, and hydrogeological parameters, which complicate decision-making processes. Further, the optimization algorithms often struggle with finding optimal solutions in large search spaces that need rigorous hyperparameter tuning. While, the governance shortcomings, such as insufficient policy integration and lack of stakeholder engagement, need to be addressed to improve the implementation of WEFE nexus strategies. Future research should aim to integrate these factors into a (S-O) model for managing the WEFE nexus. This approach will help mitigate decision biases arising from numerical simulation model limitations and enhance the robustness and reliability of Pareto-optimal solutions in dynamic environments.