Theoretical Foundations for Water Management in Energy Transitions: Insights from the Spree River Basin

Evolutionary Algorithms and Multi-Objective Frameworks in Lusatia's Coal Phase-Out

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***Abstract*— This study examines water resource management challenges in the Spree River Basin against the backdrop of Lusatia's lignite coal phase-out. It provides the theoretical foundation with insights about data selection and a conceptual model. A Evolutionary Multi-objective Direct Policy Search framework is introduced to balance environmental conservation with human demands, including mine restoration, power plant cooling, and drinking water supply. Different pathways of assessing model results are discussed. The study provides a strong theoretical basis for model based decision support for the Spree River Basin, with an acknowledgment of the model's current limitations, such as the omission of water quality factors. Recommendations include iterative refinement and incorporation of quality metrics for enhanced real-world applicability, aiming to support resilient water management in energy transition contexts.**

Keywords: *River Basin Management, Reservoir Management, Spree River Basin, Lusatia, Coal Phase-Out, EMODPS*

INTRODUCTION

In pursuit of a carbon-neutral future, Germany is undergoing an energy transition, with a significant focus on phasing out coal by 2038 (Morris et al., 2012). This transformative commitment presents multiple challenges, especially for regions historically intertwined with coal mining (Nikas et al., 2020; Siontorou, 2023; Schuster et al., 2023). Lusatia, located in northeastern Germany, stands as a testament to this coal-rich legacy (Schwartzkopff and Schulz, 2015). During the 1980s, mining operations in Lusatia required the diversion of nearly 1.2 billion cubic meters of water annually, which most of it was released into the Spree River (Wolkersdorfer and Tbiem, 1998). This massive influx has had lasting effects, with artificially pumped groundwater now constituting about 50% of the Spree's average discharge rate (Uhlmann et al., 2023). In drier periods, this contribution can surge to 75%, underscoring the river's dependence on this supplemental source (Uhlmann et al., 2023).

The Spree River, flowing through Lusatia's industrial heartlands, supporting the lower and upper Spreewald UNESCO Biosphere Reserve, and eventually converging into the Havel river in Berlin (Figure 1), is influenced by a diverse array of stakeholders (Messner et al., 2006). From the mining industry's cooling and post-mining needs to conservation efforts in the Spreewald, and from Berlin's drinking water supply to its wastewater management, these stakeholders have developed a reliance on the river, adjusting their expectations to its artificially elevated water levels (Uhlmann et al., 2023).

However, the imminent decline in lignite mining operations, along with the corresponding reduction in groundwater extraction, presents a looming threat to the established hydrological balance (Uhlmann et al., 2023). Add to this the impending challenges of climate change and burgeoning water demand, and the Spree River Basin confronts a complex dilemma: reconciling the emerging disparity between dwindling water supply and increasing demands.

Amid these challenges, the basin's unique geography, with both natural and human-made water bodies, emphasizes the paramount importance of coordinated and sustainable water management. This study aims to introduce a modeling framework for the Spree River Basin that supports decision-makers in finding optimal operation strategies. Recognizing the benefits of model-based decision support, this approach is designed to navigate the challenges of meeting the essential needs of various water-dependent stakeholders in the basin.

A control volume approach is utilized to represent the states of the river basin. Initial discussions focus on essential data requirements, followed by the development of the conceptual model, establishing the fundamental architecture of basin representation. Subsequently, the quantitative model lays the mathematical groundwork, incorporating the Evolutionary Multi-Objective Direct Policy Search (EMODPS) framework. The results assessment illustrates potential pathways of analyzing results and assessment techniques specific for this modeling framework.

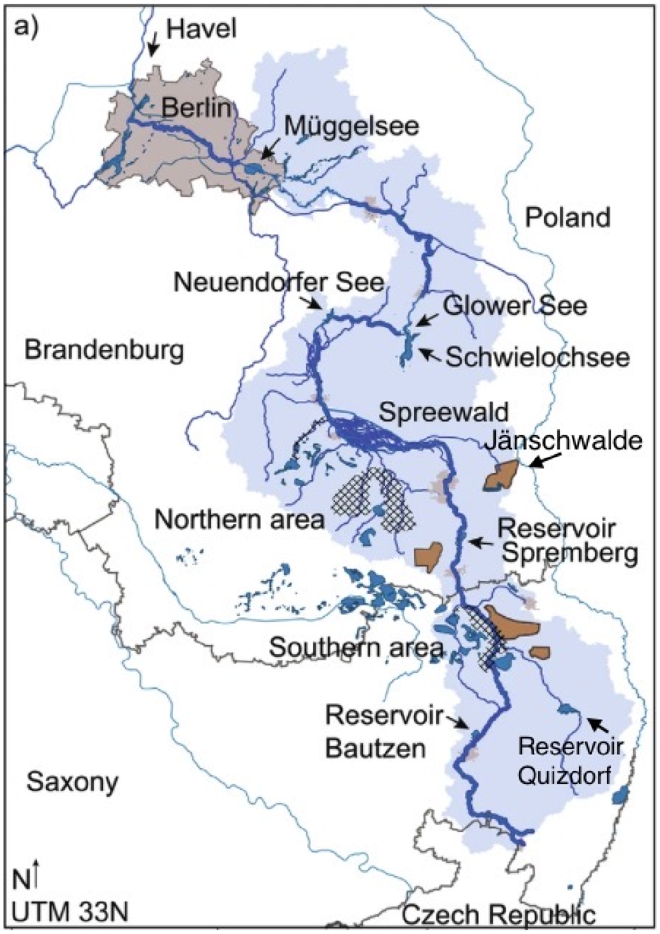

Fig. 1: Schematic of the Spree River Basin, delineating crucial hydrological components and mining influences. Reservoirs like Spremberg, Bautzen, and Quizdorf, urban areas such as Berlin, and the four active mines (brown are distinctly marked, illustrating the basin's diverse elements and their spatial interactions. Adapted from (Kommana et al., 2023)

Modeling Approach

This section outlines the model's theoretical foundation, discusses data selection, presents a conceptual representation of the Spree River, and introduces an initial quantitative model draft.

Data Selection

For modeling river reservoir systems, acquiring precise and pertinent data is essential. Information about the storage characteristics of each reservoir are paramount, necessitating information on the storage capacities and in/outflow dynamics of the system's components.

Storage Constraints - Accounting for the storage bounds is pivotal. The physical limitations of a reservoir define its maximum storage capacity, while maintaining structural and vitality necessitates a minimum storage threshold.

Stream-flow Data - A comprehensive understanding of river flow variability is imperative. Historical stream-flow data elucidates seasonal nuances and extremities. Yet, the unique context of the Spree River, augmented by artificially introduced groundwater, mandates a discerning approach. Such influences could potentially skew the genuine stream-flow characteristics in a post-mining landscape. Leveraging long-span datasets, obtainable from national hydrological bodies or global river flow compilations, is thus advocated.

Synthetic Stream-flow Generation - Complementing the historical data with prospective sequences is advantageous for model robustness across diverse scenarios (Herman et al., 2016). The Kirsch-Nowak synthetic stream-flow generator offers this capability, engendering stream-flow patterns that, while historically unobserved, remain within the realm of possibility (Kirsch et al., 2013; Nowak et al., 2010).

Groundwater Addition Data - Given the pronounced influence of groundwater on the Spree's flow dynamics, integrating historical data on groundwater extraction and addition is important. Potential sources encompass mining entities and regional ecological authorities.

Demand Constraints - Demand characteristics should be gathered via stakeholder participation underpinning a holistic modeling approach (Serrat-Capdevila et al., 2011). This participatory strategy should encompass public discourses, dialogues, and collaborative sessions with local inhabitants, industrial players, and preservation bodies.

Detailed data can be retrieved from regional entities. The Ministry for Agriculture, Environment, and Climate Protection, alongside the Ministry for Economy, Energy, and Labor, emerge as primary governmental interfaces. Moreover, dedicated governance institutions such as the State Office for Environment—mandated for water stewardship, and the State Office for Mining, Geology, and Raw Materials—regulating mining ventures, offer granular insights into the desired data spectrum. Mining companies, exemplified by LEAG, due to regulatory imperatives, retain archives of groundwater extraction data, thus emerging as pivotal data reservoirs. At a macroscopic level, global data troves like the Global Runoff Data Center (GRDC) and the World Meteorological Organization (WMO) cater to expansive data requirements.

Conceptual Model

The Spree River traverses multiple distinct regions, from heavily industrialized zones associated with the energy sector to nature reserves and urban landscapes. The diverse array of stakeholders, each wielding their unique interests and objectives, intensifies the complexity of modeling the Spree River Basin. Employing a control volume approach, the model seeks to navigate this complexity by emphasizing a meticulous balance between detail and manageability.

Crucial spatial considerations, such as the major water reservoirs of Bautzen, Quitzdorf, and Spremberg, the interactions between these reservoirs, tributaries like the Schwarze Schöps, and the impact of lignite mines such as Reichwalde, Nochten, and Welzow Süd, are included (Figure 2). Temporally, the model could aim at a time horizon of 20 years and a time step of one month to discern the imminent mining phase-out, while also ensuring a reflection of seasonal variations and long-term shifts. Later this might be adjusted based on modeling scope.

In its essence, the model aims to support decision-making regarding the management of the river basin within the context of the imminent coal-phase out. To maintain focus, it considers *(a)* reaching target volume for the restoration demand for the open pit mine Jänschwalde, *(b)* ensuring reliable amount of water for the cooling demand for the powerplant Schwarze Pumpe, *(c)* ensuring reliable flow for the natural conservation demands for the lower and upper Spreewald, and *(d)* ensuring reliable discharge for the drinking water supply for the metropolitan area of Berlin.

Restoration Demand
The restoration demand primarily focuses on the open-pit mine at Jänschwalde, due to cease operations in 2024, sooner than other mines such as Reichwalde, Nochten, and Welzow Süd, which are expected to continue until 2030. Given this imminent closure, the immediate focus on Jänschwalde's water demand for restoration purposes is crucial. Groundwater extraction, anticipated to continue until 2044, is explicitly modeled at each open-pit mine, allowing for the incorporation of other mines in future model iterations as their closure approaches.

Powerplant Cooling
The Schwarze Pumpe power plant, reliant on the Spree River for its cooling needs, maintains its significance in the model even post-coal phase-out underscoring its continued dependence on the Spree's waters for cooling purposes. By optimizing this objective function, the model aims to ensure that the power plant operates efficiently with a consistent and adequate supply of cooling water, minimizing any potential disruptions due to water supply inadequacies.

Environmental Conservation
In terms of environmental conservation, the model prioritizes the inland deltas of the lower and upper Spreewald, noteworthy nature reserves in Brandenburg. Optimizing this objective ensures a focused effort on maintaining robust ecological health within the Spree River Basin, promoting the sustainability of natural habitats and biodiversity.

Drinking Water
The model also recognizes the urban water demands, particularly spotlighting Berlin as a significant stakeholder due to its substantial population of over 3.8 million. The city's reliance on the Spree River for its drinking water supply is captured within the model. Optimizing against this objective fosters a strategy that prioritizes the stability and reliability of the urban water supply, ensuring that the daily water demands of the city, particularly Berlin, are consistently met, supporting the well-being and functionality of the urban area.

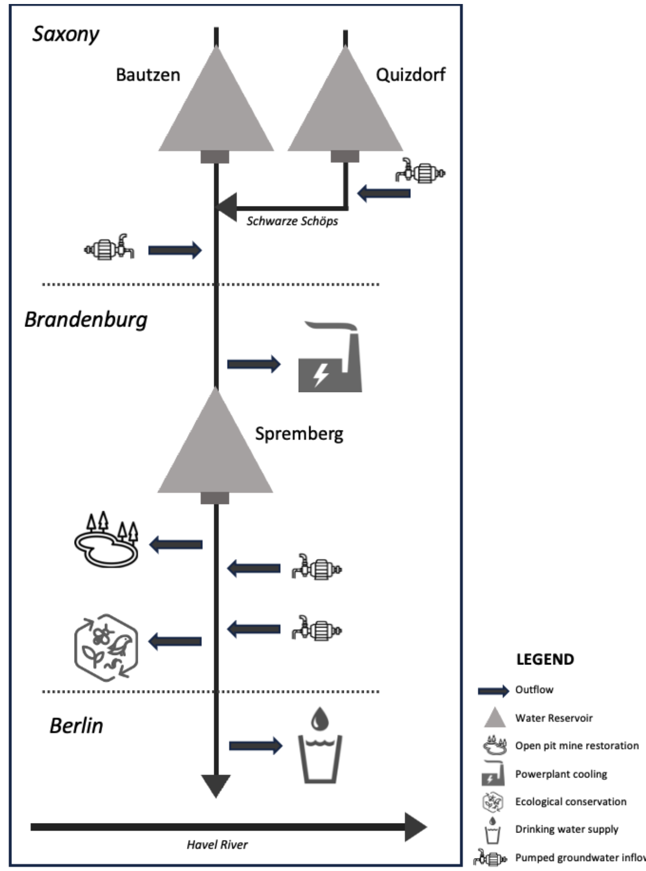

Fig. 2: Schematic representation of the Spree River Basin. The diagram illustrates major reservoirs (Bautzen, Quitzdorf, Spremberg), key inflow sources, including natural river flow and groundwater from mining activities, are detailed, along with essential outflows catering to various sector demands like open-pit mine restoration, power plant cooling, ecological conservation, and urban water supply in Berlin.

In conclusion, while the model is designed to simplify the intricate web of interactions within the Spree River Basin, it captures the essence of key players. Based on that, the model will aim at providing insights about the optimal release strategies for the reservoirs, setting a robust foundation for informed decision-making.

Quantitative Model

The task of modeling the River Spree Basin is initiated by laying the mathematical groundwork of the control volume approach, the objective functions and the framework of Evolutionary Multi-Objective Direct Policy Search (EMODPS).

Control Volume Approach

The spatial methodology enables the application of conservation laws, especially the principle of continuity, encapsulating the river system's dynamism via the change of storage S over time:

$$\frac{dS}{dt} = I(t) - Q(t) \tag{1}$$

where $I(t)$ describes the inflow and $O(t)$ the outflow at time t. Following that, a general water reservoirs within the basin, is represented as:

$$S_{t+1} = S_t + \sum fiI_{t+1} - \sum Q_{t+1} \tag{2}$$

where S_t is the storage at time t, I_t represents the inflow, R_t is the release, and W_t symbolizes the spill at time t.

To account for storage capacities, denoted by K any attempt to store water beyond this limit would result in a spillage representing water that cannot be stored. Thus, the excess of water that cannot be stored is represented by:

$$W_t = S_{t-1} + Q_t - R_t - K \tag{3}$$

However, when the reservoir does not exceed its capacity, W_t is simply set to zero ($W_t = 0$).

In order to meet the water demands, denoted as D, water reservoirs have to cater specific water demands that vary, in this case, stemming from *(a)* restoration demand, *(b)* cooling demand, *(c)* environmental conservation, and *(d)* drinking water supply. The release conditions are thus governed by these four primary objectives, rooted in distinct stakeholder interests.

Objective Functions

Herein, a first preliminary discussion about the mathematical formulations are presented (Table I), drawing inspiration from existing models such as those applied in the Susquehanna River Basin (Salazar et al., 2016).

Restoration Demand

The restoration demand objective function is articulated to embody the essence of the water restoration demands of old open-pit mines:

$$J_{OMR} = \max\left(0, V_{target} - \sum_{t=1}^{H} R_t\right) \tag{4}$$

In this equation, V_{target} signifies a predefined volume of water necessary for restoration activities. It represents a fixed goal that the water management strategy strives to meet. The term $\sum_{t=1}^{H} R_t$ denotes the cumulative volume of water actually released for restoration purposes over a specific period, H.

The objective here is to minimize any shortfall in the water volume required for restoration. Incorporating $\max(0, \cdot)$ within the function ensures that it accounts only for unmet water demands, avoiding penalties for exceeding the target water volume. This construct facilitates a focus on scenarios where the actual water released falls short of the target volume, thus emphasizing the effective fulfillment of restoration demands in the optimization process.

(Power Plant Cooling

The objective function related to power plant cooling is designed to reflect the adequacy of water supply for cooling purposes.

$$J_{PC} = 1 - \frac{1}{H}\sum_{t=1}^{H} \frac{\min(S_t, D_{PC,t})}{D_{PC,t}} \tag{5}$$

In this equation, S_t denotes the available supply of cooling water, and $D_{PC,t}$ represents the demand for cooling water at the power plant at each time t over the horizon H.

The objective is to minimize the value of the objective function, J_{PC}, to ensure that the power plant's cooling water demand is reliably met. The equation is structured to normalize the minimum of the supply and demand by the demand, effectively calculating a ratio that signifies the fulfillment of the cooling water needs. Subtracting this ratio from one provides a value which results in a measure of supply inadequacy or shortfall.

Environmental Conservation

The environmental conservation objective is formulated to safeguard the ecological health of the Spree River Basin, emphasizing the preservation of natural habitats and biodiversity:

$$J_{SI} = \frac{1}{H}\sum_{t=1}^{H} \left(\frac{\max(Z_t - Y_t, 0)}{Z_t}\right)^2 \tag{6}$$

In this function, Z_t represents the required environmental flow or the flow needed to maintain ecological balance and health. The actual flow or the water available for environmental conservation is denoted by Y_t. The objective seeks to minimize the shortage index (SI), which quantifies the deficit in achieving the necessary environmental flows.

The formulation aims to penalize deviations from the required environmental flow, with a more significant penalty attributed to larger deficits. By squaring the shortages, the function gives higher weight to more substantial discrepancies, ensuring that solutions with significant shortages are suitably penalized, promoting strategies that better fulfill environmental flow requirements.

Drinking Water Supply

For the objective of drinking water supply, the focus is on ensuring that the urban areas, particularly Berlin, have access to a reliable and adequate volume of water to meet their daily demands:

$$J_{R_i} = \frac{1}{H}\sum_{t=1}^{H}\frac{Y_t^i}{D_t^i} \tag{7}$$

In this mathematical representation, Y_t^i symbolizes the volume of water supplied daily, and D_t^i denotes the daily water demand. Each term is averaged over a certain period, H, to smoothen out daily fluctuations and focus on a longer-term reliability aspect.

The objective here is to maximize the reliability of the water supply, ensuring that the volume of water delivered aligns closely with the demand. The equation is structured to evaluate the proportion of demand met, offering a reliability ratio that is optimized to ensure consistency and adequacy in the water supply.

If the sum of the previous storage S_{t-1} and the current inflow Q_t exceeds the demand D_t, the release is simply set to the demand (Equation 8). However, in scenarios where the available water (the sum of the previous storage and current inflow) is less than or equal to the demand, the reservoir releases all the available water (Equation 9).

$$R_t = D_t \tag{8}$$

$$R_t = S_{t-1} + Q_t \tag{9}$$

In situations where the system strives to match demand, yet the actual release is constrained by the available water volume, optimizing release decisions becomes paramount to ensure maximal benefits for all stakeholders.

Evolutionary Multi-Objective Direct Policy Search

To find optimal release decisions, the EMODPS framework (Giuliani et al., 2016), also called parameterization-simulation-optimization triad in water resource systems modeling (Koutsoyiannis and Economou, 2003), is recommend. It utilizes the synergy between the Direct Policy Search (DPS) approach, a method that can parameterize policies using global approximators such as Artificial Neural Networks (ANNs) or Radial Basis Functions (RBFs)and Multi-Objective Evolutionary Algorithms (MOEAs), a heuristic optimization strategy. The advantages of such an approach includes adeptness at navigating discontinuities and diverse Pareto front shapes, capability to generate the entire Pareto set in a solitary run, a proficiency to yield solutions even in the face of limited prior knowledge, and competence in handling intricate objective functions (Giuliani et al., 2016; Coello, 2007; Salazar et al., 2016).

Integral to this framework global approximators mapping states to actions. Among these, Gaussian RBFs hold special significance owing to their versatility and computational efficiency (Busoniu et al., 2009). A Gaussian RBF is mathematically encapsulated as:

$$\Phi(r) = \exp\left(-\frac{(x-c)^2}{2\rho^2}\right) \tag{10}$$

where $\Phi(r)$ signifies the RBF, x is the input vector which would include data about the reservoirs storage states or hydroclimatic conditions, c denotes the centroid of the RBF, and ρ defines its spread. For comprehensive decision-making, RBFs are summarized in a weighted manner. Consequently, a cumulative decision using Gaussian RBFs is parameterized as:

$$u_k = \sum_{i=1}^{N} w_i \exp\left(-\frac{\|x_k - c_i\|^2}{2\rho_i^2}\right) \tag{11}$$

with N representing the total RBF count, w_i the weight for the ith RBF, c_i its center, ρ_i its radius, x_k the input vector for time k, and u_k the corresponding outcome.

Given the characteristics of the Spree river—limited water availability combined with multifaceted cross-sector objectives, this approach will provide a Pareto front that encapsulates release strategies for each reservoir, representing arrays of ideal trade-offs among the different objectives.

Results Assessment

This section provides a methodical evaluation of the results obtained from an EMODPS modeling of the Spree River Basin water management system.

Tradeoff Analysis

The Spree River Basin's complex interplay of stakeholders and objectives necessitates a detailed trade-off analysis. Using parallel coordinates plots, one can visualize the performance of policies within the Pareto frontier. Such visualizations elucidate potential conflicts between objectives, like possible trade-offs between water provisioning for Spreewald conservation and power plant cooling requirements. Recognizing these trade-offs is pivotal for a holistic water management strategy. Prominent compromise policies can be highlighted using distinct visual markers, offering a balanced solution likely to be acceptable to the diverse stakeholder groups.

Sensitivity and Vulnerability Analysis

To ensure the robustness of chosen policies, it is essential to comprehend their performance under different assumptions. Questions that could guide this assessment include:

- Which parameters, or their combinations, have the most significant influence on policy performance?
- What are the implications of these sensitivities on the overall Spree River Basin system?
- What are potential risks and benefits emerge for the involved stakeholders?

Furthermore, by testing different model assumptions, one can discern the impact of hydrological and socio-economic uncertainties on chosen policies. As an example, seasonal

TABLE I: Summary of objective functions used in the Spree River Basin model. Each objective is detailed with its description, mathematical formulation, and the direction of optimization.

Objective	Description	Mathematical Formulation	Direction
Restoration Demand	Minimize the shortfall in water required for restoring open-pit mines.	$J_{OMR} = \max\left(0, V_{target} - \sum_{t=1}^{H} R_t\right)$	Minimize
Powerplant Cooling	Maximize the reliability of the cooling water supply to the power plant.	$J_{PC} = 1 - \frac{1}{H}\sum_{t=1}^{H} \frac{\min(S_t, D_{PC,t})}{D_{PC,t}}$	Minimize
Environmental Conservation	Minimize the shortage index, reflecting the unmet environmental flow requirements.	$J_{SI} = \frac{1}{H}\sum_{t=1}^{H} \left(\frac{\max(Z_t - Y_t, 0)}{Z_t}\right)^2$	Minimize
Drinking Water Supply	Maximize the reliability of urban drinking water supply, ensuring demands are met.	$J_{R_i} = \frac{1}{H}\sum_{t=1}^{H} \frac{Y_t^i}{D_t^i}$	Maximize

water flow changes might markedly impact power plant cooling or Spreewald conservation objectives. Addressing such uncertainties is vital for an adaptive and efficient water management strategy.

Reflection

This study provided a theoretical foundation for sustainable water management in the Spree River Basin, especially in the context of the coal phase-out and the broader energy transition. It's evident that the Spree River Basin is navigating a delicate balance. As coal mines cease operations and the region transitions to alternative energy sources, the river system encounters intertwined complexities of decreasing water supply, due to reduced mine water discharges, and increasing demand from urban and ecological stakeholders. This mounting dichotomy underscores the paramount need for a robust modeling approach, which this study has strived to introduce, to provide crucial decision support for the region's water management challenges.

There are various limitations in the model. A central challenge in modeling the Spree River Basin's water system is its pronounced reliance on historical data. Over the course of 120 years, the basin's water dynamics have witnessed significant shifts, largely shaped by the region's mining exploits. As the region transition away from this historical context, there is growing concern that models underpinned by past data might falter in forecasting future intricacies. Compounding this is the intricate political tapestry of the Spree River Basin, which encompasses three federal states, including Brandenburg, Saxony, and Berlin. The onus of coordinating water release decisions among the three main reservoirs introduces a labyrinth of administrative and logistical challenges. For the basin to maintain a consistent and sustainable water flow, it is imperative that Brandenburg and Saxony cooperate.

Adding to these complexities is a pronounced data gap, especially concerning key projects like the Jänschwalde Tagebau. The absence of detailed restoration plans for such critical areas blurs the path forward, making it arduous to formulate a comprehensive water management blueprint. Furthermore, it's essential to note that the proposed objective functions are preliminary in nature. To truly capture the intricate dynamics of the Spree River Basin and align the model with real-world scenarios, these objectives need to be continually refined. Such fine-tuning should ideally be driven by a robust process of stakeholder participation, ensuring that the model resonates with the diverse interests and concerns of all involved parties.

Additionally, this modeling approach does not account for water quality dimensions, which are, for instance, crucial for drinking water supply. Future work could delve into the common post-mining issue where rising groundwater levels, due to the oxidation of sulfate, compromise water quality by introducing contaminants into the water system.

In light of the coal phase-out and the region's energy transition, the Spree River Basin stands at a pivotal point. This study has sought to lay down the theoretical groundwork to navigate the Basin's imminent challenges. However, it is important to acknowledge the model's limitations and continuously iterate upon it, incorporating new data and multi-state collaboration. As the region transitions, fostering cooperative dialogue and refining the modeling approach will be instrumental in ensuring the Spree River Basin's sustainable future.

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