REsilienT water gOvernance Under climate CHange
within the WEFE NEXUS

Deliverable D3.1

White paper on evaluation and implications of economic instruments under a WEFE perspective

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Executive summary

We study European water policies from the Water, Energy, Food and Ecosystems (WEFE) Nexus perspective. By outlining six representative European cases, we formulate different challenges and potential policy solutions. We suggest ways to integrate the WEFE perspective in three common theoretical water models, namely hydrological models, hydro-economic models, and cost-benefit analyses. We also discuss how new policies could be tested in those theoretical frameworks. We present two applications in which the WEFE is integrated in the economic models. We also illustrate how water policies can be evaluated in these models.

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Abbreviations

EC	European Commission
ES	Ecosystem Services
EU	European Union
WEFE	Water, Energy, Food and Ecosystems
WFD	Water Framework Directive
RBMP	River basin management plan
CAP	Common agricultural policy
EGD	European green deal
SDG	Sustainable development goal
IAM	Integrated assessment model
SWAT	Soil and water assessment tool
WetSpa	Watershed Evaluation Tool for Spatio-Temporal Pollution Assessment
WEAP	Water Evaluation and Planning
CBA	Cost-benefit analysis
PES	Payment for ecosystem services
RCP	Representative concentration pathways

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1 Introduction

Water is an essential input to many activities. Consumers use water at home, firms use water in production processes, farmers irrigate their crops, and ecosystems require water to sustain. To make water available for all users, governments can devise policies to steer demand and supply. Such policies require a holistic view from policy makers, taking into account the allocation of water between different sectors. Such allocation questions will also become more pressing in the future, as climate change is expected to alter patterns of precipitation, increasing the frequency of periods with water stress. This paper studies six European cases, with their challenges and objectives, and suggests economic policies to reach the objectives. Throughout, the interconnectedness between water users, as discussed in the water, energy, food and ecosystems (WEFE) Nexus is followed carefully.

The cornerstone of EU water policies is the Water Framework Directive (WFD). It aims to ensure sustainable water management and the protection of ecosystems. By promoting governance on the river basin level and by integrating ecological, hydrological and socioeconomic perspectives, the WFD prescribes a holistic approach. However, a host of other EU policies and directives exist to govern several aspects of water, like agriculture, biodiversity, flood risk, waste water, groundwater, and more.

As Europe faces challenges such as climate change, resource scarcity, environmental degradation, and growing demand for drinking water, policies need to allocate scarce water efficiently. The WEFE Nexus approach could offer solutions as it considers different water-consuming sectors and their interconnectedness. This approach remains underrepresented in the EU. EU water policies, such as the WFD, primarily focus on water quality and ecosystem health, often treating water management as a standalone issue.

To device economic instruments for better water policies, taking into account the interconnections between the WEFE sectors, we borrow insights from the economic literature. The economic literature on policy making offers roughly three types of policy instruments, namely price policies, quantity policies and command-and-control instruments. Price and quantity instruments allow agents to reoptimize their choices, often leading to higher efficiency and the most advantageous social welfare outcomes.

The WEFE Nexus literature, as well as the economic literature on overlapping policies, advocates for an holistic approach to water policy making. Not only should one take into account all relevant sectors and their interconnections, one also needs to understand how policies interact when they overlap. Interconnections could lead to unexpected interaction effects, misallocation of resources, and unsustainable outcomes. And when policies overlap they could interact with each other, leading to unforeseen, and sometimes undesirable, incentives. An important note is that these models do require more data due to their inclusion of multiple sectors and their interconnections.

To understand the water challenges in Europe, we collect information from six case studies. These cases differ substantially in their current policy settings, but also in scale and sectors involved. In the Slovak case study the main challenge is to retain more water in agricultural lands in order to improve soil quality, ecosystem services and drought management. In Spain, droughts are one of the main challenges in the Júcar river basin. To protect ecosystems during drought spells we suggest policy interventions in the existing water market. The Upper Main region in Germany suffers from suboptimal water quality due to nitrate runoff from agricultural activities. Malta faces problems of

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freshwater scarcity due to its dense population and groundwater shortages. In the Netherlands a water board faces challenges of freshwater scarcity in periods of droughts. Alternative forms of circular water systems could be potential solutions. The Belgian case covers a residential and two industrial pilot areas, where circular water infrastructure has been installed already. Different water pricing schemes are considered to make such infrastructure financially viable.

In order to translate WEFE Nexus thinking into policy making, we propose three economic water models from the literature that can be applied to all six cases. Each model allows introducing and evaluating new policies, as well as the WEFE sectors and their interconnections. They also allow the user to include the current policy setting. This way, overlaps between new and existing policies can be studied. The three models are a hydrological model, a hydro-economic model and a cost-benefit analysis.

As an illustration, we work out the models in more detail for two of the case studies. We illustrate how policies can be evaluated in the water models using a comprehensive WEFE Nexus perspective. For the Júcar river basin in Spain and the Upper Main region in Germany, we set up the hydrology, describe the economic agents, and perform a welfare calculation to determine costs and benefits. We select these two case studies, because they cover all three elements of our economic framework. The other four cases also fit the framework, but they are more selective in which parts they use.

This paper continues as follows. Section 2 reviews the EU's policy background and the related literature. Six case studies are presented with their water challenges and potential policy solutions in Section 3. A theoretical economic water framework is described in Section 4, covering hydrological models, hydro-economic models, cost-benefit and welfare analysis, and how to integrate water policies. Section 5 provides two applications of the models. Section 6 discusses and concludes.

2 Background and related literature

This section presents the European water policy background and two strands of literature. The first strand discusses the WEFE nexus and its multisector view of water consumption. The second strand of literature discusses economic policy instruments. It discusses different policy instruments but also implications from overlapping policies.

2.1 European water policies

Europe has implemented several policies to manage and protect its water resources. These policies aim to ensure sustainable water use, improve water quality, promote sustainable food production, promote clean energy production, and protect ecosystems. These policies are captured in a host of directives, plans and strategies. From a WEFE nexus perspective one might wonder whether specific policies sufficiently take into account the overlap between sectors.

The Water Framework Directive (WFD), established in 2000, is the cornerstone of EU water policy. It aims to achieve good qualitative and quantitative status of all water bodies, including rivers, lakes, groundwater, and coastal waters. The WFD promotes an integrated approach to water management based on river basin districts, encouraging cross-border cooperation. Member states are required to develop river basin management plans (RBMPs) and Programmes of Measures (PoMs) to protect and restore water bodies.

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Several other EU directives focus on specific water-related challenges. The Floods Directive requires member states to assess and address flood risks. The Drinking Water Directive aims at protecting the quality of drinking water. The Urban Waste Water Treatment Directive prescribes how urban waste water should be collected and treated in order to protect water bodies and the environment. The Groundwater Directive prescribes the management of groundwater resources, both in terms of quality and quantity. The Nitrates Directive focuses on nitrate pollution from agricultural sources. It requires member states to monitor nitrate pollution and protect against it where necessary. Finally, the Circular Economy Action Plan encourages water reuse and efficiency in agricultural and industrial processes and foresees the revision of the Urban Waste Water Treatment Directive.

The Common Agricultural Policy (CAP) promotes sustainable agricultural practices. The CAP includes measures to reduce water pollution from agricultural sources, enhance water efficiency, and support the conservation of water resources. To support the CAP, the European Farm to Fork Strategy aims at ensuring sustainable food value chains by reducing pesticides and fertilizer use, increasing organic farming and promoting sustainable consumption patterns.

The Renewable Energy Directive supports the EU's transition to renewable energy sources, which has implications for water management. Especially hydropower requires careful management to balance energy production with the protection of ecosystems. The directive encourages the sustainable development of renewable energy projects, while ensuring that they do not compromise water quality or availability.

The EU Biodiversity Strategy aims to halt biodiversity loss and restore ecosystems, including freshwater habitats. It emphasizes the importance of healthy water ecosystems for biodiversity and human well-being. The strategy includes targets for the restoration of rivers and wetlands, reduction of pollution, and sustainable water use. By integrating water management with biodiversity conservation, the strategy supports the overall resilience of ecosystems against climate change and other pressures.

Lastly, the European Green Deal (EGD) targets multiple aspects of sustainability. For example, the EGD promotes the sustainable management of water resources, the implementation of renewable energy sources, the sustainable production and consumption of food, and the conservation of ecosystems and biodiversity. While challenging to implement in practice, the wider approach suggested in the EGD is of importance for recognizing the interactions between sectors (Adamos et al., 2023).

While the WFD promotes the use of economic instruments like pricing mechanisms, cost recovery, and financial incentives for pollution reduction and efficient water use, the implementation of these tools still leave room for improvement. Boeuf & Fritsch (2016) conduct a meta-analysis of 89 research articles on the WFD's implementation in EU member states, revealing insufficient attention to issues such as the analysis of environmental benefits and costs, cost recovery for water services, incentive pricing, and the link between participation and economic analysis. Berbel & Expósito (2018) point out the need for consensus on the definitions of economic concepts and tools included in EU water policy, particularly regarding methods for operationalization. They identify gaps such as cost-recovery, water pricing, the costs and benefits of implementing the WFD, and the valuation of water resources. Moreover, emerging economic concepts, including water accounting, the insurance value of ecosystems, rebound effects in water use due to efficiency improvements, innovative financing

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mechanisms, water markets, and the Water, Energy and Food (WEF) nexus, should be integrated into the water policy debate and practice (Berbel & Expósito, 2018).

2.2 WEFE Nexus

Nexus thinking is applied to water-related topics. Often a link is made with energy and food, referred to as the WEF nexus, but more recently the nexus is extended with ecosystems in the WEFE nexus.

Based on a review of the WEF(E) nexus literature, Henao Henao et al. (2023) provide a definition of the WEFE nexus "as an approach that integrates the management and governance of water, energy, food, and ecosystems across different scales to promote efficient use of natural resources and generate greater policy coherence [...] to reduce negative economic, social, and environmental externalities and aims for securing human rights" (Henao Henao et al., 2023, p. 14). We adopt their definition in this paper.

Several authors explain the potential of the WEFE Nexus to support transformative change and achieve the Sustainable Development Goals (SDGs) (see for example J. Liu et al., 2018; Pahl-Wostl, 2019). However, WEF(E) Nexus studies applying quantitative methods are limited and often neglect all the interconnections between the sectors. In this regard, Sušnik et al. (2023) review the literature on the WEF nexus and argue that water plays a key role in not only the WEF nexus but also in the broader development of societies. The authors highlight the interconnectedness of water with the WEF nexus and with different sectors. Water policies should therefore not see water in isolation and consider the interconnectedness. Furthermore, while policy integration is often at the core of most Nexus studies, other motivations such as economic efficiency are provided less frequently (Albrecht et al., 2018). The latter might be problematic because questions about water allocation are inherently a societal question. And economics could help answer questions about resource allocation. To support this, Kling et al. (2017) review the current state of integrated assessment models (IAMs) that take on the elements of the WEF nexus. The authors conclude that while IAMs can help evaluate changes to the system, there is room for better integration of the economic and natural parts of the models and that. One specific use case is to evaluate how climate change affects natural and economic outcomes.

2.3 Optimal policy making

Goulder & Parry (2008) provide an overview of policy instruments in environmental economics. Three classes of economic instruments are discussed, namely pricing, quantity restrictions, and mandates. Price mechanisms can either be taxes or subsidies. Quantity control can either be rigid, through non-tradable quotas, or it can be more flexible and market-based through tradable quotas or tradable permits. Mandates can focus on the mandatory adoption of certain techniques or performance standards, where the latter leaves more freedom to the firm. Each of these instruments has its pros and cons. Where mandates and quantity instruments are more likely to achieve certain targets, price instruments are often considered most efficient.

Coase (1960) states that government intervention is unnecessary under some conditions. The Coase theorem states that under well-defined property rights and without transaction costs, negotiations will lead to an optimal outcome. It is irrelevant who initially holds the property rights. Coasian bargaining will lead to a decentralized societally optimal outcome without the intervention of a government. Hardin (1968) The strategic interactions in such settings are based on game theory. In general, the solutions become more difficult to implement as the number of agents involved gets

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larger. With a limited number of agents, Ansink & Weikard (2020) show how some agents are willing to support a coalition of agents that limit access to a common resource.

Pigou (1920) introduced the concept of externalities and how they justify government intervention. When agents undertake activities that harm or benefit others they are effectively undertaking too much or too little, respectively, of that activity from a societal perspective (see also Hardin, 1968). Government intervention to adjust the amount of these activities is therefore justified. The concept of a Pigouvian tax is derived from this principle. In the case of negative externalities, a Pigouvian tax adds to the private marginal costs of agents in order to align the private marginal cost curve with the societal marginal cost curve. This ensures that the agent internalizes both private and social costs and thereby acts in the interest of society.

Baumol (1972) defends the work by Pigou and argues that the Pigouvian tax does lead to optimal resource allocation. To counteract the main critique on the Pigouvian tax, its difficulty to apply it in the real world, he shows a system of realistic taxes and subsidies can achieve the desired reductions in externalities from polluting agents.

Weitzman (1974) shows in a theoretical model how uncertainty can affect the optimal policy choice between price and quantity instruments. When marginal costs and benefits of abatement are perfectly known, a government would be indifferent between setting a Pigouvian tax or implementing a (tradable) quantity policy. When there is uncertainty about the marginal costs, Weitzman (1974) shows that the type of policy instrument does matter for welfare. When the marginal costs are steep relative to the marginal benefits of abatement, a price instrument is preferred, because it is more likely to be close to the optimal tax after uncertainty is resolved than an ex-ante quantity would be to the ex-post optimal quantity. When the marginal costs line is relatively flat compared to the marginal benefits, the reverse holds, and a quantity policy is preferred in expectation.

Tinbergen (1952) suggested that each problem requires a separate policy instrument. As societal issues have multiple dimensions, they cannot be effectively addressed with too few instruments. Think of reduced water tariffs for consumers with low incomes. The goal of a water tariff is to cover (societal) costs of water, while the goal of the tariff reduction is to increase low-income household's disposable income. One policy is used to pursue both goals. According to the Tinbergen rule this might lead to inefficiencies. The first goal is unlikely to be achieved by the reduced tariff. Instead, two goals could achieve a better outcome. For example, one could charge tariffs that cover all costs of water use and provide transfers to low-income households to ensure more disposable income for low-income households.

Policies are however not always additive. The literature on overlapping policies points to unexpected interaction effects from multiple policy instruments. These overlaps are often studied in the environmental economics literature. Perino et al. (2022) show how national environmental policies interact with supra-national policies in the case of the European cap-and-trade system for carbon emissions. Any policies at a lower jurisdictional level will cause leakage if the number of allowances of the policy instrument at the higher jurisdictional level are unchanged. The policies at the lower jurisdictional level also affect the prices of tradable permits, often benefiting the most polluting producers (Böhringer & Rosendahl, 2010). These incentives can even lead to the increase of unregulated pollutants (Novan, 2017). Such unintended effects should be taken into account when

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devising local policies (Böhringer & Fischer, 2023). However, these study are concerned with greenhouse gas emissions, which are characterized by global, and not local, externalities. Water challenges often have a large local externalities component as well, making leakage less of a concern to local policy makers. Leakage would still lead to problems elsewhere, which is undesirable and perhaps unfair.

Other literature has promoted environmental policies as a double-edged sword. Not only do such policies reduce pollution, but they also increase tax income allowing for the reduction of distortionary taxes, like labor or profit taxes. Goulder (1995) provides an overview of the earlier double-dividend literature. In a similar spirit the literature on revenue recycling discusses the benefits of raised environmental taxes. These taxes could then be used (recycled) to serve other purposes that benefit society. Parry (1995) however discusses that such recycling is imperfect. The benefits of the additional funds do not one-on-one outweigh the imposed costs from environmental taxes. As the environmental taxes introduce distortions themselves, the optimal environmental tax is found to be below the level of marginal environmental damages.

Some recent studies have analysed the design and application of economic instruments for water management in the EU. For example, Riegels et al. (2013) conducted a system analysis to assess different water pricing schemes and to propose optimal water pricing strategies. Di Cosmo et al. (2014) found different patterns of sectoral water consumption and argue that water policies should be fit for purpose. More recently, Horncastle et al. (2020) studied cost benchmarking of water services highlighting that further research is still required to identify a robust approach to benchmark water costs in Europe. Still, Tsani et al. (2020) call for the wider application of economic instruments to improve policy implementation. In this regard, Albiac et al. (2020) argue in favor of the analysis and application of more varied approaches beyond water pricing. For example, Leflaive (2024) suggest that water policies should address water use efficiency, water allocation, collective management and better monitoring.

3 Six European cases

This paper focuses on water challenges in Europe and the potential solutions in terms of water policies. It does so through the lens of six representative case studies in Belgium, Germany, Malta, the Netherlands, Slovakia and Spain. The challenge, current policies and scale differ significantly between these cases. In introducing the cases, we focus on the scale, the sectors involved, the challenges faced, and the policy interventions that are of interest. These elements will be of use when discussing the models in Section 4. Section 3.7 pulls the main characteristics of the cases together in a structured way.

3.1 Belgium: Business and residential communities

In Belgium, like in most other European countries, the standard practice is to connect homes and businesses to a central water grid and sewage system. However, this system faces challenges. Drinking water is expected to become scarcer, while more intense rainfall is likely to stress the existing sewage infrastructure, increasing the risk of floods, both locally and at the river basin level. To address these issues, decentralized water production and treatment techniques are explored. Three demonstration sites are currently up and running in Belgium, one residential area and two business parks. These sites collect and treat rainwater locally with the purpose of reuse.

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The main challenge in this case is to make these decentralized systems economically viable. For that, a comprehensive overview of costs and benefits needs to be collected. A cost-benefit analysis will then be used to evaluate the business case. Especially valuing all benefits is challenging, as the recycling systems provide several non-private benefits, like ecosystem services and intertemporal water storage. To realize or capture these benefits, several candidate policies are explored, namely (1) subsidies, and (2) fixed or volumetric water pricing.

3.2 Germany: Upper Main river basin

The Upper Main river basin overlaps with the administrative region of Upper Franconia in Germany. Recently, fluctuating natural groundwater recharge, increased agricultural water extraction, and depreciating water quality have started to threaten water security in the area. In 2018, 43.2% of the land in the region was dedicated to agricultural activities (ca. 200,000 ha), of which 67% (ca. 134,000 ha) specifically allocated to the cultivation of cereals such as wheat, barley, and maize (Regierung von Oberfranken, n.d.). Looking at the future, the challenges regarding water security in the Upper Main area concern both water availability and quality.

First, irregular rainfall patterns have undermined the existing abundance of green water in the area. Consequently, blue water reserves (groundwater aquifers, rivers, and lakes) have been exploited in order to meet the cross-sectoral water demand. However, the natural recharge of groundwater aquifers has been declining since the 2000s, raising concerns regarding future availability (Bayerischer Landtag, 2020). Additionally, weather fluctuations have repeatedly caused droughts during the cereal growing season, simultaneously reducing water supply and increasing water demand of crops. The regional government warns that the extraction rate was often higher than 4% of annual groundwater recharge in the past decade, a threshold suggested to maintain long-term sustainability of water extraction. Second, the quality of water is under stress from excessive fertilizer use in the region, which leads to runoff and leeching of nitrate pollutants into rechargeable freshwater sources.

To address these issues, the application of three candidate policies is investigated in the area. These are (1) water pricing, (2) water quotas, specifically aimed at rationing water in summer and storing water in winter, and (3) a limit on fertilizer use to address water quality issues. These policies are simulated and evaluated in a hydro-economic model that maps the hydrological characteristics of the river basin and the relevant economic agents in this context.

3.3 Malta: Water scarcity

Malta is by far the most densely populated EU country. Together with nearly rainless summers and the lack of surface water bodies, this puts significant pressure on its water systems. Malta therefore complements groundwater sources with imports from Italy and energy-intensive desalination. In these conditions Malta faces several additional challenges, namely growing water demand from population growth, the uncertain effects from climate change on water supply and demand, and groundwater nutrient pollution from agriculture activities.

Several candidate policy solutions are explored in a hydro-economic model. These policies are (1) public investments in water infrastructure, (2) information campaigns, and (3) water pricing.

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3.4 The Netherlands: Sustainable water production

While the Netherlands is known for its abundant water resources, stemming from frequent rainfall and extensive river deltas, it is increasingly facing challenges in freshwater availability. These challenges are driven by a combination of factors, including a growing population and expanding industries, more frequent and severe droughts exacerbated by climate change, and a rising impact of salt water intrusion. Compounding these issues are limitations in groundwater extraction, as ecosystems often compete for the same resources, and concerns over water quality. Nutrient runoff from agriculture and the presence of chemicals in surface water and wastewater flows strain the availability of clean, usable water.

The water authority of Hoogheemraadschap Hollands Noorderkwartier (HHNK), located in the province of North-Holland, is exploring innovative ways to implement circular water systems. For example, enhancing wastewater treatment plants can enable the recovery and upgrading of wastewater to different quality levels suitable for specific applications in the WEFE sectors. Treated water could be reused for agricultural irrigation, industrial cooling, or even groundwater recharge, thereby reducing pressure on other water resources. In urban development, circular water systems could include decentralized treatment facilities that recycle greywater from households and businesses for uses such as toilets, green roofs, or urban farming. Rainwater harvesting systems could also be integrated into city planning to reduce runoff and provide a sustainable source of water for public spaces and gardens, contributing to more resilient and self-sufficient urban water cycles.

To understand the investment decision by the water authority a cost-benefit analysis will be conducted that includes any costs and benefits associated with the WEFE sectors. For this analysis, one needs to value all the benefits from the proposed investment, including benefits to ecosystems, farmers, households and firms. Different valuation methods could be used. With a complete view of costs and benefits there are several policies that will be explored to address the business case for the investment, namely (1) dynamic pricing of different water sources, (2) price differentiation based on water quality and type of use, and (3) increased water taxes.

3.5 Slovakia: Water footprint of agriculture

The South-West of Slovakia is characterized by lowlands and rivers, including the Danube that flows through the capital of Bratislava and smaller rivers that originate in the mountains in the East. The region also contains the main groundwater sources and hosts many agricultural activities due to its fertile soil. Agriculture, ecosystems, and consumers and industry compete for the same water sources in the area, making it a compelling case for the WEFE Nexus.

The main challenge faced in the area are local water retention and preservation of ecosystems. To address this challenge, an input-output model will be employed to obtain insights into the water usage of each of the relevant sectors. Including water flows in these input-output models allows linking sectoral production to water inputs.

To address the challenges in the area, two policies will be explored, namely (1) rationing, and (2) promotion of the implementation of water efficiency measures.

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3.6 Spain: The Júcar river basin

The Júcar river is located in the East of Spain, running from the mountains of Montes Universales to Valencia at the Mediterranean Sea. The upstream areas are mostly characterized by agricultural activities. The Júcar basin is an important source of agricultural irrigation waters in the area. Further, there is a 56 MW hydroelectric dam in the upstream part of the Júcar. Midstream the river brings water to ecologically important ecosystems. Downstream the water serves urban and industrial water users.

One of the challenges policy makers in the Júcar river basin face is the protection of the ecosystems midstream. With the extraction of water upstream to serve farming activities, less water flows into the ecologically important ecosystems.

To guarantee a minimum flow through these midstream ecosystems, several policy interventions are considered. These policies come on top of the existing water market in which farmers participate. The candidate policies are (1) water banking in the way it was done during the last drought, (2) payments for ecosystem services (PES), and (3) subsidized downstream water transactions. To ex-ante evaluate these policies, they are simulated in a hydro-economic model mapping the key economic actors and the river basin's hydrology.

3.7 Overview

The challenges, involved sectors, and proposed policy solutions of the six case studies are summarized in Table 1. The table shows the different scales of the cases, the WEFE sectors involved, the challenges faced, the proposed modelling approach, and the candidate policy solutions. Additionally, the table lists relevant national policies that should be considered when evaluating new policy solutions. As discussed in Section 2, policies can overlap and interact. Any such interactions need to be taken into account.

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Table 1 – Overview of the six European case studies.

Case country	Scale	Relevant sectors	Challenges	Existing water policies	Model	Candidate policy solutions
Belgium	Residential neighborhood, business park	W, Ec	Valuing recycled water flows; business case	Integrated water bill (drinking water, wastewater, treatment; uniform tariffs); cost recovery; mandatory rainwater harvesting; charges for groundwater and surface water abstraction; charges for industrial wastewater discharge	CBA	Subsidies for decentralized systems; decentralized pricing mechanisms; fees for rainwater discharge; Cost recovery; PES
Germany	River basin	W, En, F, Ec	Future water scarcity; nitrate runoff	Water extraction charge; drinking water charges; cost recovery	Hydro-economic	Water pricing; quotas
Malta	Country, island	W, En, F, Ec	Freshwater scarcity; water quality concerns	Subsidies; Drinking water charges	Hydro-economic	Public investments; information campaigns; water pricing
The Netherlands	Water extraction area	W, En, F, Ec	Limited groundwater; water quality; business case	Drinking water charges; cost recovery; wastewater disposal permit system	CBA	Dynamic price differentiation; increased water taxes
Slovakia	Country, region	W, F, Ec	Local water retention; ecosystems preservation	Water pricing, Financial support for farmers in case of extreme floods or droughts (ad hoc)	Hydro-economic: Input-output	Rationing; water efficiency measures
Spain	River basin	W, En, F, Ec	Drought damages to ecosystems	Water Pricing, Water markets (not in use), Crop insurance (only for rainfed crops) Payments for environmental services (initial stages)	Hydro-economic	Water banking, PES, subsidized water transactions

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4 Economic framework

This section presents economic models that can be used to evaluate policies. We present three general and related models that are often used for water-related challenges. Each model has its own merits and requirements. We will discuss (1) hydrological models, (2) hydro-economic models, and (3) cost-benefit analyses. For each model we will integrate the WEFE Nexus to allow for interconnections between the different sectors in the respective models. In line with the WEF(E) literature, this allows for a more holistic approach when designing and testing water policies. Water policies and their implementations in these models are discussed separately in Section 4.4.

4.1 Hydrology

Water models often contain a description of the hydrology. These descriptions aim to describe the physics of water stocks and flows in the considered setting. These descriptions can range from simple to complex.

Some models solely consist of this hydrological description. These hydrological models exist to simulate water-related outcomes, like water flow and water stocks, but also water quality. Hydrological models work best within naturally defined areas, like river basins, and have a clear spatial element. This means that these models describe water outcomes in relation to their location.

Simpler descriptions of the hydrology might only consider the flows between a few locations in a model. Such simple descriptions are more often found in models that combine hydrology with other aspects, like economics. A combination of hydrology and economics is presented in Section 4.2.

In its most general form a hydrological model is a set of rules describing water flows and the characteristics of space. It can be best thought of as a network of nodes and linkages. Nodes can be any point of interest, like a lake or a pollution source. Linkages describe flows between nodes, like rivers or groundwater penetration. A set of rules describes how the water moves through the network and how its quantity and characteristics are altered by the nodes in the system. These rules are usually based on real-life physical characteristics, such that the model matches the hydrology under consideration. For example, in a river basin one might define in which direction the water flows, whether water evaporates, and how the soil characteristics affect the water flow. These rules can take any form. The goal of these rules is to mimic reality as closely as possible. Particular soil might, for example, have a maximum capacity to absorb water, or farmers cannot extract more water from the river than there is flow running through it.

The set of nodes, linkages and rules allow the researcher to simulate the water flow in the model. This enables scenario analysis. The researcher can alter inputs and observe the outcomes of the model. For example, a drought can be simulated by reducing the inflow of water into the system, for example from rainfall or meltwater. Outcomes are the water quantities and characteristics at each node. In theory it is possible to track many characteristics of water, like pollution levels or other water quality indicators.

In reality there are limits to what hydrological models can simulate. These limits are governed by knowledge of the actual physical environment and the accuracy of the rules. Hydrological models often require data on a specific geographical or hydrological level in order to construct realistic rules. These data requirements often do not align with the administrative boundaries within which most

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data is collected. And some natural processes are partially unknown or more complex in reality, leading to misspecification of rules.

The WEFE sectors can be included in hydrological models. Water utilities, energy generators, food producers, and ecosystems can all be entered as nodes, linkages and rules. For example, farms can be added as a node in the hydrological system, and the farmer's water usage can be approximated with a link from the water source to the farm. How much water is extracted by the farmer can be modelled with a rule. This rule can be simple, where the farmer takes a certain amount from the groundwater or surface water reserves, or it can be more complex, where demand depends on availability of water or the season. Similarly, nodes, linkages and rules can be introduced for ecosystems, energy generators, and players in the water sector.

Hydrological models usually do not model the behavior of these agents. Behavior could be added to these models. However, the resulting model would likely fall in the hydro-economic category, which we will discuss in Section 4.2.

Extensive numerical hydrological models have been developed in the literature and are often available as a software package. Let us here mention a few common models. The Soil and Water Assessment Tool (SWAT or SWAT+) allows for the study of catchment areas and how land use impacts water quantity and quality outcomes (Arnold et al., 2012; Gassman et al., 2014). The Watershed Evaluation Tool for Spatio-Temporal Pollution Assessment (WetSpa) model simulates water outcomes on a grid level. It can take into account physical properties of land as well as land use. Finally, the open source LISFLOOD model, developed by the Joint Research Centre (JRC) of the European Commission since 1997, is the model used within the European Flood Awareness System (EFAS) to simulate the hydrological response of European catchments to different extreme meteorological events.

Policies can be evaluated in hydrological models as well. For that, one needs to add additional rules, or constraints. For example, rationing policies could be simulated by constraining the amount of water a player withdraws from water bodies. To evaluate the effects of policies, one could simulate outcomes with and without the additional policy rules. Similarly, the researcher can simulate climate or weather scenarios and study changes in the outcomes of interest.

4.2 Hydro-economics

One can extend the above hydrological models with economic agents that make behavior-driven choices. The combination of these two elements, a hydrological system and economic agents with incentive-based decision making, makes a hydro-economic model. Where the above hydrological models also allow for the inclusion of economic actors, the difference is that in a hydro-economic model these actors' choices are modelled.

The researcher assigns the agents with objectives, choice variables, an information set, and constraints. The researcher further makes assumptions on the behavior of these agents, like rationality and profit maximization, and derives which decisions the agents take. For example, a farmer's objective could be to pursue maximum profits within a set of constraints. Constraints could be of different natures, like natural, behavioral, economic or policy-related limits. Constraints simply restrict the possible set of choices of the economic agent. For example, a natural constraint would be that farmers cannot extract more water from a water body than there is water available.

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Choices of individual agents in the model can depend on choices made by other agents. This would be considered strategic interaction, and economists refer to such settings as a game. The information available to the agent at the time a choice is made then becomes relevant. Some agents might move first, some agents might respond. It is up to the researcher to set up the game in line with reality.

Each of the WEFE sectors can be included in hydro-economic models. The inclusion is similar to that in the hydrological models, except that an additional layer of decision-making is added to some of the agents, as described above. This could add new elements, like demand and supply. For example, the drinking water sector could consist of producers of drinking water, who take water from a water body, face costs cleaning this water and sell drinking water on the drinking water market, and consumers of drinking water, who use water for personal use or for the production of other goods. Similarly, the agents in the food and energy sectors can be included as well. Ecosystems tend to not make choices and instead follow passive rules as in hydrological models. The complexity and the number of players is usually limited to some level in order to keep the model tractable and solvable. The researcher might also ignore certain complexities and players if those are not relevant to the research question at hand.

The economic water literature contains many examples of hydro-economic models. Most often these models are used to model river basins (see for example Harou et al., 2009). Hydro-economic models, in general, are any models that combine water management and economics. For instance, the WEAP (Water Evaluation and Planning) model takes an integrating approach to water management, as it balances water supply with demand-side issues, water quality, and ecosystem preservation and protection, also incorporating economic information such as water prices or demand curves.

The structure of a hydro-economic model closely resembles standard water resource system models but incorporates economic evaluations of each water use. These models are flexible and adaptable to different configurations, such as rainfall-runoff modeling, agronomic models, and various system operation representations. This adaptability allows for tailoring the modeling strategy to the unique requirements and data availability of each water resource system. And due to the economic components, outcomes can also be evaluated in monetary terms, often allowing for more intuitive comparisons of welfare outcomes.

In general any model that combines hydrology with economic agents can be considered a hydro-economic model. An additional example are input-output models that are extended with water-related outcomes. Instead of only tracking the trade between sectors in monetary or real terms, one could track environmental factors, like water quantities and pollution. This allows for footprint analysis.

Hydro-economic models allow for the evaluation of more complex policies, because economic agents alter behavior in response to incentives. This means that, for example, price policies can be evaluated in hydro-economic models. For example, a tax on groundwater extraction can enter the cost function of the water utility. The water utility will re-optimize its objective accordingly. This new decision alters the outcomes in this model, like different levels of groundwater extraction, potential water quality outcomes, tax income, different benefits and costs for the economic actors, water prices, and different amounts of transacted amounts of drinking water. Non-price policies can also still be evaluated, including more complex quantity instruments, like tradable permit systems.

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4.3 Evaluation and cost-benefit analysis

The above models can be used to produce outcomes needed for decision-making. Often policy makers seek to maximize total welfare. Total welfare is the aggregation of all costs and benefits of all economic agents in a society. To come to a welfare calculation, models need to be complete and accurate. The WEFE Nexus helps in that it urges the researcher to include often-overlooked sectors when evaluating water policies. Besides completeness, accuracy is important.

The above models can be used to calculate outcomes relevant for a welfare analysis. The hydrological model outputs several water-related outputs that can enter a welfare analysis, like water pollution, flood or drought information. These numerical results can be used to calculate costs and benefits. The hydro-economic model already describes many costs and benefit functions in the agents' objectives. The outcomes of this model therefore already contain several cost and benefit estimates in monetary terms. Note that both models rely on the accuracy of cost and benefit functions. It is therefore important that these functions are derived from proper valuation exercises. The main challenge of using hydrological outcomes in a welfare calculation is that outcomes are not denominated in a common currency and are therefore difficult to compare and add up.

One can also obtain cost and benefit estimates from other sources and perform a cost-benefit analysis (CBA) directly. CBA is most often used for investment decisions. Understanding what the costs and benefits are of different investment decisions allows the decision maker to choose the investment with the best outcome. Also for this analysis, completeness and accuracy are important. And while CBA is a powerful and intuitive tool, it often requires the valuation of unknown costs or benefits.

In such cost-benefit analyses (CBA), all relevant costs and benefits must be included and accurately estimated. The latter is not for all items straightforward. For example, the production costs of drinking water might be known, but the value of damages to ecosystems not. Valuation exercises could help.

As CBA is a useful tool for decision making, a large literature has amassed on the topic (see for example Layard & Glaister, 1994). The primary objective of CBA is to determine whether the benefits of a proposed action outweigh its costs, thereby informing decision makers on the most efficient allocation of resources. This method has its roots in welfare economics and is often employed in both ex-ante and ex-post evaluations (Mishan & Quah, 2020).

The WEFE can enter CBA through the inclusion of additional costs and benefits. CBA should always take someone's perspective. Depending on this perspective certain costs and benefits should or should not be included. For example, from the perspective of a private firm, costs to competitors or other agents in society might not be relevant. But from the perspective of a social planner costs to all agents are relevant. The WEFE elements are therefore especially relevant for social welfare calculations and hence policy makers.

Ignoring WEFE might lead to sub-optimal policy making as relevant costs and benefits are ignored. For example, ignoring damages to ecosystems and the consequent reductions in consumers' utility leads to an underestimation of benefits from ecosystem conservation efforts. Similarly, water, food and energy systems could have value to society beyond private costs and benefits.

Policies can enter CBA by recalculating costs and benefits under the new policy scenario. As policies alter decisions and outcomes, also costs and benefits of economic agents change. These changes

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therefore affect the bottom line. Differences in outcomes between the two scenarios can be used to evaluate the respective policy.

Additionally, when interested in evaluating policies, one should consider how some policies also affect private decision making. For example, when policies force cooperation amongst economic agents, they lead to different decisions and different private outcomes. CBA therefore is not just an exercise of addition, but also one of interactions.

4.4 Water policies

In order to perform policy evaluation with the above models, one needs to compare outcomes from a model with and without the suggested policy. It is important that the model realistically captures how a policy plays out. Here the nexus should be taken into account, because it forces the researcher to consider interactions and spillovers to other sectors. We discussed the inclusion of the WEFE Nexus in the sections above. In this section we present how the different types of policies can be evaluated in the discussed models.

The class of hydrological models allows the researcher to simulate water-related outcomes in a set of nodes and linkages. Economic actors are included as additional nodes, and their behaviors are included as additional linkages. Because these models describe water quantities and characteristics, they can be best used to evaluate quantity policies. From Table 1 those would be quotas, rationing, water efficiency measures, and water banking. As those policies dictate limits to flows, they fit the framework of hydrological models well. Especially quotas, rationing, and water banking can be implemented with relative ease as constraints on some of the linkages in the model. Water efficiency measures need to be implemented with some simplification. For example, if a policy prescribes industrial users to adopt more water efficient technologies, one could assume that water demand reduces accordingly.

Other policies can also be evaluated in a hydrological framework, but they require additional steps. For example, pricing policies require the researcher to translate the price incentives into quantity changes along the linkages. Without explicitly modeling the economic behavior of agents, this might be a difficult exercise. Previous research could provide valuable estimates that one could use for these translations.

Policies can also address other characteristics of water, like quality measures. This works in a similar way as quantity measures. But instead of adding limits to water quantities, the researcher should set limits to the changes in the other characteristics of water. As these characteristics are tracked in a numerical score, it works the same way as quantities.

As policies need to be translated to quantities along the linkages, hydrological models are not as good in evaluating policies that rely on behavioral changes or interactions between economic agents. Pricing policies can only be evaluated under strict assumptions. And also instruments like tradable quotas and water markets can only be evaluated partially. As economic agents in reality choose how many rights they buy or sell, the post-trade distribution of water rights is endogenous to the behavior of the economic agents. It might be difficult to capture the water usage from these individual actors in a hydrological model without modelling economic behavior.

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As presented in this section, hydro-economic models add agents' behavior to the hydrological model. This allows for more detailed behavioral responses to policies and strategic interactions between agents. Several policies can therefore be evaluated better in such models compared to pure hydrological models.

Two prominent examples are pricing policies and tradable permit schemes. Pricing policies incentivize agents to reconsider their optimal choices of quantities. They therefore require the relationship between prices and quantity choices, an economic element. Tradable permit schemes require a model to allow for interaction between agents. Agents are allowed to buy and sell permits from and to each other. The economic elements in hydro-economic models can facilitate such interactions and make outcomes more realistic.

Since hydro-economic models also encapsulate the hydrological element, they could perform equally well on the policies suitable for hydrological models. However, sometimes the researcher simplifies the hydrology in a hydro-economic model in order to add the economic elements and keep complexity at bay. If so, the hydro-economic model might perform worse on some quantity policies, because simplified hydrological models could produce less trustworthy quantity outputs.

Other policies from Table 1 that can be evaluated well in hydro-economic models are subsidies, information campaigns, price differentiation, PES, subsidized water transactions, investments, and water banking. However, in order to evaluate these policies, one needs to construct the model to allow for it. For example, information campaigns can be evaluated only if information enters the decision functions of agents. If the researcher assumes full information, the model cannot be used for the evaluation of information campaigns.

Depending on the complexity of the hydro-economic model the researcher should interpret its outputs as quantitatively accurate or more as qualitative indications. For example, if hydrology is simplified, the exact water outcomes are likely not perfectly in line with reality. But if the objectives of agents are modelled well, one could use the model to compare policy evaluations between different models.

Cost-benefit analyses are best suited for investment decisions. It therefore is well suited to evaluate investment subsidies or other lumpsum policies. Those subsidies can easily be added to the benefits. CBA is also well-suited for price policies, as long as those policies are not expected to change quantities too much. For example, one could compare the benefits from water sales under different pricing policies, like increasing block tariffs or variable water taxes. If quantities are expected to change, benefits will also differ due to the quantity change. The researcher should either model this change, for example by using a demand function, or abstain from evaluating price policies in CBA.

In general, any policy that can be represented by a change in costs or benefits can be evaluated. However, in reality these models are best suited for the evaluation of policies that are expected not to change quantity choices too much. CBA is therefore also not very well suited to evaluate quantity policies.

In choosing the appropriate model, the researcher should understand which policies can and cannot be evaluated with them. Similarly, the researcher should understand the limitations of the models, as discussed earlier in this section.

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The researcher should also be aware that one does not need to stay within the boundaries of one type of model. Instead, one could combine modelling approaches. The hydro-economic model is a good example of this, as it encapsulates a hydrological model. And also in CBA the researcher can use insights from other models to value relevant costs and benefits. Similarly, the researcher can and should use insights from other models and literature.

5 Applications

To illustrate how the WEFE Nexus can be integrated in economic water modelling and how policies can be devised accordingly, we provide two examples, based on the cases discussed in Section 3. The Spanish case covers a full river basin, while the German case covers the upstream part of a river basin. For each model we explain the hydrology, the economic and the welfare analysis. We select these two cases as examples, because they cover all three elements from the models discussed in Section 4. The other four cases also fit our framework, but are more selective in the parts from the economic framework that they utilize.

5.1 The Júcar river basin

The Júcar river basin spans 22,261 km² in a semi-arid region of Eastern Spain, featuring the 512 km-long Júcar stream. Annual precipitation averages 473 mm, with high demand necessitating adaptive management. The basin's water resources face challenges from climate change, causing potential reductions of up to 40-50%. This reduction would impact urban users, agricultural production, hydropower generation, and ecosystem health. The basin hosts 31 hydropower plants, and its largest reservoirs, Alarcón, Tous, and Contreras, allow interannual regulation of water resources. The main challenge in the basin is to sustain agriculture and protect vital ecosystems, while adapting to increased water scarcity and extreme events due to climate change.

For this application we illustrate how policy interventions in the agricultural water markets can address drought damages in the ecosystems of the Júcar river basin. To do so, we present a simplified hydrology, we introduce several economic agents, and we show how policies could improve welfare outcomes. The WEFE sectors and interconnections are included in this application.

5.1.1 A simplified hydrology

We model the river’s flow as a line starting at an origin and ending in the Mediterranean Sea. This hydrology is presented in Figure 1. It describes the direction of flow with arrows. All arrows are numbered in order to distinguish locations. Note that all four WEFE sectors are represented. A hydro-power station is found upstream, two groups of farmers are located up and downstream, ecosystems are located midstream, and consumers and industry are found downstream. Unique to river systems is that downstream agents are dependent on water users further upstream. For example, the farmers located upstream affect water availability to ecosystems, downstream farmers, and the consumers and industry. Also note that farmers and ecosystems use water from the river, but that there are also return flows back to the river system, namely f_3 and f_7.

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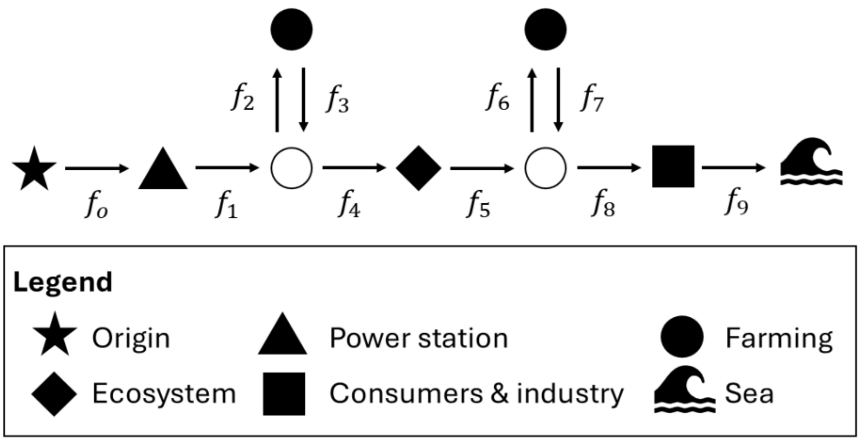

Figure 1 – Simplified hydrological system of the Júcar river basin.

5.1.2 Nodes and economic agents

The nodes in the hydrological system of Figure 1 could be passive or active. Passive nodes are the origin, ecosystems and the sea. They do not take active decisions, but they do affect the flows in the river system. The active nodes represent economic agents and comprise the hydro-power operator, farmers, and the consumers and industry. Both types of nodes are assigned rules described in functions. These functions can take multiple input variables, but at a minimum they contain the inflow into the node as an input variable. Eventually the function at the node determines the outflow of water from that node. We describe these functions at each node in the following subsections.

In this simple model, we abstain from evapotranspiration to keep the model tractable and focus on the policy analysis. We also abstain from functional forms, to provide a more general solution.

5.1.2.1 Origin, sea, and ecosystems

At the origin a given amount of water enters the river system, described by f_1. We do not specify the quantity nor whether this quantity follows from an uncertain (statistical) process. We do note that this starting flow is an important determinant of all other flows.

The outflow at sea is not relevant in this model. In this setup there are no costs or benefits to society from the flow f_9.

Ecosystems have value to society. Damage to these ecosystems therefore has negative welfare effects. The total damages to ecosystems are described as

$$D^e = d^e(f_4) \tag{1}$$

where ecosystems face the damage function d^e, and the inflow at location 4 determines damages. The damage function d^e is downward sloping and convex. We assume ecosystems do not extract water from the system, such that $f_4 = f_5$.

5.1.2.2 Hydro-electric dam operator

The operator of the hydro-electric dam makes the decision whether to release water from the dam or not, in order to maximize profits from electricity generation. She also faces restrictions from policies, as the government requires the dam to release water for the downstream users. And there are

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physical constraints, like the capacity of the reservoir and the impossibility of releasing more water than available in the reservoir.

Barring evaporation, the dam does not affect the amount of water passing through, but it only affects when the water passes through. The operator therefore makes an intertemporal decision. Her benefits are described as

$$B_{p,t} = q_{p,t}(f_{1,t}, h_t)p_{p,t} \quad (2)$$

where the electrical power production $q_{p,t}$ at time t depends on the amount of water that the dam releases into location 1, $f_{1,t}$, and the water pressure, measured by the head height of the water in the reservoir. The operator can sell the generated electricity at price $p_{p,t}$ which might vary with time t. Subscript p denotes variables relevant for the power producer.

The operator further faces a set of constraints.

- Law of motion for the reservoir head height: $h_t = h_{t-1} + f_{0,t}$
- Max and min head height: $h^{min} \leq h_t \leq h^{max}$
- Regulation: $f_{\{1,t\}} \in \{ f^R\}$

Such a decision could be solved using recursion:

$$V_t = B_{p,t} + \delta \mathbb{E}[V_{t+1}|h_t] \quad (3)$$

where V is the value function. The operator must choose the set of $\{f_{1,t}\}$ such that V_t is maximized while abiding by the constraints.

5.1.2.3 Farmers

Farmers take water from the river to irrigate their crops and to keep their livestock. We assume that all runoff water ends up back in the river. The farmers' benefits of water extraction a are described by

$$B_l^a = q_a(a_l)p^a \quad (4)$$

where the production function q_a only uses water and is strictly concave, and downward sloping from some positive a_l onwards. The logic is that overwatering reduces total yield. The location of the farmers is indicated by l. Agricultural produce is sold at market price p^a. We assume that p^a comes about on the world market and that the supply by the farmers in this river basin has a negligible effect on this market and hence the market price. Of all water used by farmers, share ρ finds its way back into the river, as depicted by return flows in Figure 1.

The following restrictions apply:

Water usage is not negative: $a_l \geq 0$

5.1.2.4 Consumption and industry

In the city industrial users and consumers pay a water utility for tap water. Their inverse demand function is described by $p^u(q^u)$, which is downward sloping.

The water utility behaves like a monopolist and faces costs to clean and supply water to the end-users. The total costs are described as

$$C_u = c_u(q_u, f_8) \quad (5)$$

where the cost function c_u is convex in q_u but concave in the flow at location 8, f_8.

The profit, or producer surplus, of the water utility becomes

$$PS = \pi^u = p^u(q^u)q^u - c_u(q_u, f_8) \tag{6}$$

while the consumer surplus is the area under the demand curve until the equilibrium price p^{u^*}

$$CS(q) = \int_0^q p^u(q^u)dq^u - p^{u^*}q \tag{7}$$

5.1.3 Evaluation of new policies

In order to evaluate policies in this framework one needs to solve the model with and without the policies of interest. Differences in outcomes can then be attributed to the policies. In this application we are interested in implementing a price incentive for water trades in an already-existing water market.

In order to determine the optimal tax or subsidy on these water trades, we solve the model from the private perspective and compare it to the social planner's perspective. In the private perspective each agent maximizes her objective without coordination with other agents and without regard for other's objectives. In the social planner's perspective, an hypothetical social planner dictates the behavior of all agents, thereby maximizing social welfare.

5.1.3.1 Existing policies: the water market

In the Júcar river basin groups of farmers trade water rights in a water market. We model this as transactions of water rights between the two groups of farmers in the hydrological model in Figure 1.

Water rights are assigned by the water authority. We specify these rights as $r_l = \alpha_l f_l$, such that farmers can extract a given share of water from the river system, namely α_l. Note that water extraction can exceed the initial allocation of water rights, as long as these rights are bought from farmers elsewhere. This way, the total amount of water extracted by farmers is capped.

Effectively the water market alters the farmer's objective and constraints. The water market adds another revenue or cost source to the farmer's profit function. Instead of only the benefits B^a, farmers can trade water rights at market price p^w, making the profit function

$$\pi_l^a = q_a(r_l + t_l)p^a - t_l p^w - \gamma|t_l| \tag{8}$$

with r the assigned water rights, t_l the transfers of water rights to location l, and γ the transaction costs of water which are born by both the seller and the buyer.

The following restrictions apply in this case:

- Water usage is not negative: $a_l \geq 0$
- Water usage cannot exceed water rights: $a_l \leq r_l + t_l$
- Each buyer finds a seller (the water market clears): $\sum_l t_l = 0$
- Water endowments are determined ex-ante and are defined as $r_l = \alpha_l f_l$, i.e. a fixed share of the water passing by at the given location. If all farmers use all the water available, this can be further described as $r_l = \alpha_l f_1 \prod_{i=1}^{l-1}(1-(1-\rho)\alpha_i)$, where $\alpha_i = 0$ for all locations i where there are no farmers.

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5.1.3.2 *Private equilibrium with existing policies*

For the private equilibrium we must determine each agent's private decision. We find this decision by solving the objectives of each agent.

The hydro-electric dam operator solves the intertemporal problem discussed earlier and chooses the set of flows $\{f_{1,t}^*\}$ such that V_t is maximized while abiding to the constraints. We abstain from the functional form solution in order to proceed with a static solution for the other players. For this particular application we are not interested in the behavior of the hydropower operator, but instead we focus on the interaction between farmers and the resulting damages to ecosystems.

The first-order condition (FOC) (with respect to t_l) for the farmer's objective gives

$$q_a^a(a_l)p^a = p^w + \gamma sign(t_l) \tag{9}$$

where the sign originates from the absolute operator in equation *(8)*.

In the case of no water market, we would simply get $q_a^a(a_l)p^a = 0$ when we take the FOC with respect to a, which is true for one unique value of a_l because q^a is strictly concave and has a maximum.

In case of a water market, there are two solutions. Either farmers trade, or farmers do not trade. Which situation holds, depends on the marginal benefits of trade and the transaction costs. Water market clearing leads to the optimal level of trade in these two situations

$$\begin{cases} t_l = 0\ \forall\ l \text{ if } |q_a^a(r_2) - q_a^a(r_6)| \leq \dfrac{2\gamma}{p^a} \\ |q_a^a(\alpha_2 f_1 + t_2\ ) - q_a^a(\alpha_6(1-(1-\rho)\alpha_2)f_1 - t_2)| = \dfrac{2\gamma}{p^a} \text{ otherwise} \end{cases} \tag{10}$$

The water utility maximizes profits, or producer surplus, by choosing the amount of drinking water to produce, q^u, pinned down by the FOC

$$\frac{\partial \pi^u}{\partial q^u} = p^u(q^u) + p_q^u(q^u)q^u - C_q^u(q^u, f_8) = 0 \tag{11}$$

where the price terms remain because prices change with supplied quantity.

5.1.3.3 *Social equilibrium*

The social planner takes into account damages to ecosystems, and maximizes the sum of all benefits and costs across all players. It therefore would choose a different level of trade between farmer groups.

Assume we are in the case where trade is taking place. Note from the river system in Figure 1 that trade affects the ecosystems in between the two farming locations. The social planner's equilibrium can therefore be determined by taking the private objectives and adding to those the damages to ecosystems from trade. Note also how it is the upstream trade that is causing more damages to ecosystems. Therefore the social planner considers an extra cost to upstream trade t_2. Through this logic we derive that the optimal t_2 is smaller in the social planner's equilibrium than in the private equilibrium, or $t_2^{SP} \leq t_2^{private}$, where the equality only occurs if there is no trade, i.e. when $t_2^{SP} = t_2^{private} = 0$.

Since the additional damages from trade to ecosystems are

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$$d^e\big(f_1 - (1-\rho)(r_2 + t_2)\big) - d^e(f_1 - (1-\rho)r_2) \tag{12}$$

t_2^{SP} can be found by adding the derivative of these additional costs to the private equilibrium's trade decision

$$\big(q_a^a(a_1) - q_a^a(a_2)\big)p^a = 2\gamma sign(t_1) - d_f^e(\overline{f_4} - (1-\rho)t_2)(1-\rho) \tag{13}$$

where $\overline{f_4}$ is the no-trade flow at location 4.

Although not relevant for the intervention in the water market, the social planner would make other choices on drinking water production. She would maximize the combined producer and consumer surplus, $PS + CS$, leading to the following FOC

$$\frac{\partial[PS + CS]}{\partial q^u} = p_q^u(q^u) - C_q^u(q^u, f_8) = 0 \tag{14}$$

5.1.3.4 *Private equilibrium with additional policies*

The social equilibrium already shows how the optimal trade levels can be incentivized through a tax on trade. Setting a tax/subsidy equal to the damages from upstream trade will incentivize farmers to align their trade decisions with that of the social planner's. For that the tax on t_2 should be

$$\tau = -d_f^e(\overline{f_4} - (1-\rho)t_2)(1-\rho) \tag{15}$$

per unit. This also means that downstream trade is subsidized, or in other words t_2 should be promoted with a subsidy equal to $-\tau$.

5.1.4 Extending the hydro-economic model

This hydro-economic model can be meaningfully extended. A computational model is under development for the Júcar river basin that uses the Explicit Stochastic Programming Advanced Tool (ESPAT) created by Macian-Sorribes et al. (2017). The model operates on a monthly time scale and simulates outcomes either using stochastic optimization or deterministic optimization.

The Júcar river hydrological system will be represented by:

- 27 nodes
- 8 surface reservoirs
- 5 groundwater bodies, modeled using the Embedded Multi-reservoir Model
- 7 sub-basins
- 18 consumptive demands
- 9 hydropower plants
- 6 minimum environmental flows (5 based on habitat suitability curves for native fish species and 1 for the minimum discharge to the sea)

The hydro-economic model in development for the Jucar river basin is part of a chain of models which focus on other aspects, as summarized in Figure 2.

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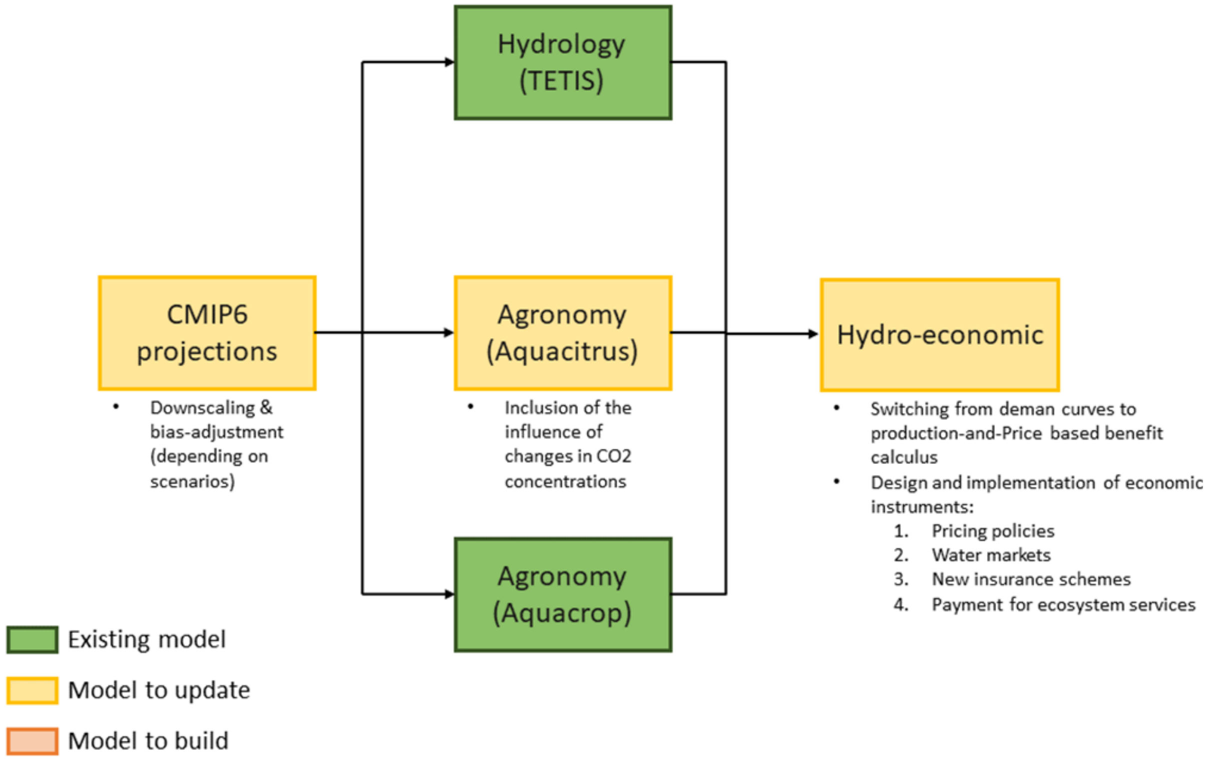

Figure 2 – Model schematic of the Spanish case study.

5.2 The Upper Main river basin

The Upper Main river basin faces the threat of water scarcity due to increased agricultural water demand, combined with volatile precipitation patterns due to climate change. Excessive fertilizer application leads to nitrate runoff, which decreases water quality. As a result, uncertainty regarding water security threatens the region's ability to sustain cereal production. Utilizing the WEFE Nexus approach through the implementation of System Dynamics and Stochastic Frontier Production models, we integrate hydro-economic and agroeconomic subsystems to structure the highly interdependent nexus, generating projections under different scenarios from 2000 to 2050.

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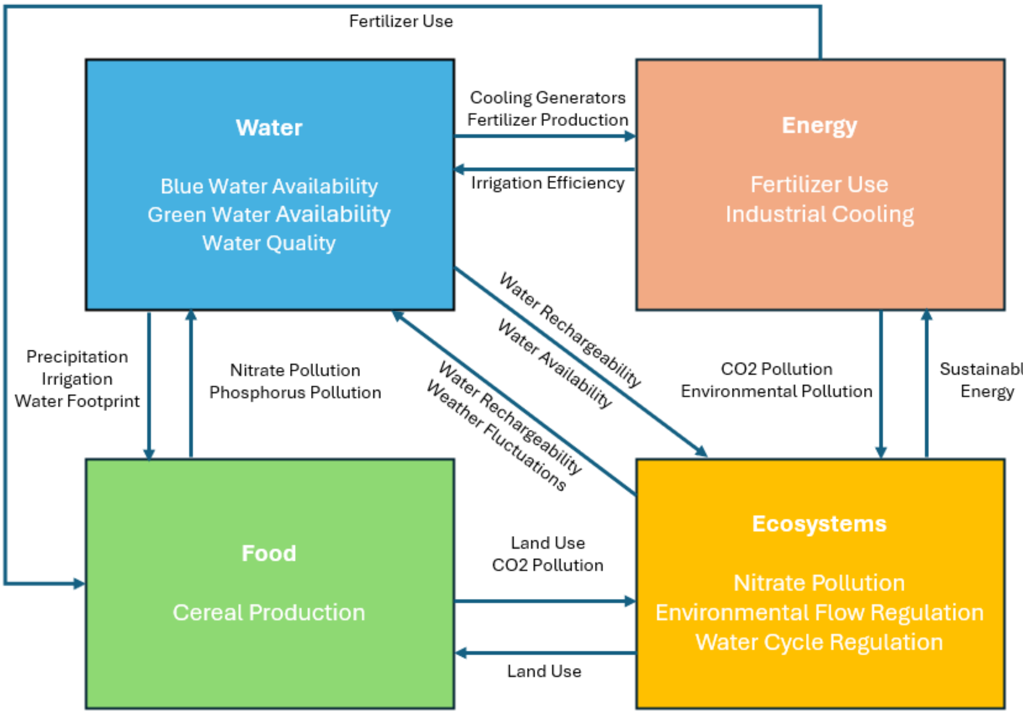

Figure 3 – Model schematic of the German case study. Source: Cian Twohig, 2024.

5.2.1 System Dynamics Modelling

System Dynamics Modelling (SDM) is widely used to map and analyze complex environmental systems. Its strength lies in identifying and quantifying causal relationships between system variables over time. SDM uses equations to simulate system behavior, incorporating uncertainty through stochastic simulations to optimize performance and guide evidence-based policies even with limited data (Sušnik et al., 2021). It enables scenario analysis, sensitivity analysis, and policy testing (D. Liu et al., 2018; Qin et al., 2019).

SDM suits this case study due to its ability to address interconnected and dynamic issues. Castelli et al. (2022) highlight the challenges of modeling water supply impacts on economic metrics, emphasizing the importance of carefully selecting system boundaries and variables to balance simplicity and accuracy. While sufficient data is needed to define system equations, SDM is relatively robust to data limitations (Elsawah et al., 2017).

The spatial unit of the Upper Main River Basin is ideal for analysis due to its self-contained nature, reducing risks of overgeneralization. An initial causal loop diagram (CLD) can provide a qualitative system overview, defining boundaries and subsystems (Phan et al., 2021). Using the VENSIM software, the final model can comprise of six subsystems, namely (1) hydrological supply, (2) household/industrial/other water demand, (3) agricultural water demand, (4) agroeconomic cycle, (5) water quality, and (6) metrics like groundwater withdrawal and freshwater shadow price.

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Initial precipitation (P) input data forms the inception of the model and is modelled to split into environmental flow requirement (*EFR*), evapotranspiration (*EVAP*), soil retention (*SR*), surface water runoff (R_{SW}), recharging of groundwater reservoirs (R_{GW}) and green water (*G*),

$$P(t) = EFR(t) + EVAP(t) + SR(t) + R_{SW}(t) + R_{GW}(t) + G(t)$$
$$t \in [2000, 2050] \tag{16}$$

Evapotranspiration $EVAP(t)$ and soil retention $SR(t)$ data will be acquired through SWAT model outputs and assumed to increase proportionally with the decline of natural groundwater recharge over time. The environmental flow requirement $EFR(t)$ will be calculated by scaling spatial data provided by X. Liu et al. (2021) to the Upper Main River Basin. The volume of surface water and groundwater aquifers follow the same stock structure,

$$Q_i(t) = Q_{i0} + \int_{t_0}^{t} \left(R_i(t) - q_{ii}(t) - q_{ij}(t) - q_{ik}(t) \right) dt$$
$$i \in S\ (River\ and\ Streams\ Surface\ Water), G\ (Groundwater)\}$$
$$j \in \{H\ (household), I\ (industrial), AG\ (agricultural)\} \tag{17}$$
$$k \in \{OF\ (Outflow), REvap\ (Recharge\ Evapotranspiration),$$
$$BS\ (Baseflow\ and\ Seepage), Spr\ (Spring\ Water)\}$$

where $Q_i(t)$ is the current level of stock i, Q_{i0} is the initial level at the start of the simulation, $R_i(t)$ is the inflow of the stock, $q_{ii}(t)$ is outflow of the stock to another stock (i.e., water yield from groundwater to surface water) and $q_{ij}(t)$ is the outflow of the stock due to external water demand from household, industrial or agricultural purposes (i.e., groundwater extraction). Lastly, to reflect the natural discharge of the groundwater aquifer, the hydrological outflow $q_{ik}(t)$ of seepage, recharge evapotranspiration and baseflow are also modelled.

A water stock is capped at a maximum capacity $\bar{Q}$,

$$Q_i(t) \leq \bar{Q}_i(t) \tag{18}$$

Following this logic, if the following holds true, then the total level of the water stock shall decrease over time, as the sum of the total extraction and natural discharge exceeds the recharge rate of the water stock,

$$\sum_i R_i(t) < \sum_i \sum_j q_{ij}(t) + \sum_i \sum_k q_{ik}(t) \tag{19}$$

Agricultural extraction only takes place if the minimum cereal water requirement (*MCWR(t)*) is not met by green water supply through precipitation (*G(t)*),

$$q_{iAG}(t) = \begin{cases} MCWR(t) - G(t) & if \quad MCWR(t) > G(t) \\ G(t) & if \quad G(t) \geq MCWR(t) \end{cases} \tag{20}$$

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Water quality is measured by the additional nitrogen water pollution, nitrogen inflow, (*NI(t)*) per unit of agricultural fertilizer applied (*F(t)*) from the FADN database which is publicly available. The nitrate absorption gradient (β_1) is first estimated through linear regression.

$$Nitr(t) = \beta_0 + \beta_1 \cdot F(t) + \epsilon \tag{21}$$

5.2.2 Stochastic Frontier Analysis

Stochastic Frontier Analysis (SFA) is a commonly used technique to measure the use of input resources to produce output, introduced by Aigner et al. (1977). SFA differs from other econometric approaches through the inclusion of both a technical inefficiency term and a stochastic error term, allowing for the differentiation of technical efficiency and random noise when comparing the output productivity of different economic units. The aim of the SFA in this study is to estimate the marginal product of several agricultural inputs in the production of cereal. Capital (K), land (A), labor (L), fertilizer (N) and water (W) are taken as the agricultural inputs (Benedetti et al., 2019; Tonini, 2012). All other input variables are incorporated into the error term, thereby absorbing the effect of an omitted variable.

$$\begin{gathered} y_i = f(x_i;\beta) \cdot exp\{-u_i\} \cdot exp\{v_i\} \\ u_i \sim |N(0,\sigma_u^2)| \\ v_i \sim N(0,\sigma_v^2) \end{gathered} \tag{22}$$

Equation 7 depicts the general form of the SFA (Benedetti et al., 2019), where y_i depicts the cereal output for the *i*th economic unit, u_i represents the inefficiency term and v_i accounts for random error. The error terms are assumed to follow a normal distribution and to be independent. The equation can be rewritten to log-log form,

$$ln\, y_i = ln\, f(x_i;\beta) + v_i - u_i \tag{23}$$

5.2.3 Scenario Analysis

System dynamics easily allows for scenario analysis. Varying levels for three exogenous input variables are of interest. We evaluate these impacts on water availability, water quality and agricultural production. First, precipitation scenarios under different Representative Concentration Pathways (RCP) emission scenarios will influence the natural recharge rate of groundwater and the annual amount of green water precipitation. Second, as the future minimum amount of water required by cereals to produce output is largely uncertain given rising temperatures, three scenarios are simulated to reflect different agricultural conditions in accordance with the FAO's guidelines on cereal production (Brouwer & Heibloem, 1986). Third, two fertilizer scenarios will be considered, namely a constant scenario in which fertilizer use remains at 2000 levels, and a decreasing scenario in which the current trend of decreasing fertilizer use is extrapolated (Ritchie et al., 2022).

6 Discussion and conclusion

This deliverable provides a comprehensive framework for applying economic instruments and policies to the Water-Energy-Food-Ecosystem (WEFE) nexus. It explains how theoretical concepts can be turned into practical applications, specifically in the context of RETOUCH case studies. The approach includes leveraging modelling frameworks to identify gaps and set objectives for water management. Implementing the WEFE approach requires coordinated action across sectors, stakeholders, and

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governance levels, yet existing frameworks tend to be fragmented and sector-specific. To address these issues, stronger institutional coordination, dedicated funding, and the development of tools that can effectively assess and manage the interdependencies between water, energy, food, and ecosystems are essential. These frameworks are used to develop and integrate economic tools like water pricing, tradable water rights, and renewable energy incentives, which are tested through scenario analysis. Data collection, stakeholder engagement, and feedback loops are key elements for refining the models to ensure they provide effective solutions for real-world challenges, leading to sustainable management practices across the WEFE sectors.

Transitioning from theoretical concepts to practical applications is essential for effectively evaluating and refining policies and management practices within the Water-Energy-Food-Ecosystem (WEFE) nexus. This process involves leveraging economic instruments and policies and integrating them into modelling frameworks to address real-world challenges specific to the RETOUCH case studies. Such frameworks are necessary in order to bridge the conceptual work in Task 3.2 with the applied focus of Task 3.3. They include the identification of gaps in current applications of policy instruments for water management in the case studies. They also include the specification of objectives such as improving water use efficiency, supporting sustainable agricultural practices, or balancing energy production and ecosystem services. Establishing these objectives ensures a focused approach tailored to the unique needs and conditions of the case studies. Both analyses (i.e. specifying objectives and identifying gaps) have been performed in this deliverable.

Developing and implementing economic instruments is a key aspect of the modelling frameworks. This deliverable serves as a conceptual guideline for this objective. These instruments may include, for instance, water pricing, subsidies for water-saving technologies, tradable water rights, and incentives for renewable energy use. Integrating these instruments into the model involves creating scenarios that simulate their impacts on various sectors included in the WEFE nexus. For example, the modelling framework can be applied to analyze how different water pricing strategies affect agricultural water use and crop yields, providing insights into potential trade-offs and benefits in a specific case study.

The next step involves bringing the modelling frameworks to the data. In most cases, data needs pertain to data on both the biophysical and economic side of the WEFE nexus such as data on water availability, demand, energy production, agricultural outputs, and ecosystem requirements. In addition, data on costs and benefits of water use in the various sectors is needed to both establish baseline conditions as well as compare and evaluate the impact of implementing economic instruments under the modelling framework in each of the case studies. Partly, the required data for this purpose has already been collected in Task 3.1.

Once the modelling frameworks are brought to the data for application purposes, stakeholders need to be involved. Engaging stakeholders is an essential component that can shape the transition from the conceptual analysis performed in Task 3.2 to the application to case studies in Task 3.3. This transition involves collaborating with stakeholders, including farmers, energy producers, water managers, and environmental groups to ensure the economic instruments and policies to be analyzed by the models are practical and acceptable. Additionally, stakeholder feedback is invaluable for refining model parameters and assumptions, leading to more accurate and effective solutions. For instance, water pricing strategies could be adjusted based on stakeholder willingness to pay and their acceptance of the proposed measures. This feedback process involves iterative refinement that will

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assist in refining the economic instruments and their implementation. This dynamic approach ensures that the modeling remains relevant and responsive to changing conditions, ultimately leading to more sustainable and effective water management practices.

In conclusion, this deliverable outlines a structured pathway to apply economic instruments and policies within the WEFE nexus, moving from theoretical concepts to practical applications. By following these steps, theoretical concepts of economic instruments within the WEFE nexus can be effectively translated into practical, actionable modeling scenarios that address specific case study challenges. By integrating economic tools, leveraging data, and engaging stakeholders, the framework aims to achieve sustainable management practices tailored to the unique challenges of each case study. The iterative process of model refinement and stakeholder collaboration ensures that the solutions developed are both effective and adaptable to real-world conditions, ultimately contributing to a more sustainable and balanced WEFE nexus.

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