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A participatory system dynamics approach to assess transboundary nutrient pollution: modelling the water-energy-food-ecosystems nexus in the Lielupe River Basin, Lithuania and Latvia

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ABSTRACT

Managing natural resources in transboundary river basins is a complex task in which societal needs and environmental impact are intertwined. The nexus paradigm engages with such a challenge by analysing synergies and trade-offs across Water-Energy-Food-Ecosystems (WEFE) sectors. We present a WEFE nexus operationalisation using a participatory modelling approach in the transboundary Lielupe river basin, shared between Latvia and Lithuania. Using a modelling cycle approach, we illustrate a stakeholder-driven pathway from generic and qualitative to increasingly quantitative system tools useful for basin-scale policy analysis. Stakeholders prioritised agricultural nutrient pollution as a critical nexus issue strongly linked to land-use. Three policy alternatives to address this issue were co-identified with stakeholders from both riparian countries: (i) implementing nature-based solutions; (ii) transitioning to organic agriculture; and (iii) promoting arable land-use transitions to former native landscapes. The long-term effect of such policies is explored using a System Dynamics simulation model. Results highlight the importance of promoting active transboundary cooperation for water quality control, as unilateral action hampers the effect of long-term ambitious policies. Even highly ambitious unilateral action can delay the achievement of river basin quality objectives in the order of a decade, a critical finding for the wider Baltic region and the achievement of EU water quality objectives. Based on an exploratory analysis, we found that implementing basin-scale solutions for nutrient control would reduce nitrogen concentration by around 30 % with a 2 % co-benefit of increasing vegetation stocks, yet at the cost of decreasing cereal production by 8 %. This work illustrates the capabilities of a tailor-made simulation model crafted to answer locally relevant policy questions with a nexus perspective in a transboundary river basin. Developing and using a simulation model in a participatory way can explore policy futures while fostering dialogue among riparian stakeholders. This is a promising way to promote cooperation towards solving critical socio-environmental issues in transboundary rivers.

1. Introduction

The nexus perspective is an integrated sustainability paradigm focusing on the cross-sectoral connections and management of critical resources for society (Albrecht et al., 2018; Liu et al., 2018). Global policy and academic discourses have long considered the importance of an integrated perspective on resource management, yet nexus approaches have raised interest in recent years (Mohtar and Lawford, 2016). As proposed by Hoff (2011), the nexus perspective highlights the interconnections between the Water-Energy-Food (WEF) resource sectors, as well as the synergies and trade-offs that exist among them (Sušnik, 2018) (see Box 1). Since its introduction, policy and academic groups concerned with natural resource management have rapidly adopted nexus thinking (Allouche, 2024). Despite such popularity, scholars highlight the current gap between nexus *thinking* and *action* (Simpson and Jewitt, 2019b). Nexus thinking is wide and generic, but its implementation is a highly contextual task (Liu et al., 2017; Sušnik and Staddon, 2021).

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Many challenges and opportunities emerge when the nexus perspective is applied in different contexts and scales, starting with defining which sectors constitute the *nexus* (Sušnik and Staddon, 2021) (see Box 1). For instance, moving beyond a resource-focused perspective to recognise a wider environmental dimension in nexus assessments has promoted the use of *WEFE nexus* terminology, which explicitly incorporates *ecosystems* (Carmona-Moreno, Dondeynaz, and Biedler, 2019; Lucca et al., 2025; Sušnik and Staddon, 2021; van den Heuvel, Blicharska, Masia, Sušnik, and Teutschbein, 2020). Explicitly addressing ecosystems brings further complexities to nexus implementation as it extends the scope from resource management to a wider socio-environmental perspective (Ghodsvali, Dane, and de Vries, 2022; Lucca et al., 2025). Such a broader approach is suitable for exploring complex settings such as river basins (Gain et al., 2020).

In addition to biophysical processes, river basins exhibit high complexity as people live and develop economic activities in them (Bakhshianlamouki, Masia, Karimi, van der Zaag, and Susnik, 2020; Ravar, Zahraie, Sharifinejad, Gozini, and Jafari, 2020). Such complexity can be exacerbated as rivers often flow across country borders forming a transboundary river basin. Some 60 % of global freshwater flows are transboundary, hosting about 40 % of the world's population (Munia et al., 2016). Upstream and downstream countries are therefore connected through water and beyond (Zeitoun, Goulden, and Tickner, 2013). Due to their significance, considerable efforts have been made to understand how riparian countries interact about their shared water resources (Bernauer and Böhmelt, 2020; Yoffe, Wolf, and Giordano, 2003).

Such a complex socio-environmental setting calls for an integrated perspective to highlight the interactions across WEFE sectors in transboundary basins (De Strasser, Lipponen, Howells, Stec, and Bréthaut, 2016; Lawford et al., 2013). Abundant research has focused on understanding how decisions around water resources affect other sectors such as food (e.g. crop production) and energy (e.g. hydropower generation), generating important socio-economic costs and benefits for riparian countries (see Arjoon et al., 2016). For instance, technical-oriented approaches have been proposed to address complex water allocation problems (Kucukmehmetoglu and Guldmann, 2010; Scott, El-Naser, Hagan, and Hijazi, 2003) and foresee optimal operation of river infrastructure in transboundary settings (Digna et al., 2018; Verhagen, van der Zaag, and Abraham, 2021). A nascent WEFE nexus approach on transboundary issues is bringing new perspectives around river basin planning and management.

Applying the WEFE Nexus at the transboundary river basin scale can be done by using qualitative, quantitative, or mixed approaches. Emerging qualitative frameworks raise the importance of engaging riparian stakeholders for actively debating and committing to addressing transboundary nexus challenges (De Strasser et al., 2016). These dialogues should involve multiple local stakeholders and can be facilitated by external experts coming from diverse organisations (e.g. multilateral, governmental, non-governmental and academic) (Armitage et al., 2015; Daher, Hannibal, Mohtar, and Portney, 2020; Tuler et al., 2023). Quantitative nexus approaches are often developed via integrated modelling tools (Endo et al., 2015, 2020; Kaddoura and El Khatib, 2017). Making use of models can be helpful to explore long-term policy questions in a simulation environment. In this way, using integrated models can facilitate learning by exploring the effect of policies in a 'safe' virtual space before implementing them in the field (Medema, Mayer, Adamowski, Wals, and Chew, 2019; Pereira Ramos, Kofinas, Sundin, Brouwer, and Laspidou, 2022; Sušnik et al., 2018). For instance, quantitative nexus approaches have been applied to explore cooperation strategies focused on water quantity in contested transboundary river basins (Elsayed, Djordjevic, Savic, Tsoukalas, and Makropoulos, 2022) and to identify leverage points for nexus-wide change in river basin planning (Coletta et al., 2025). Despite the high potential of integrated modelling for informing WEFE Nexus policies in transboundary rivers, its use remains limited (Bwire, Mohan, Karthe, Caucci, and Pu, 2023). One plausible cause of this is the difficulty of engaging riparian stakeholders and integrating their knowledge in a modelling endeavour; this calls for mixed nexus approaches.

Mixed nexus approaches make use of both qualitative and quantitative tools in the context of river basins and beyond. Recent frameworks can facilitate this integration by considering mixed methods across a modelling cycle in the context of complex socio-environmental settings, such as river basins (Amorocho-Daza, Sušnik, van der Zaag, and Slinger, 2025; Jakeman et al., 2024). In recent years, there have been important contributions with a mixed nexus approach at different scales. Sušnik et al. (2021) present the development of a System Dynamics quantitative approach engaging local stakeholders to evaluate national-level nexus policies in Latvia. Similarly, Roy et al. (2024) present a whole-cycle System Dynamics approach to explore the drought-food security nexus in Bangladesh yet without explicit stakeholder participation. On a more local scale, González-Rosell et al. (2020) illustrate a participatory System Dynamics approach to understanding WEF Nexus interactions and evaluating strategies for the region of Andalusia, Spain. Almulla et al. (2022) propose a mixed nexus approach integrating stakeholder dialogues across the development of a WEF model used to evaluate long-term policies for the Souss-Massa basin in Morocco. Likewise, recent participatory modelling research is adopting nexus thinking to understand agriculture-related challenges—both at local and river basin scale—focusing on long-term trends across water, ecosystems and food sectors (Pagano et al., 2025; Rashidian et al., 2025). Despite these advances, the academic literature still lacks research about mixed nexus approaches in the context of transboundary river basins, particularly with a focus on water quality.

This article presents the output of a participatory modelling (PM) experience aiming to explore the WEFE Nexus in an international river basin context. The approach is implemented in the Lielupe River Basin (LRB), an agriculture-intensive transboundary river basin shared between Latvia and Lithuania, as one of the case studies of the Horizon2020 "Facilitating the next generation of effective and intelligent water-related policies utilising artificial intelligence and reinforcement learning to assess the water-energy-food-ecosystem (WEFE) nexus"—NEXOGENESIS project (nexogenesis.eu). Here we present a WEFE Nexus application at a transboundary river basin showcasing both qualitative and quantitative modelling outcomes, following an integrated PM cycle. In this article, our focus lies on two products or

Box 1
Nexus approaches.

Among many sustainability paradigms, the nexus perspective brings attention to the synergies and trade-offs among resource sectors (Allouche, 2024; Liu et al., 2018). Synergies exist where interventions in one sector have a positive effect on other(s); for example, the relation between water availability and hydropower generation. In contrast, trade-offs occur when interventions in a certain sector negatively affect other(s); for example, by developing intensive agriculture, river water quality is negatively affected via diffuse nutrient pollution. Nexus research therefore strives to reach a holistic understanding of the resource interdependencies to promote synergies and minimise trade-offs across resource sectors (Simpson and Jewitt, 2019a).

Despite the evident importance of the WEF sectors for society, researchers and practitioners promptly pointed out the need to include other sectors in the Nexus. For example, various scholars proposed including land and climate (WEF-CL) in specific case studies (Laspidou, Mellios, and Kofinas, 2019; Sušnik et al., 2021). Others also pointed out that explicitly considering the ecosystems in the nexus was of critical importance as they underlie the resource sectors and beyond (Folke et al., 2021; Rockström et al., 2009; Sušnik and Staddon, 2021; van den Heuvel et al., 2020). For instance, the Water-Energy-Food-Ecosystems (WEFE) Nexus is emerging as a flexible approach integrating research and policy perspectives toward sustainable resource management (Carmona-Moreno et al., 2019; Lucca et al., 2025). While nexus terminology and focus are evolving (WEF, WEF-CL, WEFE, and others), the field remains focused on promoting an integrated perspective toward sustainable resource planning and management.

outcomes of a PM intervention: the simulation model and the policy insights that can be derived from using it (Gray et al., 2018). More specifically, we show how the simulation model capabilities enable the exploration of long-term outcomes of locally relevant policies amid uncertainty.

2. Methods

Our methodological approach begins with an overview of our framework of choice, a policy analysis framework based on a modelling cycle (Section 2.1). We then present the case study and the participatory setting in which the framework is applied (Section 2.2). The subsequent Sections (2.3–2.5) explain the global phases of the modelling cycle as implemented in the case study. We intentionally present the model's development and characteristics as part of the methods rather than the results. This decision is based on two main reasons: (1) our chosen framework focuses on policy analysis, taking a step further from model building and testing; and (2) literature on participatory modelling (PM) emphasises that the value of a PM intervention lies not only in the model itself but also in the policy insights it generates (Gray et al., 2018). Accordingly, our methods section focuses on the modelling process as a means to derive those insights, which are reported in the results (Section 3).

2.1. *Policy analysis framework — a participatory modelling cycle under uncertainty*

We adopted Amorocho-Daza et al.'s (2025) framework as a structured policy analysis approach to formulate a socio-environmental System Dynamics (SD) model with stakeholders while considering uncertainty throughout the process. Each of the three global modelling phases, namely (1) modelling foundations, (2) model-building and testing, and (3) model use and policy evaluation, was followed in developing the SD model for exploring the WEFE Nexus in the context of a transboundary basin (Fig. 1). For each modelling phase, we implemented specific tools that contributed to making a model useful for policy analysis ('gears' in Fig. 1).

In Phase I, the modelling foundations are established. Here, modellers and stakeholders worked together to scope the issue and begin its conceptualisation. Scoping activities helped to focus on the problem of interest, particularly regarding the definition of a locally rooted vision of sustainability (Nabavi, Daniell, and Najafi, 2017). For the conceptualisation, we developed a qualitative system representation of the defined issue with stakeholders. This formed the foundation for developing a quantitative model (Freebairn et al., 2019).

During Phase II, we built and tested a quantitative simulation model. We used SD as the modelling paradigm. A quantitative SD model takes the form of a Stock and Flow Diagram (SFD) (Naugle, Langarudi, and Clancy, 2024). Here, the conceptualised relationships were operationalised as a network of parameters, flows, and stocks that can be mathematically represented as coupled differential equations (Ford, 2010; Sterman, 2000). The model was verified in terms of structure and behaviour with the help of stakeholders and pre-existing/historical data.

Phase III focuses on model use, particularly to evaluate socio-environmental policy alternatives. This phase relates to the scoping activities of Phase I by using the simulation model to test policies that can potentially contribute to resolving the identified socio-environmental issue(s). At this stage, stakeholders used the model as an experimentation and learning tool and provided feedback for its potential later use in decision-support settings.

2.2. *Case study*

The modelling framework is applied to explore WEFE policies in the Lielupe transboundary river basin (Fig. 2). The Lielupe River Basin (LRB) is one of the transboundary river basins shared between Latvia and Lithuania (Fig. 2). It has an area of ca. 17,800 km^2, distributed almost equally across Latvia (8850 km^2) and Lithuania (8940 km^2) (NEXOGENESIS, 2022). The LRB is one of the main river basins shared between Latvia and Lithuania, occupying around 14 % and 16 % of the countries' areas, respectively (FAO, 2016). Lithuania, the upstream country, contributes about 56 % of the river basin's annual flow. The rivers Mūša (Lithuania) and Nemunėlis (at the Lithuanian-Latvian border) merge into the Lielupe River in the city of Bauska (Latvia)

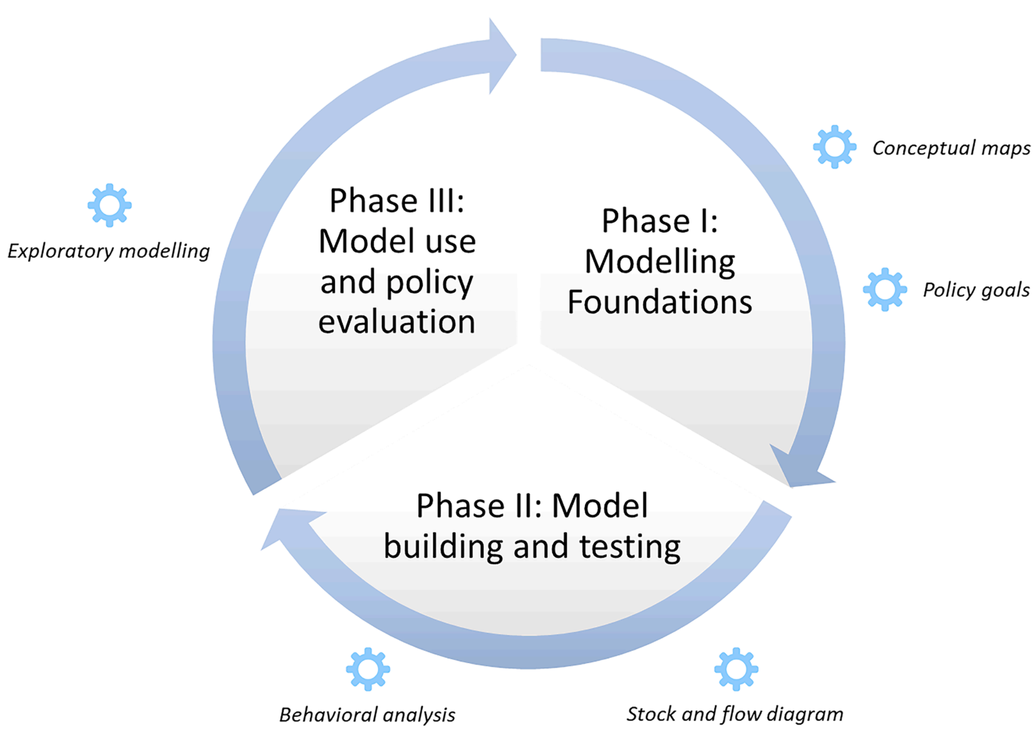

Fig. 1. The modified three-phase modelling framework (after Amorocho-Daza et al. 2025).

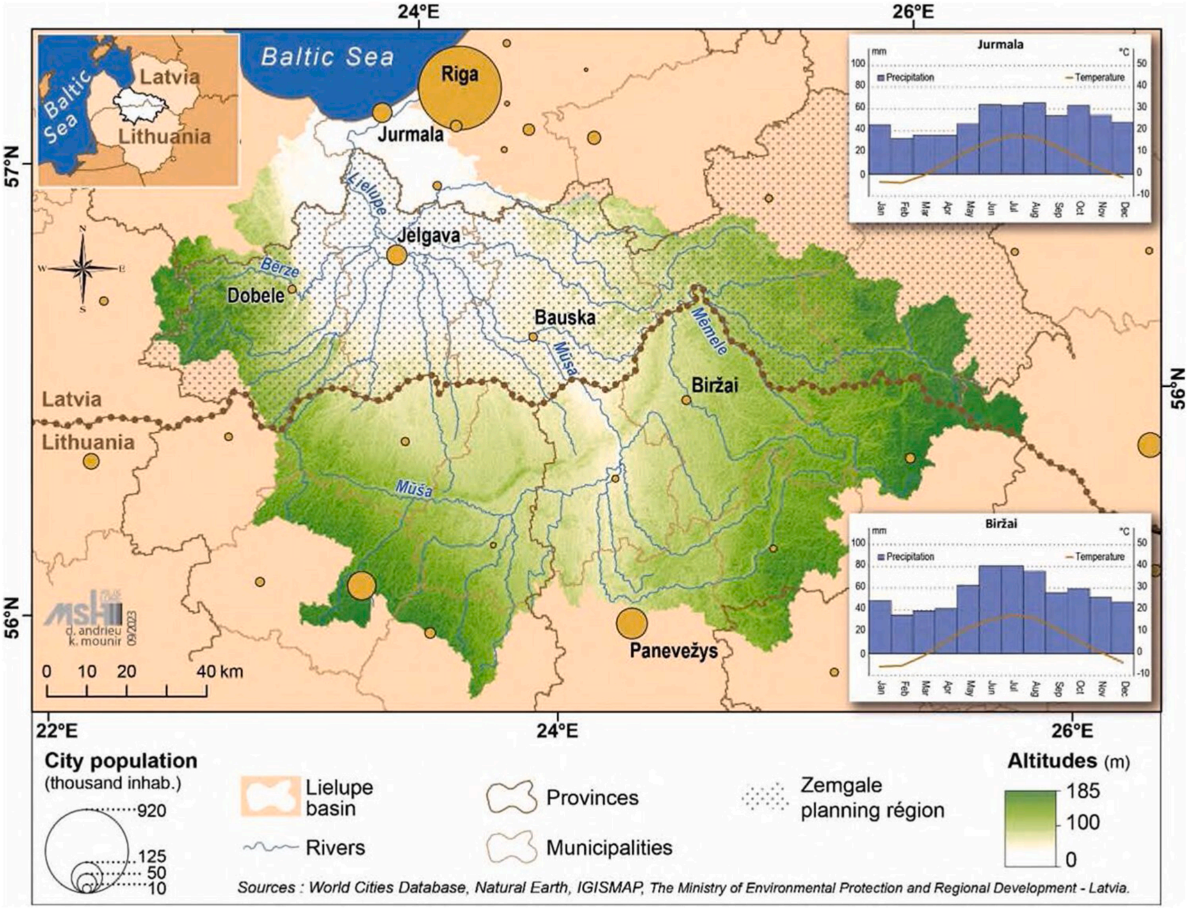

Fig. 2. Lielupe River Basin (Mooren et al., 2024).

(European Regional Development Fund, 2019). From this point on, it flows north for 119 km into the Gulf of Riga, with a mean flow of 3540 Mm^3/year (112 m^3/s) (FAO, 2016).

The socio-economic activities in the LRB affect local ecosystems. The river basin is home to ca. 12 % of the Latvian population and 11 % of the Lithuanian population, in total ca. 800,000 inhabitants, half in urban areas (NEXOGENESIS, 2022). The main economic activities of the LRB are related to the services and agriculture sectors. Regarding land use, the main land uses of the basins correspond to arable land and forests, each one accounting for 43 % of the total basin's area (See SI Table 1). Agricultural land use competes with the natural grassland habitats of the region. Productive activities, particularly agriculture, have caused high nutrient concentrations in the river for decades (Siksnane and Lagzdins, 2020; Stålnacke, Grimvall, Libiseller, Laznik, and Kokorite, 2003). According to FAO estimates, >70 % of the total nitrogen and >40 % of the total phosphorus inland load is caused by human activities (FAO, 2016). The main source of nitrogen pollution is related to agriculture, while the main contributors of phosphorus are municipal and industrial wastewater. Controlling nutrient pollution in the basin is required to reduce existing negative pressures on aquatic ecosystems, not only in the river itself but also in the Baltic Sea basin as a whole (Limburg, Breitburg, Swaney, and Jacinto, 2020). These river basin issues, therefore, resonate with a larger 'wicked' problem connecting agricultural landscapes to water bodies across the European Union (Wiering et al., 2020).

Table 1
Summary of the stakeholders' affiliation (LV = Latvia; LT Lithuania).

Stakeholders' main classification	Organisations
National authorities	Ministry of Agriculture (LV), Ministry of Environment (LT), Latvian Environment Geology and Meteorology Centre (LEGMC) (LV) Lithuanian Hydrometeorological Service (LT)
Regional planning authorities	Zemgale Planning Region (LV)
Local municipalities in Latvia and Lithuania	Jelgava (LV), Bauska (LV), Panevėžys (LT) Biržai (LT)
Research institutions/ universities	Latvia University of Life Sciences and Technologies (LV) University of Latvia (LV)
Other associations	Farmer groups: NGO Association "Farmers' Parliament", LPKS "LATRAPS" Environmental NGOs: Green Liberty (LV), Salgale rural support association (LV), Center for Environmental Policy (AAPC) (LT)

2.2.1. *Stakeholder participation*

Stakeholders of the LRB are engaged in a WEFE Nexus policy co-creation initiative, including a strong focus on participatory modelling, following a structured approach as reported in Hüesker et al. (2022). Further details about the stakeholder engagement strategy in the Lielupe and the rest of the NEXOGENESIS case studies, including stakeholder selection, modes of engagement and overall outcomes of the participatory process, can be found in Avellán et al. (2025). Local case study partners —BEF Latvia (an environmental NGO focusing on the Baltic Region)— identified and engaged stakeholders that either have an "interest in the application of project results and products" and/or are "directly engaged in the project implementation and/or outcomes". A summary of stakeholders' affiliations is shown in Table 1.

Table 2
Summary of stakeholder workshops.

Workshop	1	2	3	4	5	6
Date	10/02/2022	02/11/2022	15/06/2023	06/02/2024	02/10/2024	27/05/2025
Location	Online	Riga, LV	Vilnius, LT	Riga, LV	Riga, LV	Riga, LV
Phase of the modelling framework	Modelling foundations	Modelling foundations	Modelling foundations	Model building and use	Model use and policy evaluation	Model use and policy evaluation
Number of participants	10	10	10	18	11	17
Workshop purpose	Identification of main nexus issues in the basin	Discussion about the current state of the basin and the required policies to improve it	Nexus policies prioritisation for the basin	Presentation of preliminary results of a simulation model with policies for the basin	Stakeholder interaction with a web-based decision support system	Discussing the practical implications of policy alternatives in the context of the local/transboundary governance roadmap
Facilitation approach	Small group discussions	Collective brainstorm on policy alternatives for Nexus sectors	World Café (WEFE sectors) on policy instruments Dot voting on policies prioritisation per WEFE sector	Plenary discussion about preliminary results of the model Q&A session - modelling capabilities, assumptions and limitations	Supported testing of the tool in groups (+task) Feedback (plenary) to improve the model and tool functionalities	Plenary discussion on policy package validation Dot voting for characterising the needed activities to reach the basin's policy goals
Inputs (modelling cycle tools)	Early conceptual map	Early conceptual map	Draft policies by sector	Simulation model results	Decision support system (with the model in the background)	A set of policy tools and their expected (modelled) performance
Outputs (modelling cycle tools)	Identification of the key nexus issues in the basin	Revised conceptual map	Prioritised nexus policy goals	Stakeholder feedback and requests for: updating the model and designing a DSS to use it	Stakeholder feedback about: the DSS functionalities and improving the precision of some key modelling outputs	Stakeholder feedback about: Opportunities and limitations of taking the proposed policy packages into action.
Online summary	Link	Link	Link	Link	Link	Link

Stakeholders took part in six workshops across three years, as summarised in Table 2. For each workshop, a purpose aligned with the proposed phase of the modelling framework was identified. Additionally, the table presents the facilitation approach implemented in each workshop, as well as the main inputs and outputs. An online summary of each workshop is available via links in Table 2 for interested readers.

2.3. Phase I

The most relevant outputs of the stakeholder workshops 1 to 3 in terms of the modelling cycle tools were the conceptual map and the prioritised policy goals for the basin. These are important inputs for developing a simulation model.

2.3.1. Conceptual map

The conceptual map represents an effort to account for the interlinkages and causal relations among the variables of the nexus system in the basin. Stakeholders were introduced to an early conceptual map of the WEFE Nexus system in Latvia, originally proposed by Sušnik et al. (2021), during Workshops 1 and 2. This served first as a discussion starter to prioritise the main issues of the basin from a nexus perspective, and later to adapt it to the scale and priorities of the Lielupe (see Table 2). Stakeholders were able to debate whether the pre-identified links were relevant or not and to add new ones to the map. Fig. 3a presents the WEFE Nexus conceptual map for the Lielupe river basin after incorporating stakeholder feedback. It shows a deeply interconnected and complex system consisting of the six nexus sectors identified as relevant for the river basin: *Water, energy, food, ecosystems, land*, and *climate*.

The conceptual map highlights how the identified variables affect one or more sectors in the LRB. Despite the myriad processes and interactions in the system map, it is important to highlight some key sectors and interactions. For instance, the *land* sector was identified as a central sector that affects many other sectors via processes that happen on land. Land use is closely connected to food and renewable energy production and drives trade-offs such as water quality deterioration and/or reduction of natural landscapes. Given the predominance of agriculture, the *food* sector shows several connections and impacts with other sectors. The causal relationships across nexus sectors are further explored and formalised in Phase II of the modelling cycle (see Section 2.4). A final version of the map presents an extension considering the countries' interactions in the basin. That is, the conceptual system map explicitly considers the two riparian countries independently yet connected via water flowing from the Lithuanian to the Latvian side of the basin (Fig. 3b).

2.3.2. Policy goals

The policy goals represent priority points for improving the current state of the LRB in accordance with a local vision of sustainability. As part of workshop 3, stakeholders were introduced to a list of policy

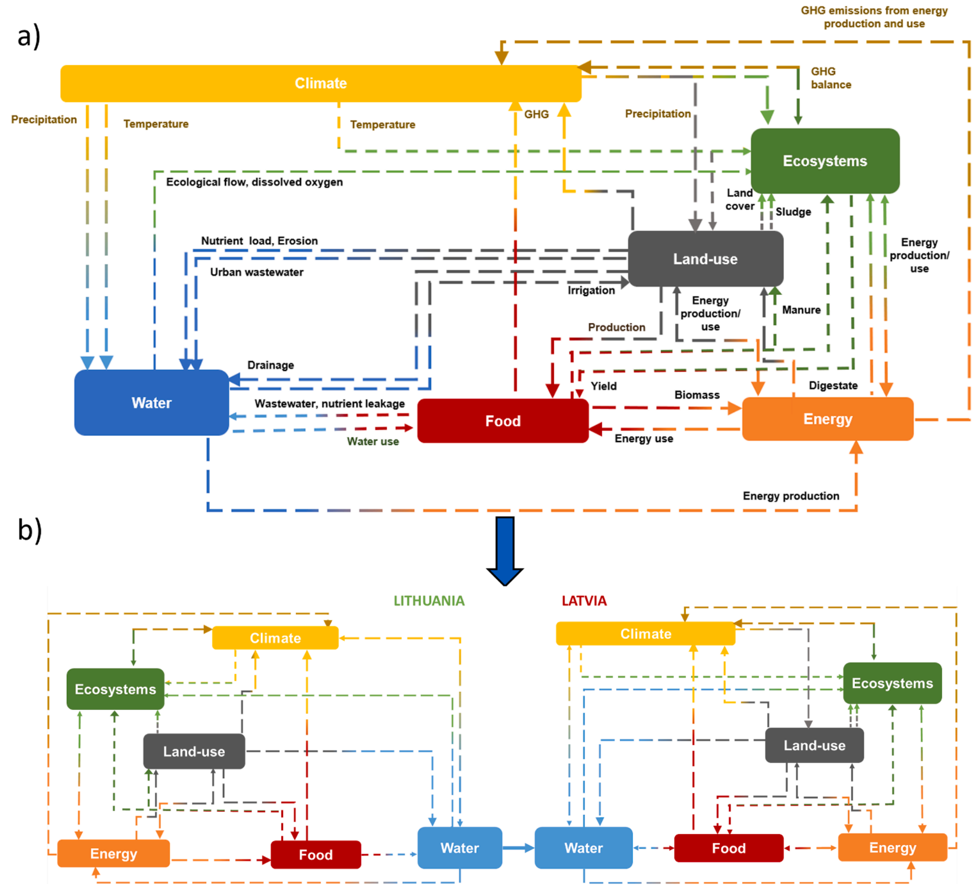

Fig. 3. a) Conceptual system map of the nexus sectors in the Lielupe River Basin b) conceptual representation of upstream and downstream nexus system connected by water in a transboundary setting.

alternatives potentially relevant to address local WEFE goals—based on a screening of national objectives, both in Latvia and Lithuania. Using the World Café approach (Löhr et al., 2020), in a first iteration, stakeholders revised, discussed, modified, and even proposed new policy alternatives for each WEFE sector in small groups. In a second iteration, stakeholders prioritised the policy alternatives that were more relevant to achieve river basin goals—making use of dots to vote for their preferred options. In the absence of a clear WEFE policy landscape with quantifiable river basin objectives (Mooren et al. 2024), the feedback from stakeholders provided a grounded perspective to connect means (policy alternatives) to ends (policy goals) in the participatory modelling exercise. In short, the workshop outcomes helped the NEXOGENESIS team narrow down a list of policy goals that could potentially be impacted by implementing relevant policy alternatives in the Lielupe and could be evaluated in a simulation environment. The final list of goals focused on aspects related to water quality and protection of natural ecosystems in the LRB (Table 3). These goals were subsequently incorporated within the SDM to assess the potential nexus-wide impacts of their implementation and to highlight possible policy synergies and trade-offs.

2.4. Phase II

This phase focuses on the development of a quantitative simulation model based on the Phase I foundations.

2.4.1. Stock and flow diagram - overview

A Stock and Flow model was developed based on the foundations identified above (Fig. 3 and Table 3). Fig. 4 presents an overview of the main stocks and variables considered in the model. The dotted lines identify the WEFE sectors in the model (i.e. land, water, food, ecosystems). Here is important to mention that not all the sectors characterised in the conceptual map were included in the simulation model (i.e. climate and energy); this evidences a transition from a generic systems perspective to a more focused analysis of a local problem from a systemic perspective. For instance, as the issue of nutrient pollution gained prominence in the stakeholder discussions, the energy sector remained relatively isolated and out of the model scope; similarly, the climate sector was less emphasised yet considered as a driver of biophysical changes in the basin. As recognised from the conceptual map, the *land* sector is central to the nexus in the basin. Four important land stocks are identified as *Forests, Grasslands, Arable land*, and *Arable land with nutrient treatment*. Arable land is the current dominant land use in the basin (ca. 43 % of the land area), a condition that requires transformation according to the stakeholders' local sustainability vision. Hence, three policy levers are considered as future interventions in the basin (highlighted in purple): (1) conversion of arable land to grasslands, (2) implementation of nutrient reduction options, and (3) transition to organic agriculture. Depending on the extent of such policies, cascading effects are expected on the *ecosystems, water,* and *food* sectors.

For the *Ecosystem* features, transitioning back to a condition of more *natural* land use in the basin has important effects. Considering the basin's main land uses gives a proxy of the total carbon mass stored in vegetation in the basin. Natural land cover features such as grasslands and forests are the main contributors to the total vegetation stocks in the basin (see Fig. 4, Ecosystems, interlinkages in bold); in contrast, the contribution of arable land to this stock is negligible (see SI, Figure 10 and 11). Vegetation stocks are related in complex ways to other forms of biodiversity, such as animal species. Here we explore the effect of river basin vegetation stocks on animal biodiversity in the basin.

Table 3
Policy goals for the Lielupe basin.

Goal	Description	Indicator	Year	Target
Goal 1. Reduce the nitrogen concentration in Lithuania by 15 % in 2050	Reduce the nitrogen concentration in the Lielupe River Basin (Lithuania) by 15 % in 2050	Percentage of nitrogen concentration reduction compared with the baseline (2015)	2049	-15 %
Goal 2. Reduce the nitrogen concentration in Latvia by 20 % in 2050	Reduce the nitrogen concentration in the Lielupe River Basin by 20 % (Latvia) in 2050	Percentage of nitrogen concentration reduction compared with the baseline (2015)	2049	-20 %
Goal 3. Equitable contribution from Lithuania to control transboundary nutrient pollution	Lithuania contributes (in proportion to its catchment area) to control nutrient pollution in the basin	Lithuania's contribution to control nutrient pollution in the basin	2015–2049	53 %
Goal 4. Equitable contribution from Latvia to control transboundary nutrient pollution	Latvia contributes (in proportion to its catchment area) to control nutrient pollution in the basin	Latvia's contribution to control nutrient pollution in the basin	2015–2049	47 %
Goal 5. Increase bird biodiversity by 20 % in 2027.	Increase bird biodiversity (species richness) in the Lielupe River Basin compared with the baseline (2015)	Bird biodiversity	2027	+20 %
Goal 6. Promote organic farming in Lithuania	Develop organic farming in 13 % of agricultural land by 2028 in Lithuania	Fraction of arable land with organic farming in Lithuania	2028	13 %
Goal 7. Promote organic farming in Latvia	Develop organic farming in 25 % of agricultural land by 2030 in Latvia	Fraction of arable land with organic farming in Latvia	2030	25 %

The *Food* sector is modelled from a food production perspective, focusing on the dominant crops of the basin (see SI, Table 2) (see Fig. 4, Food, interlinkages in bold). Food production is estimated as the product of arable land and crop yield. To capture long-term uncertainty in crop production, crop yield is modelled as an exogenous variable responding to climate change scenarios. We also incorporated a probabilistic change in productivity based on the implementation of organic farming practices. Although this approach can capture a wide range of variability in food production and respond to endogenous land use changes, it has limitations. The approach does not endogenously model the impact of soil quality on food production, a modelling approach thoroughly illustrated by Rashidian et al. (2025). Notwithstanding, our relatively straightforward modelling approach emerged from the participatory process, where stakeholder discussion did not focus on accurately representing food production but rather on assessing food-related trade-offs with other sectors, particularly water quality.

For the w*ater* sector, intensive agricultural activities export nutrient loads into surface water. Nutrients of importance are in the form of nitrogen (nitrate – NO_3^-) and phosphorus (phosphate – PO_4^{3-}); here we focus on nitrates as they are of special concern for stakeholders for two reasons: first, as they constitute the dominant contributor to total N; and, second, due to their persistently high concentration, not only in the LRB but in other Baltic basins (Siksnane and Lagzdins, 2020; Stålnacke et al., 2003). The nitrogen leaching from arable land is highly mobile from the soil to the water systems (e.g. groundwater, rivers, and estuaries). High nitrogen loads and concentrations in the basin are associated with eutrophication in the Gulf of Riga (Baltic Sea), the discharge point of the Lielupe River (Finni, Kononen, Olsonen, and Wallström, 2001; Lundberg, 2005; Murray et al., 2019). The model focuses on capturing nitrogen accumulation and transport processes, from soil to rivers and from rivers to estuaries, in a conceptual and aggregated way. Surface water flow is considered as a model parameter that drives the nitrogen leaching rate, and that can be used in combination with the nutrient loads to estimate river nutrient concentration (see Fig. 4, water, interlinkages in bold; SI Section 1.3 for a detailed explanation). This high-level understanding of the nutrient movement across the river basin facilitates exploring the effect of different policies at a river basin scale to reduce, intercept and remove nitrogen before it enters the surface water system.

Various input variables, marked with green in Fig. 4, are considered as long-term time series estimated via climate change projections following the CMIP6 runs (See SI Table 10). Most of the biophysical variables were obtained via the third phase of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b), a cross-sectoral framework for climate change projections (Frieler et al., 2017; Warszawski et al., 2014). Biodiversity-related variables are estimated with the aid of the Globio 4 model, a global biodiversity model (Schipper et al., 2020). Their application to the Lielupe River Basin and other case studies of the NEXOGENESIS project are further described by Trabucco et al. (2024). Similarly, variables identified with blue in Fig. 4 are stochastic parameters derived from the academic literature (See SI Table 11).

A more detailed account of each sector's modelling strategy and equations is available in Section 1 of the Supplementary Information.

2.4.1.1. Transboundary interactions. Modelling nutrient flow across the basin offers an opportunity to characterise the transboundary nitrate mass flow. As proposed in the conceptual map (Fig. 3b), the stock and flow diagram presented in Fig. 4 can be transformed to account for upstream and downstream interactions. Such a change emerged from stakeholder feedback during Workshop 4, as they pointed out that assuming policies are implemented across the whole basin in the simulation model does not reflect Lielupe's transboundary reality, in which lack of coordination and unilateral actions regarding water quality management currently predominates (see Mooren et al. 2024). In response to this feedback, Fig. 5 shows the modelling strategy to decouple the upstream and downstream riparian countries. Such a structure explicitly indicates that the Lithuanian nutrient load outflow is an input for Latvia, which adds to the diffuse nutrient pollution generated downstream. In other words, both countries are connected by the water flow, which transports nutrients from upstream to downstream.

This model structure builds on the conceptual map but focuses on water quality rather than quantity (which is not presently a major issue in the basin). Such a model structure explicitly shows the asymmetry of a transboundary setting, offering flexibility to simulate the likely effect of implementing unilateral or bilateral environmental policies in the basin (Elsayed et al., 2022; van der Zaag, 2007).

2.4.2. Model behavioural analysis

For each nexus sector, a key variable is selected to explore the simulated behaviour over time without including policies. In this analysis, the main land stocks remain static and, therefore, the behaviour of the key variables is explained solely by exogenous projections (see Fig. 4, variables marked in green; Section 2.4.1 for more details). The model uses a monthly timestep over 35 years (420 months), covering the 2015–2050 period. The chosen timestep allows for harmonising data input from multiple datasets and global models (see SI Table 10), also

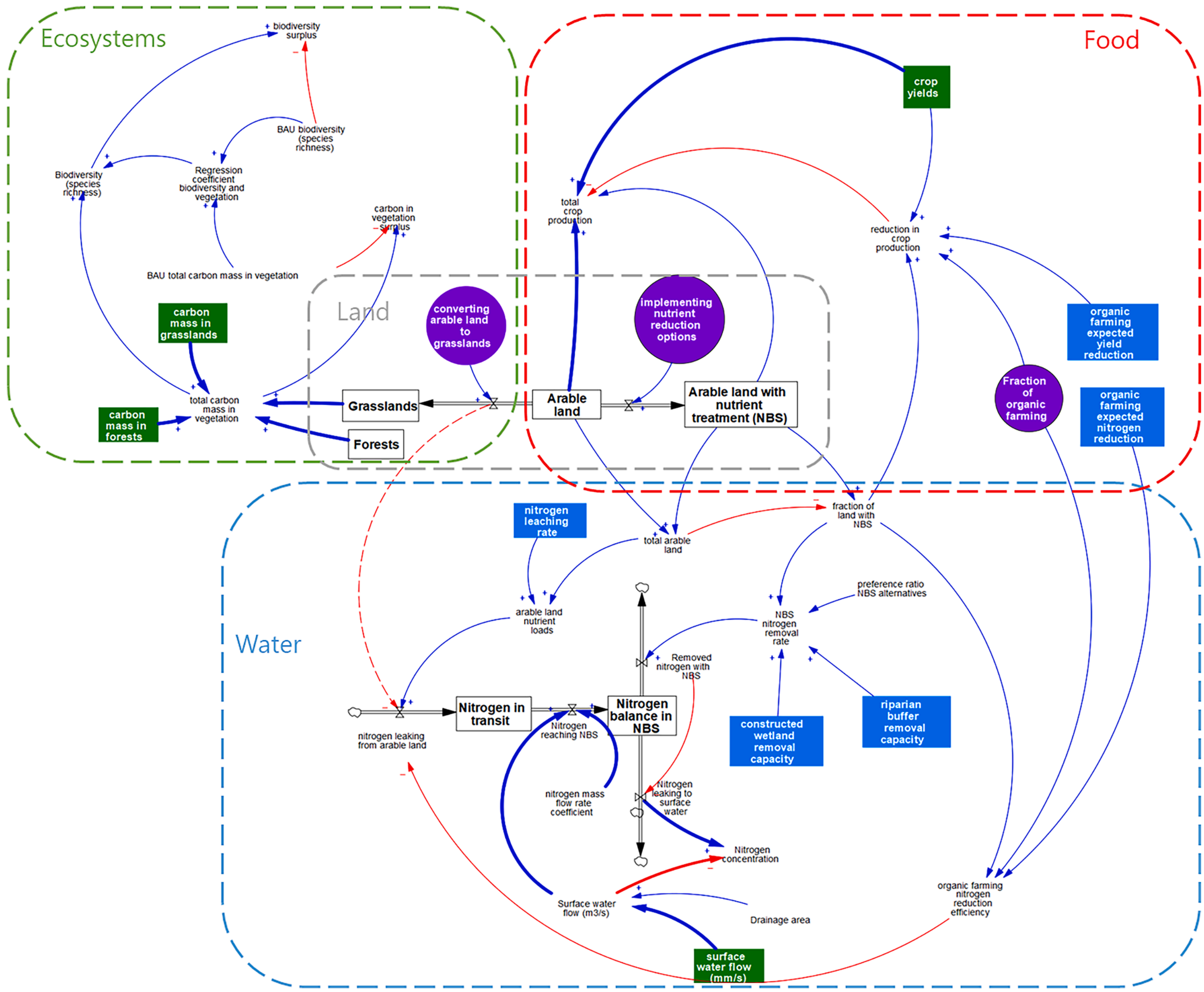

Fig. 4. Stock and flow diagram of the Lielupe river basin.

allowing for capturing seasonal dynamics of key variables (e.g. water quality). The simulation timespan reflects a medium-term planning horizon that allows system trends to be captured while giving time for corrective action to be taken; yet it is not so long that uncertainty dominates the narratives. Its initial and final year also reflect the data harmonisation across multiple input data sources under common climate change projections (i.e. CMIP6 – RCP2.6 and RCP8.5 scenarios), as detailed in the SI file. The behaviour of each selected variable is shown using a 90 % dynamic confidence interval based on 1000 simulations of the SD model under the RCP2.6 scenario (see Figs. 6–8) and using a Sobol sequence sampling with the stochastic parameters as summarised in SI Tables 10 and 11.

For the food sector, we selected cereals' total monthly crop production (combining summer and winter wheat, and maize). This decision is based on the fact that wheat and maize crop areas only account for two-thirds of the basin's total arable land, and the crops are comparable in yield terms (see SI: Table 2, Figure 1). An important disclaimer is that, although crop yield typically is relevant at the seasonal or yearly time scale, we chose to estimate a monthly and uniform equivalent value of food production to facilitate comparison with other variables at every simulation timestep. Fig. 6 shows the dynamic confidence interval for cereal production. The variable exhibits fluctuations in crop yield across the model timespan (see SI, Figure 1). However, as the median, minimum, and maximum values remain fairly consistent over time, the monthly crop production can be described by a uniform distribution with a mean value of ca. 200,000 ton/month (115,000–283,000; 90 %CI).

For the ecosystems sector, we selected the total carbon mass in vegetation. This variable is selected as it is a common feature of different land uses and can be aggregated at the river basin level. Fig. 7 shows the dynamic confidence interval for the total carbon vegetation stocks. The variable exhibits two different behaviours across the simulation. During the first half of the timespan, the carbon mass in vegetation increases linearly within a relatively narrow range. In contrast, during the second half of the simulation, the median value tends to decrease and exhibits larger uncertainty. This two-stage behaviour resembles the forecasts of average carbon mass density in vegetation, particularly carbon density in forests (see SI, Figure 7). Vegetation stocks start at 67 M ton C (66–68; 90 % CI) and increase to a maximum of 80 M ton C (78–81; 90 % CI), to later decline to 75 M ton C (72–78, 90 % CI).

For the water sector, nitrogen concentration was selected as a key variable because local authorities periodically measure it as a water quality proxy. Fig. 8 shows the dynamic confidence interval for nitrogen concentration at the endpoint of the basin. As presented in SI's Eq. 18, nitrogen concentration is estimated as the ratio of nitrogen mass flow to water flow. The variable exhibits strong fluctuations that resemble

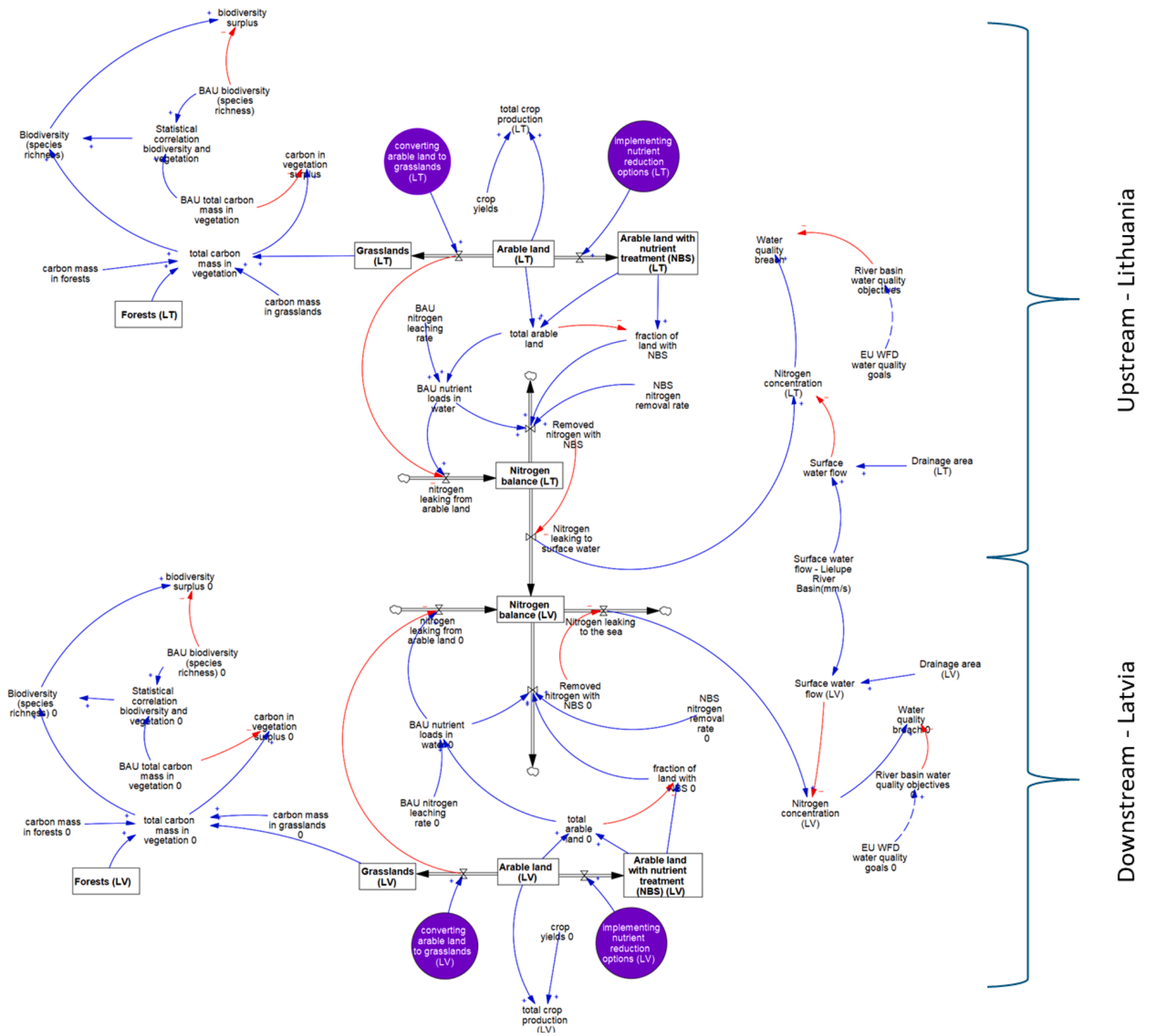

Fig. 5. Stock and flow diagram reflecting the Upstream-downstream interaction in the basin.

seasonal flow variations (see SI, Figure 3). The low values of concentration have a median value of 0.3 mg/L (0.2–4.2; 90 % CI). Mean values of concentration exhibit a median value of 1.6 mg/L (0.8–7.4; 90 % CI). High values of concentration exhibit a median value of 5.9 mg/L (3.3–9.4; 90 % CI). The magnitude of these values and their seasonal behaviour are consistent with previously reported long-term behaviour of nitrogen concentration in the basin (see Stålnacke et al., 2003).

Table 4 presents numerical values of the median and 90 % confidence interval for the variables discussed above at discrete points in time. Four 'snapshots' are considered at the beginning of every decade in the period 2020–2050 as a proxy of the variables' change over time. These values are later used as a reference baseline for the key variables, useful in comparing the effects of policies in the exploratory modelling stage.

Stakeholders were particularly interested in exploring and improving the model's capabilities to represent water quality in the basin, particularly during workshops 4 and 5. To validate the model, we used the same data source as for the calibration of the water module (SI Table 3). However, we only used the most recent two years of observations, as they were not included in the calibration. Fig. 9 presents water quality monitoring monthly observations in the period 2018–2020 alongside three time series of model outputs (5 %, median and 95 % of 1000 model instances) over the same period.

A regression analysis between the median response and the observed nitrate concentration in the river was performed (See SI: Table 6 and Figure 7). The regression coefficient is a significant predictor of the observed data ($P = 4.06E\text{-}05$), able to account for more than half of the observed variance (Adj-R2 = 0.54). The coefficient value is estimated as 0.92, with an estimated value in the range of 0.55–1.3. As the value of 1 lies in the confidence interval, there is statistical confidence that the proposed model accurately captures the nitrogen concentration behaviour in the Lielupe. The approach explained above explains the nutrient concentration dynamics based on a biophysical variable—surface flow—which is also modelled stochastically as an exogenous variable (See SI Fig. 3). This means that the nitrogen concentration baseline is exogenously, not endogenously, driven. This is a simple yet robust mechanism of modelling nutrient transport (See SI Section 1.3),

After establishing an exogenous and biophysically driven baseline

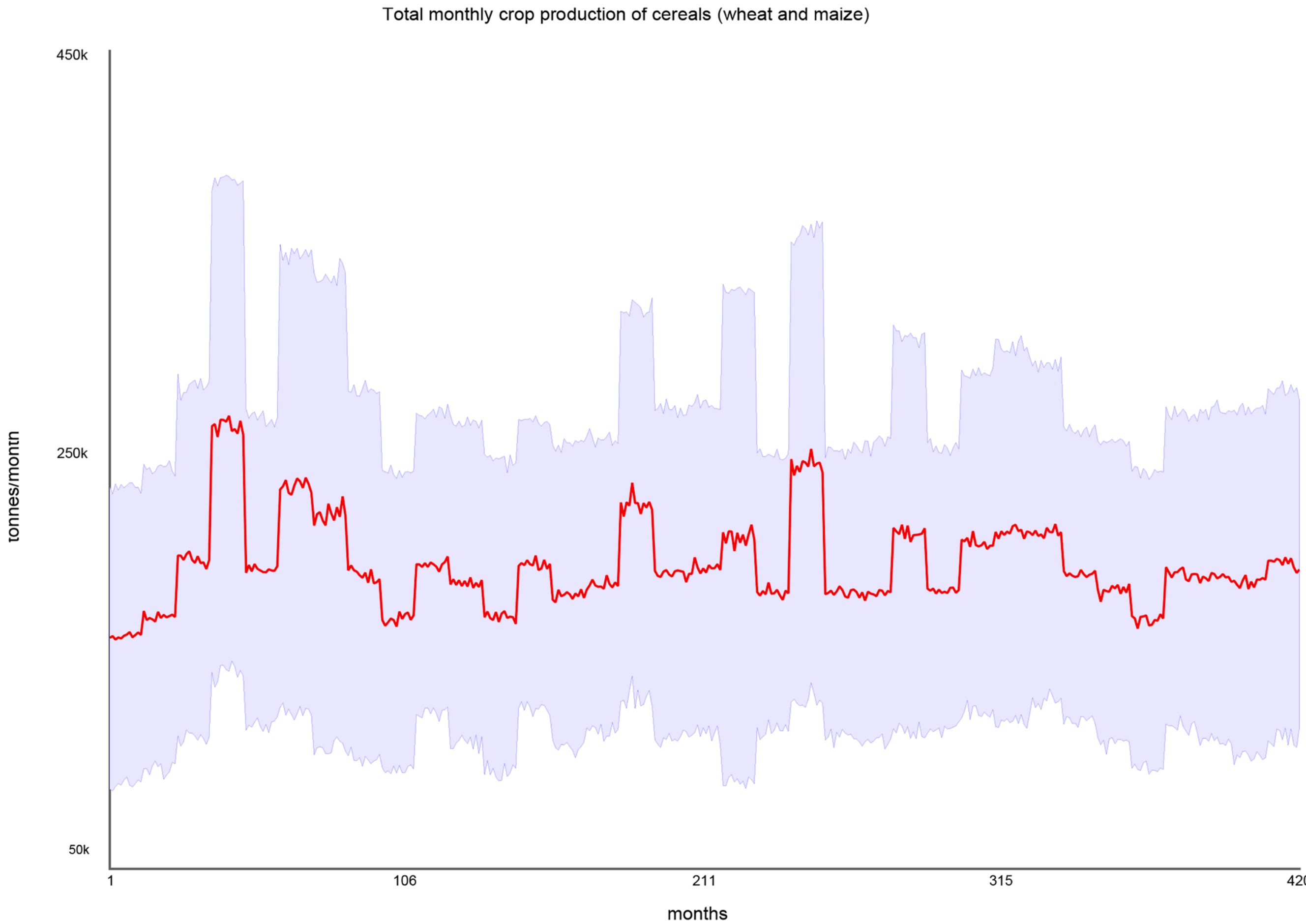

Fig. 6. Dynamic 90 % confidence interval for total monthly crop production of cereals.

behaviour for the three proposed variables, the following section focuses on assessing the expected effects of land-use change as an endogenous and policy-driven exploration. When implementing policies, the model stocks are not static but exhibit a dynamic behaviour that 'activates' most of the identified interlinkages as a cascading effect of long-term land-use change in the basin (see Fig. 4, non-highlighted interlinkages). For instance, the proposed land-use policy levers (see Fig. 4, variables marked in purple) can be tested to evaluate nitrogen reduction, interception and removal. Similarly, although cereal production is driven by crop yield, and the basin's total carbon in vegetation depends on vegetation types, these variables also respond endogenously to land-related policies. For instance, cereal production is a function of arable land, and carbon mass in vegetation is affected by the extension of grasslands. In short, although our modelling approach uses exogenous factors to estimate the behaviour of the key model's variables, the core model insights emerge from analysing the endogenous effect of policies on such variables. The following section details our exploratory perspective for policy evaluation.

2.5. Phase III

We proposed an exploratory modelling approach to use the model for policy evaluation. More specifically, we considered two perspectives, one analysing a limited but structured set of policy futures, and the second using an open, wider policy exploration.

2.5.1. Comparing policy ambition and transboundary cooperation

For the exploratory analysis of policies, we compared the change occasioned by implementing a policy relative to the previously defined reference baseline (Table 4). Two interacting criteria are considered for the analysis: Transboundary cooperation and policy ambition. For the first criterion, we consider levels of cooperation: bilateral, unilateral (Lithuania), and unilateral (Latvia). For the second, we consider the ambition level of the deployed policies as null, low, medium and high, based on the policy combinations as described in Table 5. Unilateral scenarios assume that while one riparian country deploys the policies to some degree (e.g. low to high policy ambition), the other country does not make any contribution (i.e. null policy ambition). The interacting criteria result in a 3 × 3 results matrix (see Table 7) to be compared with the baseline, as presented in Table 4.

2.5.2. Open policy exploration

Although the approach above enables a structured in-depth analysis, it considers only a limited number of policy combinations (i.e. 9 instances). Therefore, instead of exploring a well-defined and deterministic policy package (Table 5), here we explore the broader expected effects of the proposed policies in both riparian countries using a large and stochastic decision space following an exploratory modelling paradigm (Auping, 2018; Moallemi, Kwakkel, de Haan, and Bryan, 2020). Table 6 summarises the probability distribution and parameters considered for each of the policies that were introduced in Table 5. Therefore, one instance of the analysis will imply assigning a random value for each of the policies listed below. By simulating multiple runs of the simulation model, each one with stochastic instances of the policy variables, it is possible to explore the effect of the policies on the WEFE system under deep uncertainty (Moallemi et al., 2020). In other words, by performing an open policy exploration, it is possible to estimate the effect of testing a large set of policy combinations in both riparian countries.

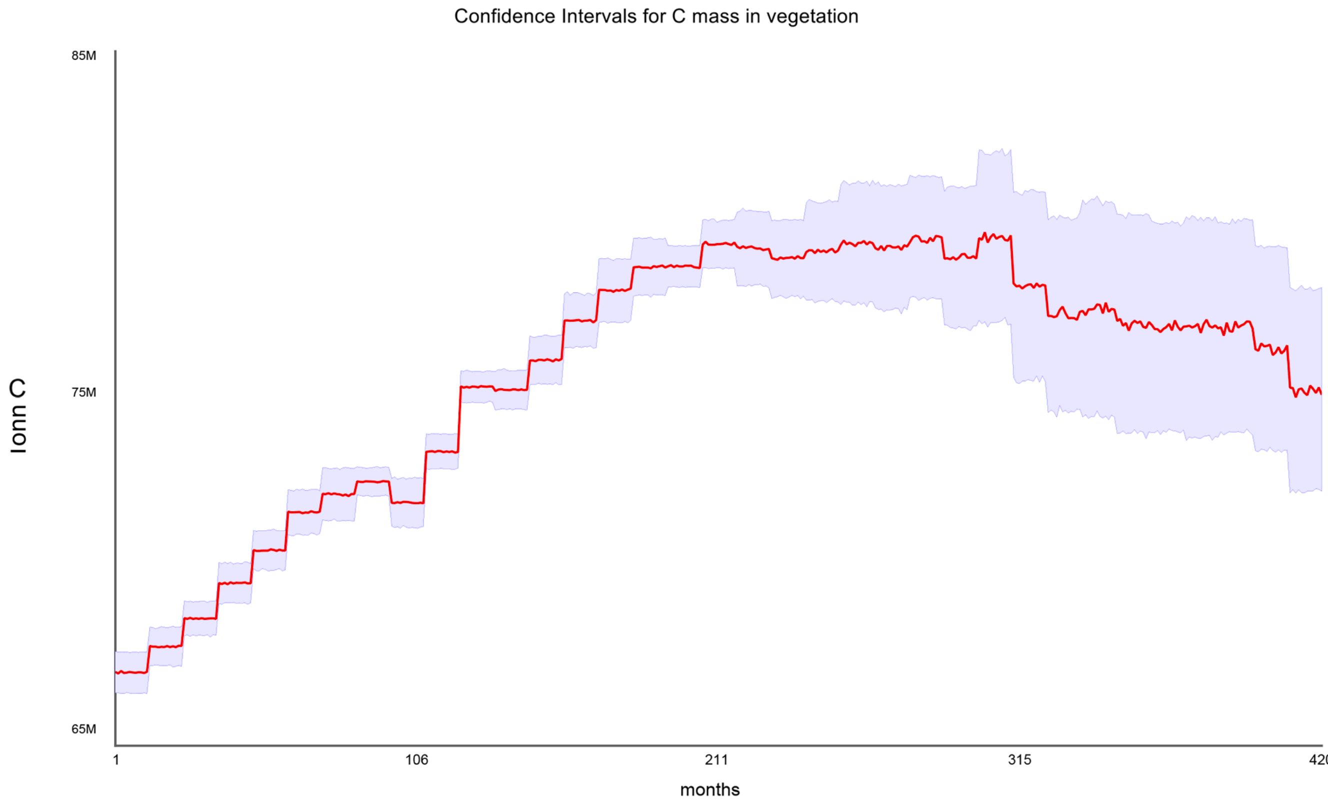

Fig. 7. Dynamic 90 % confidence interval for carbon mass in vegetation.

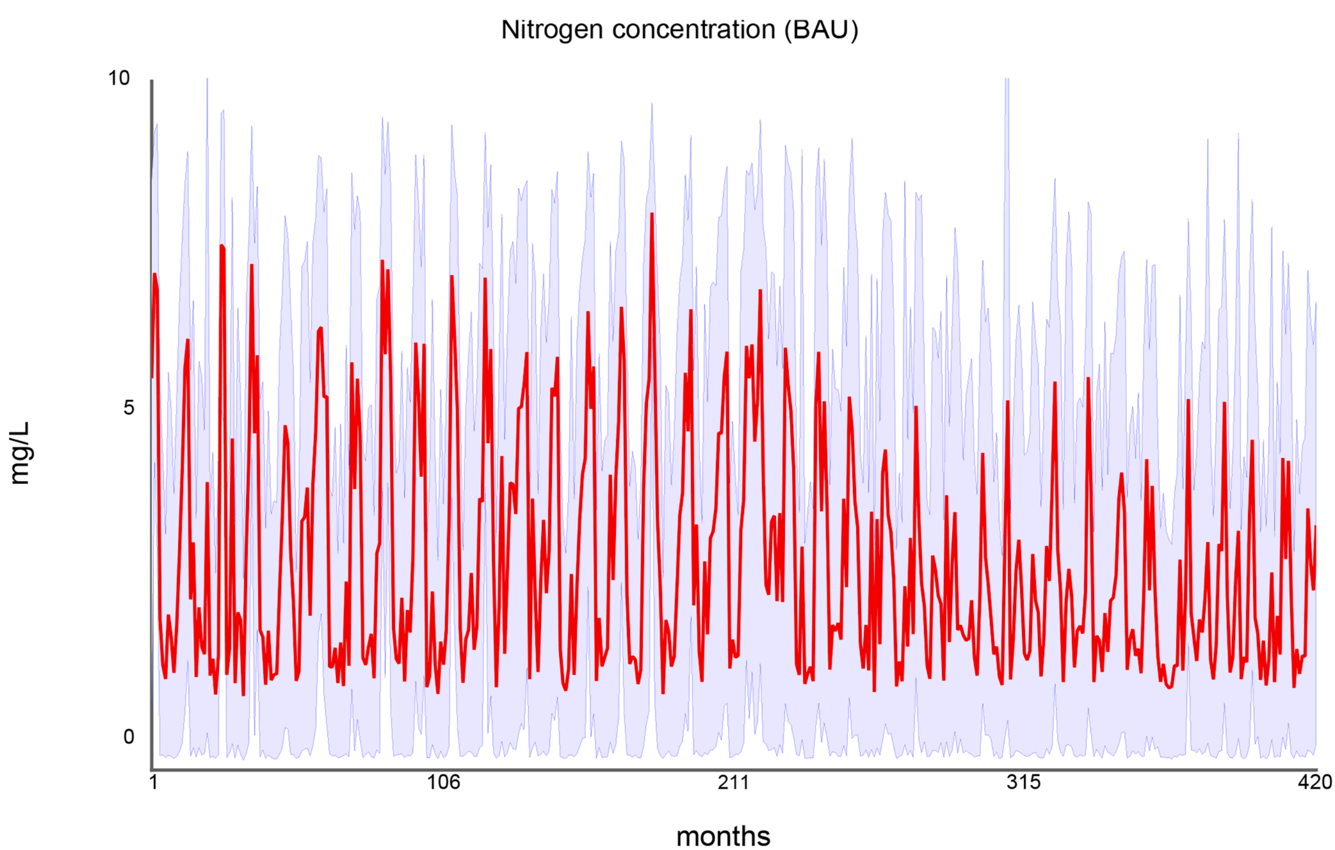

Fig. 8. Dynamic 90 % confidence interval for the nitrate concentration.

Table 4
Key variables' model baseline with a 90 % CI across four decades.

Key variables	Percentile	2020	2030	2040	2050
Total cereal production(1000 ton/ month)	5 %	120	119	120	117
	50 %	194	189	185	201
	95 %	272	257	254	283
Total carbon mass in vegetation (Mton C)	5 %	70.1	77.2	77.0	72.4
	50 %	70.6	78.1	79.0	75.3
	95 %	71.2	79.0	81.1	78.1
Nitrogen concentration(mg/L)	5 %	0.5	0.8	0.8	0.4
	50 %	5.4	6.1	5.2	3.8
	95 %	8.1	8.5	7.9	6.9

3. Results

Here we focus on the policy insights as a product of the PM intervention (Gray et al., 2018). They are derived from implementing Phase III of the PM cycle, that is, using the SD model for policy evaluation. Policy insights arise from two analyses, the first exploring the effect of policy ambition in a transboundary context, and the second, an open policy exploration.

Interested readers and potential users can also explore the model and implement policies using the Nexus Assessment Policy Assessment Tool (NEPAT) (nepat-dev.nexogenesis.eu), a web-based decision support tool that was developed to foster policy dialogues with riparian stakeholders (Echevarría, Dkouk, and Nievas, 2024; Mooren et al., 2025).

3.1. Comparing policy ambition and transboundary cooperation

Combining multiple levels of policy ambition alongside levels of transboundary cooperation offers a rich picture of the policy futures for the Lielupe. The results reported in every grid of the matrix are the key variables' estimates after applying every combination of levels of policy ambition along with the different levels of transboundary cooperation (Table 5). The median and 90 % CI for the key variables were estimated in 1000 simulations of the SD model (see SI Table 12), using a Sobol sequence sampling with the stochastic parameters as summarised in SI Table 10 and 11.

To ease the analysis, Table 7 presents the simulated relative changes and 90 % CI of the key variables for every combination of the distinct levels of transboundary cooperation and policy ambition, compared with the baseline scenario. The table is colour-coded based on the desirability (green- desirable, red – undesirable) of each variable to increase or decrease: for instance, decreasing cereal production is undesirable (red), decreasing nitrogen concentration is desirable (green), and increasing vegetation stocks is desirable (green). The colour code is consistent across the 9 combinations of each variable, showing darker (lighter) colours based on the values with higher (lower) magnitudes. The following paragraphs report on the results, analysing the matrix by rows (level of transboundary cooperation).

A visual inspection of Table 7 shows that bilateral cooperation brings the most marked changes in the variables under consideration. Results exhibit a trade-off between the food sector at the expense of improvements in the water and ecosystems sectors, broadly consistent across a 90 % confidence interval. The total cereal production shows a significant drop in the transition to the decade 2030 for every level of policy ambition. This is due to the policy of grassland expansion, which considers a 10 % grassland transition from arable land by 2030. Additionally, as organic agriculture expands (medium and high levels of ambition), the expected drop in total crop production is steeper, ranging from 12 to 26 % by 2050 (due to the reduced crop yield of organic agriculture, see SI Table 9). The grasslands policy implies a consistent but relatively low increment of the basin's carbon mass in vegetation of ca. 3 %. More ambitious policies show only marginal increments in the basin's vegetation stocks. Nutrient concentration exhibits a gradual decrease as the fraction of land with nutrient control increases. The expected decrease in nutrient concentration exhibits a wide range between -56 and -22 % by implementing (high to low) ambition policies by 2050.

Unilateral actions exhibit the same trends as described in the scenario of bilateral cooperation, yet with differences in magnitude in each riparian country. Considering unilateral actions by Lithuania, the

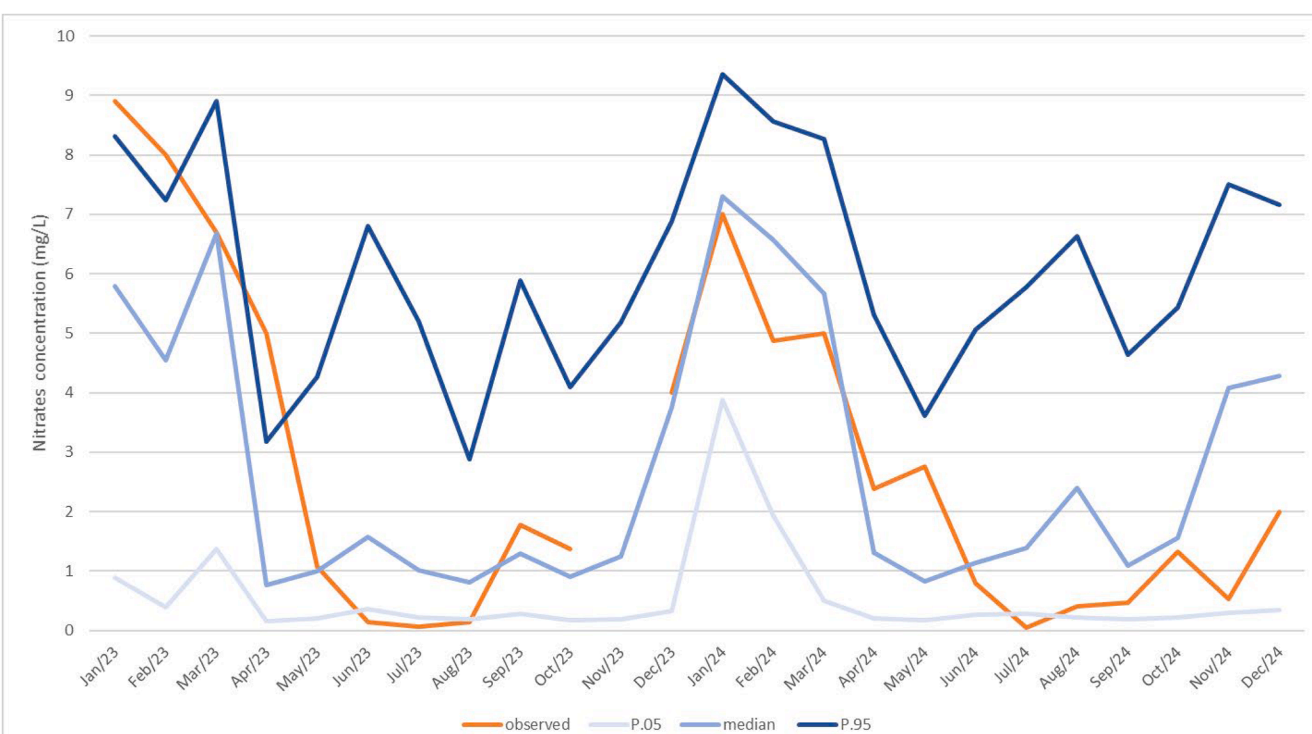

Fig. 9. Observed vs. model outputs - nitrogen concentration.

Table 5
List of policies categorised by policy ambition.

Policies	Description	Policy ambition			
		Null	Low	Medium	High
1. Implementation of nutrient reduction options in arable land	Implementing nutrient reduction options in a fraction of the total arable land (fraction of land with nutrient reduction) by 2050	0	0.25	0.5	0.75
2. Implementing riparian buffers	Implementing riparian buffers to intercept 50 % of the agricultural runoff of the arable land with nutrient reduction (Along with policy 1)	No	Yes	Yes	Yes
3. Implementing constructed wetlands	Implementing constructed wetlands to intercept 50 % of the agricultural runoff of the arable land with nutrient reduction (Along with policy 1)	No	Yes	Yes	Yes
4. Implementing organic agriculture	Implementing organic agriculture in a fraction of the arable land with nutrient reduction	0	0.25	0.5	0.75
5. Conversion of arable land to grasslands	Converting 10 % of the total arable land into grasslands by 2030	No	Yes	Yes	Yes

Table 6
Policies and stochastic ranges considered for an open exploration.

Policies	Description	Range in Lithuania	Range in Latvia
1. Implementation of nutrient reduction options in arable land	Implementing nutrient reduction options in a fraction of the total arable land (fraction of land with nutrient reduction) by 2050	UNIF (0–0.75)	UNIF (0–0.75)
2. Implementing riparian buffers	Implementing riparian buffers to intercept a fraction x of the agricultural runoff of the arable land with nutrient reduction (Along with policy 1)	UNIF(0–1)	UNIF (0–1)
3. Implementing constructed wetlands	Implementing constructed wetlands to intercept a fraction y of the agricultural runoff of the arable land with nutrient reduction (Along with policy 1). Note that the sum of the fractions of riparian buffers (x) and wetlands (y) is equal to 1.	UNIF(0–1)	UNIF (0–1)
4. Implementing organic agriculture	Implementing organic agriculture in a fraction of the arable land with nutrient reduction	UNIF (0–0.75)	UNIF (0–0.75)
5. Conversion of arable land to grasslands	Converting 10 % of the total arable land into grasslands by 2030	[0,1]	[0,1]

expected drop in cereal production at the basin level will be in the range of -13 to -8 % by implementing (high to low ambition) policies by 2050. Similarly, total vegetation stocks are expected to slightly increase in the range of 1–2 % by implementing (low to high ambition) policies by 2050. Nutrient concentration by Lithuanian action is expected to have a reduction in the range of -29 to -11 % by implementing (high to low) ambition policies by 2050.

Unilateral actions in Latvia show a relatively lower effect compared to Lithuanian unilateral action. If Latvia operates in isolation, the expected drop in cereal production at the basin level will be in the range of -12 to -7 % by implementing (high to low ambition) policies by 2050. Similarly, total vegetation stocks are expected to slightly increase by ca. 1 % by implementing (low to high ambition) policies by 2050. Nutrient concentration by only Latvian action is expected to have a reduction in the range of -26 to -6 % by implementing (high to low) ambition policies by 2050.

The simulated changes associated with unilateral actions by either Latvia or Lithuania can be traced to the current land use in the riparian countries. As evidenced in SI Table 1, Lithuania accounts for roughly two-thirds of the basin's arable land. This explains that policies have a more marked effect if taken only in Lithuania compared with Latvia.

Results also indicate that unilateral action hampers the effect of long-term ambitious policies in the basin. This is evident by exploring the case of ambitious unilateral action of the riparian countries in the long term. By taking such an approach, Latvia and Lithuania could reach the target of 20 % nitrogen reduction by 2040. In contrast, a scenario of medium ambition and bilateral action would reach the same target in 2030. This suggests that choosing bilateral cooperation over unilateral action can lower the individual burden of riparian actions and achieve water quality objectives faster, in the order of decades.

3.2. *Open policy exploration*

Results of the open policy exploration are compared with the reference baseline. The median and 90 % CI for key variables are presented in SI Table 13. These values were estimated based on1000 simulations of the SD model, using a Sobol sequence sampling with the stochastic policies (Table 6) and parameters (see SI: Table 10 and 11). To ease the analysis, Table 8 presents the expected relative changes and 90 % CI of the key variables.

The results of Table 8 are congruent with the observed behaviour of policies as presented in the previous section (Table 7). That is, even by deploying the policies in a large decision space, water and ecosystem variables show dynamic improvement at the expense of reducing food production in the long term. By deploying the policies presented above, nitrogen concentration is expected to decrease by 29 %, and total carbon mass in vegetation is expected to increase slightly by ca. 2 %. In contrast, total cereal production is expected to drop by ca. 8 %.

However, some differences of magnitude are worth noting in comparison with the previous section. First, the fall in total food production is not as sharp as presented in Table 7 (26 % for ambitious bilateral cooperation). This might be due to considering a wide range of organic agriculture implementation, not forcing it to be as high as presented at the ambitious policy level (see Table 7). Second, a reduction of 29 % in nitrogen concentration for 2050 aligns with the scenario of medium bilateral cooperation in 2040.

To complement the previous analysis, which focused on tracking the temporal evolution of the key variables, Table 9 shows summary statistics to track the effect of policies considering the whole simulation timespan. These results are overall consistent with previous analyses (see Tables 7 and 8), highlighting the synergies between nitrogen concentration and carbon mass in vegetation, with a trade-off for total cereal production. Yet, new insights emerge from analysing the standard deviation of the key variables. For cereal production, there is a slight reduction in variability, possibly linked to reductions in arable land. For carbon mass in vegetation, the variability increases; this can be

Table 7
Relative change of key variables for every combination of transboundary cooperation and policy ambition, compared with a baseline scenario.

Level of transboundary cooperation	Variables	Perc.	Low 2020	Low 2030	Low 2040	Low 2050	Medium 2020	Medium 2030	Medium 2040	Medium 2050	High 2020	High 2030	High 2040	High 2050
Bilateral	Total cereal production	5%	-2.4%	-13.9%	-12.5%	-11.8%	-8.1%	-13.5%	-18.2%	-22.4%	-8.3%	-20.1%	-24.8%	-22.1%
		50%	-2.2%	-11.0%	-9.8%	-12.2%	-3.2%	-13.6%	-15.9%	-18.2%	-7.5%	-19.5%	-21.9%	-26.3%
		95%	-4.2%	-8.2%	-10.7%	-10.6%	-4.4%	-13.0%	-15.7%	-16.5%	-8.0%	-16.5%	-22.7%	-25.6%
	Total carbon mass in vegetation	5%	1.1%	2.6%	2.6%	2.8%	1.2%	2.9%	2.9%	2.9%	1.3%	3.0%	3.1%	3.2%
		50%	1.2%	2.7%	2.7%	2.6%	1.1%	2.9%	2.9%	2.7%	1.3%	3.1%	3.1%	3.0%
		95%	1.1%	2.9%	2.5%	2.7%	1.1%	3.1%	2.8%	3.0%	1.2%	3.2%	3.0%	3.1%
	Nitrogen concentration	5%	9.3%	-14.9%	-6.3%	-19.8%	-7.3%	-31.9%	-25.6%	-34.8%	-17.6%	-27.1%	-52.2%	-52.7%
		50%	-3.4%	-10.3%	-19.9%	-22.4%	-7.1%	-20.7%	-35.9%	-35.6%	-11.5%	-30.5%	-55.9%	-56.2%
		95%	-0.9%	-9.6%	-18.0%	-16.5%	-4.4%	-18.1%	-31.7%	-33.7%	-11.2%	-29.1%	-47.6%	-49.0%
Unilateral (Lithuania)	Total cereal production	5%	-5.4%	-9.1%	-7.5%	-8.3%	-3.2%	-6.5%	-11.1%	-13.1%	1.1%	-7.6%	-13.6%	-12.2%
		50%	-2.4%	-5.1%	-5.8%	-6.3%	-1.7%	-6.7%	-8.3%	-9.5%	-1.9%	-9.1%	-9.7%	-12.2%
		95%	-2.3%	-3.4%	-5.7%	-6.1%	-3.0%	-4.9%	-6.8%	-7.0%	-1.9%	-7.5%	-9.7%	-10.8%
	Total carbon mass in vegetation	5%	0.6%	1.6%	1.6%	1.5%	0.6%	1.7%	1.7%	1.7%	0.7%	1.7%	1.7%	1.8%
		50%	0.6%	1.6%	1.6%	1.4%	0.7%	1.7%	1.6%	1.6%	0.7%	1.7%	1.8%	2.0%
		95%	0.6%	1.7%	1.5%	1.6%	0.6%	1.8%	1.5%	1.6%	0.6%	1.9%	1.7%	1.8%
	Nitrogen concentration	5%	17.7%	-19.9%	-4.9%	-3.5%	16.6%	-16.6%	-9.0%	-19.8%	-5.9%	-27.7%	-13.3%	-26.0%
		50%	-1.0%	-4.7%	-11.7%	-10.8%	-5.1%	-9.1%	-19.6%	-18.8%	-6.0%	-16.3%	-29.0%	-28.7%
		95%	-0.2%	-5.1%	-11.2%	-8.2%	-2.5%	-8.4%	-18.0%	-18.9%	-4.9%	-14.1%	-25.7%	-26.4%
Unilateral (Latvia)	Total cereal production	5%	-3.3%	-5.9%	-6.0%	-9.1%	0.4%	-6.9%	-6.8%	-7.3%	-0.4%	-6.3%	-10.1%	-12.0%
		50%	-1.3%	-5.6%	-3.3%	-5.7%	-1.4%	-4.5%	-4.6%	-5.8%	-0.5%	-6.2%	-4.8%	-8.7%
		95%	-1.2%	-4.0%	-4.9%	-6.2%	-3.2%	-5.4%	-6.4%	-5.8%	-3.9%	-6.2%	-6.3%	-7.2%
	Total carbon mass in vegetation	5%	0.5%	1.2%	1.1%	1.2%	0.5%	1.2%	1.3%	1.2%	0.5%	1.3%	1.4%	1.5%
		50%	0.5%	1.2%	1.1%	1.0%	0.5%	1.3%	1.2%	1.0%	0.5%	1.3%	1.3%	1.3%
		95%	0.5%	1.3%	1.2%	1.2%	0.5%	1.3%	1.2%	1.3%	0.5%	1.4%	1.3%	1.6%
	Nitrogen concentration	5%	5.6%	-17.8%	10.6%	-7.5%	-11.8%	-22.2%	-19.8%	-11.5%	-13.1%	-16.4%	-22.2%	-25.7%
		50%	-2.2%	-5.5%	-8.6%	-7.1%	-5.2%	-7.8%	-14.3%	-13.1%	-2.3%	-10.5%	-22.7%	-25.7%
		95%	-1.1%	-3.9%	-9.1%	-6.0%	-0.3%	-6.6%	-12.6%	-14.4%	-4.3%	-10.2%	-20.0%	-19.3%

explained from policies exploring the substitution of arable land—a land use that does not contribute to this variable— for grasslands and NbS (e.g. wetlands and riparian buffers)—land uses that bring (stochastic) benefits in terms of carbon in vegetation. Notably, there is also a significant decrease in nitrogen concentration. This is an important finding, as it shows that the policies under consideration—which are strongly focused on nutrient control—would be effective not only to decrease nutrient concentration but also to reduce its long-term variability. Our exploratory analysis, therefore, demonstrates that deploying policies 1 to 5 (Table 6) offers significant and quantifiable benefits to improve long-term water quality in the basin, even under deep uncertainty.

4. Discussion

4.1. Nexus modelling for the Lielupe

This research contributes to ongoing efforts to develop nexus modelling in a participatory way (Pagano et al., 2025; Hurtado et al., 2024) and so responds to recent research calls for a transition towards stakeholder-driven and interdisciplinary nexus research and practice (Sušnik and Staddon, 2021). Using a modelling cycle approach and adopting a nexus perspective, we illustrate a stakeholder-driven pathway from qualitative to increasingly quantitative system tools in exploring plausible futures for the Lielupe river basin. Although we focus on using a simulation model and its results, our structured approach illustrates how a quantitative model can evolve according to stakeholder priorities. Our research experience in the Lielupe followed a

Table 8
Relative change of key variables for an open policy exploration compared with a baseline scenario.

Variables	Perc.	2020	2030	2040	2050
Total cereal production	5%	-1.2%	-8.2%	-10.0%	-12.6%
	50%	-2.3%	-5.2%	-7.1%	-8.4%
	95%	-3.1%	-4.7%	-7.0%	-9.0%
Total carbon mass in vegetation	5%	0.3%	0.4%	0.7%	0.9%
	50%	0.6%	1.5%	1.6%	1.4%
	95%	1.0%	2.6%	2.1%	2.2%
Nitrogen concentration	5%	4.3%	-31.1%	-17.7%	-37.1%
	50%	-5.2%	-14.1%	-26.4%	-28.6%
	95%	-3.8%	-12.2%	-20.5%	-20.6%

Table 9
Summary statistics for the model's key variables over the simulation timespan, taking the median values of 1000 model simulations in two scenarios: baseline and open exploration.

Summary statistics	Total cereal production(1000 ton/month)			*Total carbon mass in vegetation(Mton C)*			*Nitrogen concentration (mg/L)*		
	BL	*OE*	*Relative change*	BL	*OE*	*Relative change*	BL	*OE*	*Relative change*
Mean	199.3	185.8	-7.3 %	75.8	76.7	1.2 %	2.9	2.4	-18.4 %
Median	194.7	179.8	-8.3 %	77.2	78.3	1.5 %	2.0	1.6	-26.7 %
Standard Deviation	22.1	21.5	-2.4 %	3.7	4.0	8.4 %	2.1	1.8	-12.2 %
Minimum	160.1	154.3	-3.8 %	67.1	67.1	0.1 %	0.8	0.6	-30.4 %
Maximum	274.5	264.2	-3.9 %	79.7	81.0	1.6 %	8.2	7.7	-6.5 %

BL = Baseline, OE = Open exploration.

path that started from a generic WEFE systems representation and culminated in a more focused nexus problem. This resonates with a basic, but often neglected principle in System Dynamics, in which the epistemic purpose of modelling is not to represent a system *per se*, but rather a problem from a systemic perspective (Sterman, 2000, pp. 89). The participatory modelling approach led to the exploration of policies to address the wicked problem of nutrient pollution by focusing on assessing synergies and trade-offs across three main nexus sectors: water, food and ecosystems—with a strong emphasis on water quality.

Our results show both synergies and trade-offs across nexus sectors in the Lielupe river basin. Generally, alternatives that favour nutrient concentration reduction (water sector) have a minor benefit in the basin's vegetation stocks (ecosystems sector), yet reduce food production (food sector). This means that environmental benefits come at a cost, a common-sense economic finding. We found that implementing solutions for nutrient control (NBS, organic farming, and arable land reduction) reduces crop production. This comes from two factors: first, from the expected drop in crop yield from organic farming (Meemken and Qaim, 2018), and second, from the land-use trade-offs required to build the NBS or to transition to other landscapes such as grasslands (Trodahl, Jackson, Deslippe, and Metherell, 2017). It is worth noting that the first factor is limited by our approach of modelling crop yields exogenously rather than endogenously, which would imply estimating yield as a function of soil quality. Other research has found that considering soil quality allows for a counterfactual scenario in which organic practices promote the preservation of a relatively high yield versus a scenario of long-term yield reduction due to soil degradation (Rashidian et al., 2025). Despite this limitation, our model covers a wide range of climate change-driven crop yield projections, an essential feature for performing exploratory analysis. The second factor of land-use trade-offs is modelled endogenously; such a modelling feature provides wide analytic capabilities and further insights about the scale of change that is needed to achieve local sustainability goals.

Overall, our results illustrate nexus synergies between water and ecosystems, but also a trade-off —a cost — that will likely affect the food sector. Yet, such a cost is relatively minor compared to its expected benefits. Deploying an open policy exploration analysis on the nutrient control options shows that achieving a nutrient concentration reduction of 30 % would imply a reduction of <10 % in food production, with a 1.5 % increase in vegetation stocks. These findings are in line with previous research highlighting the role of wetlands in addressing the trade-off between water quality and crop production (Cheng, Van Meter, Byrnes, and Basu, 2020; Matsuzaki et al., 2019) and with recent modelling experiences developed in Latvia highlighting trade-offs across food and ecosystems sectors (Sušnik et al., 2021). Although we consider a trade-off between organic farming practices and crop yield based on authoritative meta-analyses (Meemken and Qaim, 2018; Tuomisto et al., 2012), recent evidence suggests that implementing organic farming-related practices may maintain crop yield over the long term whilst providing biodiversity benefits (Berger et al., 2025). As this is a complex and contextual problem (Seufert and Ramankutty, 2017), future studies—both empirical (e.g. Berger et al., 2025) and model-based (e.g. Paturu and Varadarajan, 2025; Rashidian et al., 2025) —are necessary to better understand the potential long-term synergies and co-benefits of practising organic farming in terms of crop yield and biodiversity in the Lielupe and in the wider Baltic Region. Significantly reducing nitrogen concentration in the Lielupe requires large-scale and long-term cooperation in the basin. By cooperating, basin-scale benefits are achieved a decade faster and with 25 % less individual effort compared to a scenario in which one riparian country acts and the other remains idle. Limits to scale are related to the nitrate reduction efficiency of the NBS systems, which is about 50 %. This means that even by controlling all agricultural runoff using NBS as end-of-pipe treatment, aiming for nitrate reductions above 50 % would require focusing on reducing nitrogen inflows, instead of only outflows (Galloway, Bleeker, and Erisman, 2021). Such alternatives include lowering the use of fertilisers (e.g., organic agriculture) or transitioning to other land uses (e.g., grasslands). Additionally, a long-term perspective is needed due to the NBS project's construction lead times and the basin's natural nitrogen accumulations. Nietch et al. (2024) recently reported that the design and construction of an advanced constructed wetland system of 55 ha took 11 years. Likewise, natural basin accumulations that delay nitrogen transport from fields to water bodies are in the range of 4–20 years (Dessirier et al., 2023; Melland, Fenton, and Jordan, 2018; van Meter and Basu, 2017; Vervloet, Binning, Borgesen, and Hojberg, 2018). This research engages with modelling and communicating these uncertainties and delays to stakeholders. We therefore contribute to helping prevent unrealistic and short-term expectations that can dominate nutrient policies at the river basin, national, and regional scales (Baltic Sea Centre, 2024; Basu et al., 2022; Meadows, 2008; Petersen, Blicher-Mathiesen, Rolighed, Andersen, and Kronvang, 2021).

Remarkably, intercepting a high proportion of the total agricultural runoff using NBS is not a land-intensive alternative. For instance, Nietch et al. (2024) recently reported a wetland to drainage area ratio of 1 % for a wetland treatment system in the US, an estimate in line with other modelling exercises (Castellano, Archontoulis, Helmers, Poffenbarger, and Six, 2019). Our results suggest that significant long-term reductions in nitrogen concentration (ca. 35 %) can be reached if half of the total basin's agricultural runoff has nutrient control. This means, for instance, that the effective land devoted to constructed wetlands would be roughly equivalent to 0.5 % of the current Lielupe's arable land area (ca. 40,000 ha). Coming from an SD approach, these figures are aggregated and not spatially explicit. Thus, results may not be interpreted as if a large-single nutrient control intervention should be the only way forward to improve water quality in the Lielupe. On the contrary, significant water quality improvements at the river basin level are likely to be realistically achievable as the sum of many small-scale initiatives across the Lielupe's arable land area (for instance, across half of the farms in the basin) (Jacobsen, Anker, and Baaner, 2017).

4.2. Beyond the model: local trends and perspectives on a more sustainable future for the Lielupe

Local advances in the basin signal that this might be a plausible future in the basin. A first wave of constructed wetland pilots has already been built and is constantly monitored to assess the system's nutrient reduction efficiency (Grinberga, 2022; Lagzdiņš, 2025). Very recently, in April 2025, the Latvian Ministry of Agriculture announced the allocation of a 4 M Euro budget to build new constructed wetlands (Latvijas Sabiedriskais medijs, 2025). According to a local expert, this budget may allow for building around 40 new wetlands (ca. 100k Euro per wetland) (Lagzdiņš, 2025). Following the budget allocation, deciding how to distribute such land and the design of the NBS is not a trivial task. It would require the involvement of multi-stakeholders (e.g. farmers, landowners, government officials, academics and NGO representatives) and should be informed by multiple fields of knowledge (e.g., landscape architecture, civil and environmental engineering, economics, management, law, sociology, and others).

An important dimension that can inform the decision-making after establishing land requirements for NBS is to develop an economic evaluation of nutrient control policies. A first approach would imply developing a whole life-cycle economic evaluation of the NBS transition, including capital costs (e.g., cost of purchasing plots to build NBS and construction costs) and maintenance costs discounted to present value (Chairat and Gheewala, 2024; Nietch et al., 2024). Further, a more comprehensive evaluation can include environmental benefits alongside financial costs (Alshehri, Harbottle, Sapsford, Beames, and Cleall, 2023). Despite this being a complex and fuzzy task, it can be done using simulation models, like the one proposed in this article, that dynamically consider locally relevant environmental variables and their response to policy alternatives (e.g., nitrogen concentration and carbon mass in vegetation) (Alshehri et al., 2023; Chairat and Gheewala, 2024; Sušnik, Masia, Kravčík, Pokorný, and Hesslerová, 2022). Other options to help quantify environmental benefits include preventing the payment of economic penalties due to unmet water quality objectives under international agreements, such as the Water Framework Directive (Kallis and Butler, 2001; Martin-Ortega, 2012). Likewise, increasing vegetation stocks and restoring fluvial and delta ecosystems can be associated with a broad set of services, such as provisioning, regulating, and cultural (Maseyk, Mackay, Possingham, Dominati, and Buckley, 2016; Riis et al., 2020) and even be connected to financial schemes such as payment for ecosystem services (Salzman, Bennett, Carroll, Goldstein, and Jenkins, 2018), though care would need to be taken so as not to 'commodify' ecosystems (Wunder et al., 2020).

Despite this being a promising way forward, it is one likely to face resistance. All across Europe, powerful farmer groups, often representing the interests of large-scale actors, have been actively opposing environmental policies in recent years (van der Ploeg, 2020). A steep increase in large-scale farming in Latvia at the expense of reducing native grasslands might be an indicator of this situation also taking place in the Lielupe over the 21st century (Melece and Shena, 2018). In such a contested situation, it is safe to assume that farmers and other actors (e.g. academics and government officials) frame agro-environmental issues differently. According to Brugnach et al. (2011), a possible way forward in this context might be to take a negotiation strategy. Following that path could mean that progressive policies and compensation mechanisms are implemented to secure farmers' livelihoods, as they are required to make landscape changes (e.g. implement NBS in their farms) or reduce crop yields (e.g. transition to organic farming) as part of improving the basin's environmental status.

In the scenario of more dialogue taking place, more cooperative strategies could be deployed, such as developing interdisciplinary projects with a strong co-creation focus (see Mooren et al. 2025). Participatory modelling products, such as the one presented in this article—including not only a model but its associated policy insights—can therefore inform local and regional policy dialogues (NEXOGENESIS, 2024, 2025). However, beyond using models to inform policy, PM settings offer other social outcomes. Further research is needed to explore, for instance, how PM settings could promote stakeholder learning and strengthen relationships that potentially inform and facilitate policy transitions in the Lielupe and other basins facing similar issues. Likewise, there is a need for more research into the PM processes that underpinned the development of the products presented in this paper. A deeper understanding of how to develop successful participatory approaches that not only inform but also facilitate sustainability transitions in river policy represents a promising avenue for both researchers and policymakers.

Implementing such transitions becomes increasingly complex in a transboundary setting. Yet here we showcase some of the benefits of taking a cooperative approach to improve water quality in the basin. Active cooperation can, therefore, be considered an incentive for both riparian countries to achieve currently unmet WFD objectives (Albiac, Calvo, and Esteban, 2024). Establishing cooperation mechanisms from relatively small technical scales to a high political level is needed to promote equitable achievement of water quality objectives in the basin (Milman et al., 2020; Schmeier and Shubber, 2018). Technical cooperation can be done via multiple initiatives, such as piloting NBS in both countries and even by establishing a joint water quality monitoring programme in the basin. Likewise, political cooperation could be done by creating an international river basin organisation for the Lielupe, with Latvia and Lithuania as new participants of the UN International Watercourses Convention (Gupta, 2016; McCaffrey, 2008). This organisation could coordinate the multi-stakeholder dialogues needed to implement a large-scale and long-term nutrient control strategy in the transboundary basin. Despite such broad potential, the Lielupe and other agrarian transboundary river basins have yet to reap the long-term benefits of such wide and cross-level international cooperation.

5. Conclusion

In this article, we present a model-based operationalisation of the Water-Energy-Food-Ecosystems (WEFE) Nexus approach in a transboundary river basin. The application is illustrated in the context of a transboundary and collaborative stakeholder setting to explore locally relevant policies for the Lielupe, a river basin shared between Latvia and Lithuania. By applying a model-based policy analysis framework, we showed how various stakeholder-driven milestones contributed to developing a System Dynamics simulation model that helps explore long-term WEFE policy alternatives in the basin. The results of the model offered insights regarding the long-term effects of land-use transitions in the Lielupe River basin from two analytic perspectives: the first, by exploring the effect of policy ambition in a transboundary context; and the second, via an open policy exploration. More specifically, here we illustrated three policy levers useful to understand the long-term impact and cascading effects of transitioning from an intensive agriculture landscape to a more *natural* land use in the basin: implementing nature-based solutions (NBS) to control nutrient diffusion in the basin; reducing arable land to extend native grasslands; and implementing organic agriculture.

Transitioning to an agricultural landscape that uses NBS to control nutrient pollution is a promising alternative, provided it is implemented at a large, basin scale. The larger the arable land fraction with nutrient control alternatives, the higher the expected reduction of nitrogen concentration in the basin. Yet, this comes with a relatively minor trade-off in food production —a finding which further empirical and model-based research on food production could quantify further. Our modelling results imply that the basin-scale effect of implementing NBS alternatives to reduce nitrogen concentration depends on both technical and socio-political factors. On the technical side, we explored how the intrinsic variation of nitrogen removal efficiency of the NBS systems, as well as future river flow variability, propagate into uncertainty in reaching nitrogen reduction objectives in the basin. Despite such uncertainty, results suggest that large-scale use of NBS to control nutrient pollution is a policy that exhibits robustness in meeting objectives to improve water quality in the basin in the long term. From a socio-political perspective, we showed that taking unilateral actions to improve water quality in the basin is insufficient. In contrast, by taking cooperative actions, each country enhances the efforts of its counterpart, which is translated into lower individual investments and faster achievement of objectives compared to a scenario of unilateral action.

A more radical alternative in terms of land-use change is reducing arable land to increase grasslands in the basin. Reducing arable land can lead to a long-term reduction in agricultural nitrogen loads in surface water, as the nitrogen stock in the soil will begin to deplete due to the absence of further fertiliser application. Replacing arable land with grasslands also offers the benefit of increasing carbon vegetation stocks, with potential wider biodiversity benefits in the basin. Changing land-use in this way leverages synergies across the *Ecosystems* and *Water* sectors, yet with important trade-offs in the *Food* sector. Agriculture degrowth has direct benefits in terms of water quality and ecosystems. However, this is a costly alternative as productive lands are expensive. Just as with implementing NBS, both biophysical and socio-political factors play a role in achieving the intended benefits derived from increasing grasslands in the basin. From a biophysical perspective, an important point to consider is the long-lasting nutrient leaching from agricultural fields, which persists for years after cropping activities have stopped. We also demonstrated high uncertainty in trying to account for the potential effects of increasing vegetation stocks and animal biodiversity. Likewise, socio-political factors drive key future decisions regarding the extent of agricultural degrowth and whether such initiatives happen unilaterally or in cooperation with other riparian countries.

We present a broad account of the model capabilities and results of a simulation model for a transboundary setting. The model integrates WEFE nexus sectors in the basin but keeps a distinction between upstream and downstream countries, accounting for their asymmetrical relationship. This modelling strategy, exhibiting both joint and decoupled features, offers opportunities for future research in the field of modelling and policy analysis. Future SD models can adapt this strategy to other transboundary basins, aiming to reflect challenges that were not accounted for in this article (e.g. water scarcity and floods). In the field of policy analysis, new studies can explore how this model, or similar participatory modelling applications, might be useful in enhancing and providing learning opportunities for stakeholders in the context of transboundary WEFE policy dialogues. Here we show how integrating biophysical and socio-political dimensions provides analytic opportunities to enhance transboundary resource dialogues. By exploiting these capabilities, riparian stakeholders may use co-created simulation models to facilitate dialogue and even negotiate their role in solving resource nexus challenges in transboundary river basins.

CRediT authorship contribution statement

Henry Amorocho-Daza: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Janez Sušnik:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Jill H. Slinger:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Pieter van der Zaag:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Janez Susnik reports financial support was provided by European Union Horizon 2020 research and innovation programme. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2025.111417.

Data availability

The model file and data are described and presented in the SI section

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