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NEXOGENESIS
STREAMLINING WATER RELATED POLICIES

D3.7 Final report on the WEFE Nexus Index methodology and visualisation

Lead : JAWS
Date : August 2024

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

Project Deliverable

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101003881	NEXOGENESIS	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

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Final report on the WEFE Nexus Index methodology and visualisation

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Authors (organisations)
Blaine Haupt (JAWS), Chaymaa Dkouk (EUT), Gareth Simpson (WSP)
Reviewers (organisations)
Alice Harvey (JAWS), Janez Sušnik (IHE)

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Abstract

This deliverable details the Water Energy Food and Ecosystems Footprint's framework, including pillars, sub-pillars, and indicators. Furthermore, it details how the data was treated, normalised, and aggregated. This included selecting weightings, directions, and an approach for data aggregation. Lastly, the deliverable presents a visualisation of the WEFE Footprint.

The WEFE Footprint is comprised of four pillars, with nine sub-pillars and sixteen indicators. The approach to determine the WEFE footprint included the following:

1. Aggregate the indicator data into yearly time steps and treat for outliers.
2. Apply directions to the indicators (positive for all indicators except "Water demand", "Nitrogen concentration" and "Emissions (CO_2 equivalents)").
3. Normalise the indicator data based on the distance of the indicator in "Year n" from the initial indicator value in "Year 0".
4. Aggregate the data using a weighted arithmetic mean approach with equal weights assigned to:
    a. Pillars within the WEFE Nexus Index
    b. Sub-pillars within pillars and
    c. Indicators within sub-Pillars
5. Present the data visually in the form of the WEFE Footprint

The approach above was developed and implemented within the NExus Policy Assessment Tool (NEPAT), available online at https://nepat-dev.nexogenesis.eu/. It includes visualising the WEFE footprint with the assistance of WP4.

All WEFE footprint results/outputs in this Deliverable are representative only to demonstrate that the WEFE Footprint determination and resulting WEFE footprint visualisation are included in NEPAT as of the time of writing.

Keywords

WEFE, Footprint, methodology, indicators, data, visualisation, case studies, nexus, composite indicator

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Disclaimer

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Abbreviations/Acronyms

AGM	*Annual General Meeting*
CLD	*Causal Loop Diagrams*
CS	*Case study*
D	*Deliverable*
DSS	*Decision Support System*
JRC	*Joint Research Centre*
JRC-COIN	*JRC's Competence Centre on Composite Indicators and Scoreboards*
MS	*Milestone*
MSR	*Mean Species Richness*
NEPAT	*Nexus Policy Assessment Tool (previously Self-Learning Nexus Assessment Engine (SLNAE))*
NXG	*NEXOGENESIS project*
OECD	*Organisation for Economic Co-operation and Development*
RCP	*Representative Concentration Pathway*
SDG	*Sustainable Development Goal*
SDM	*Systems Dynamics Model*
SSP	*Shared Socio-economic Pathway*
WEF	*Water-Energy-Food*
WEFE	*Water-Energy-Food-Ecosystems*
WP	*Work package*

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Introduction

During the development of the proposal for the Nexogenesis (NXG) project, the idea of a Water-Energy-Food-Ecosystems (WEFE) Footprint was conceptualised. The vision was to provide an intuitive visualisation of the key outputs associated with the Systems Dynamics Model (SDM) and/or the NExus Policy Assessment Tool (NEPAT), referred to in the Grant Agreement as the Self-Learning Nexus Assessment Engine (SLNAE). This was formalised in the NXG proposal, where it was stated that the "core outcome [of the project] will be a self-learning artificial intelligence nexus assessment engine exploiting reinforcement learning, supporting streamlining water-related policies in the WEFE nexus, *accompanied by a WEFE nexus Footprint"*.

The term "WEFE Footprint" is used herein to refer to the visualisation and underlying "WEFE Nexus Index".

This deliverable details the framework for developing the WEFE Footprint and its associated visualisation. Furthermore, it details the footprint's determination, including the selected normalisation technique, directions, weightings, and aggregation approach.

Purpose

The WEFE Footprint provides a visualisation of the WEFE system's status at a particular point in time for a specific river basin (Case Study [CS]) for a particular modelling scenario. It uses the outputs from the NEPAT, informed by the SDMs, to visualise the nexus for the Reference and Policy Future scenarios.

The Reference Scenario refers to the four combinations of Socio-economic (Shared Socioeconomic Pathway – SSP) and Biophysical (Representative Concentration Pathway – RCP) pathways described in detail in Deliverable 2.1 that are unchanged by policy interventions. A Policy Future scenario relates to a scenario where one or more policies have been applied to a given SSP and RCP to achieve a desired set of goals.

As an outcome of the third WEFE Footprint workshop, held during the General Project Meeting in Riga, the purpose of the WEFE Footprint was described as:

- A tool to communicate the status of each resource sector and their synthesised contribution to sustainability and resource security,
- A means to communicate the integration/aggregation of sectors and any trade-offs, impacts, or conflicts that may exist,
- A tool to demonstrate how governance and policies can facilitate sustainability.

Methodology

As described in MS 14 ("Methodology Associated with Developing the WEFE Footprint"), the inspiration for the WEFE Footprint included the City Blueprint, based on the Blue City Index (Gawlik et al, 2017)[i] and the Water-Energy-Food (WEF) Nexus Index.[iv] MS14 outlined the proposed methodology for developing the WEFE Footprint. The selected methodology for developing the WEFE Footprint was developed by JRC's (Joint Research Centre) Competence Centre on Composite Indicators and Scoreboards (JRC-COIN). This approach was similarly

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used to develop the WEF Nexus Index (Saisana et al., 2018)[ii] The Methodology is centred on the following ten steps(JRC-COIN, 2019)[iii]:

1. Define the concept to be measured;
2. Select the indicators;
3. Analyse and treat the data, where necessary;
4. Bring all indicators onto a common scale;
5. Weight the indicators and dimensions;
6. Aggregate the indicators and dimensions;
7. Assess the statistical and conceptual coherence;
8. Assess the impact of uncertainties;
9. Make sense of the data; and
10. Present the data visually.

WEFE Footprint Framework

Figure 1 provides an outline of the development from data to knowledge and, ultimately, the use of this knowledge to inform policy and decision-making related to NXG. In the context of NXG, Figure 1 indicates how each work package is involved in the process. As indicated, WP2 provided the data to be incorporated into the SDMs and NEPAT, which formed the basis for the WEFE Footprint.

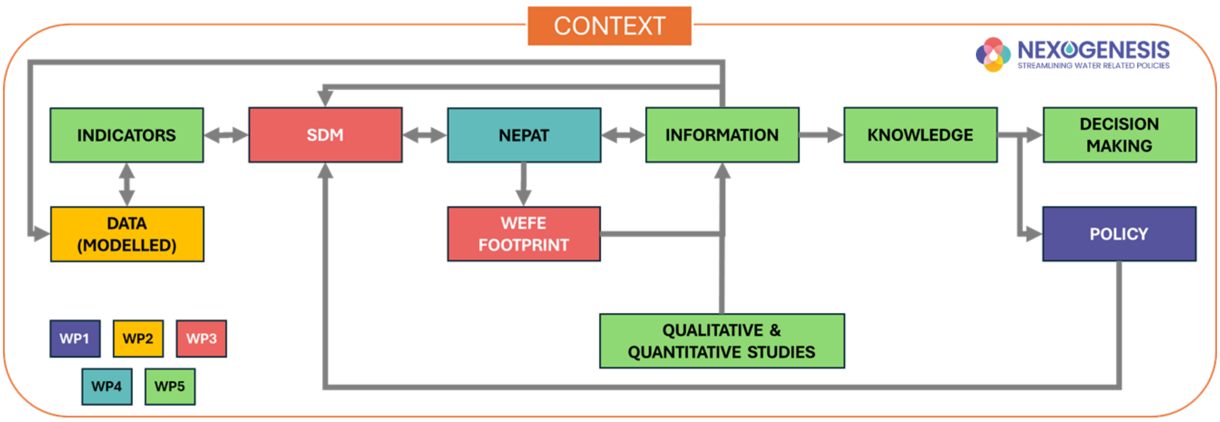

Figure 1: NXG from data to knowledge; Modified from Simpson et al. (2022)[iv], Segnestam (2002)[vi], and Waas et al. (2014)[v]

A composite indicator (or index) forms the basis of the WEFE Footprint. A composite indicator aggregates two or more indicators or data into a single composite measure (Segnestam, 2002)[vi]. The composite indicator behind the WEFE Footprint represents a complex, integrated system, presented in a visualisation per Reference and Policy Future scenario across five case studies over 35 years from 2015 to 2049.

The first step to developing a composite indicator, according to JRC-COIN's ten-step methodology[iii] is to define or develop a framework for the system being assessed. This section details the framework associated with the WEFE Footprint.

During the first WEFE Footprint workshop (20 July 2022), which included representatives from the different work packages and case studies, it was highlighted that the WEFE Footprint must be uniform across all case studies. The WEFE Footprint would comprise the same pillars, sub-pillars and indicators across the five case studies.

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The trade-offs and interdependencies between water, energy, and food have formed the basis for the development of various conceptual WEF Nexus frameworks—emphasising the interlinkages between the three pillars (Simpson et al., 2020).[vii] Leck et al. (2015)[viii] stated that the Bonn conference of 2011:

> *"was a significant catalyst for increased nexus attention from international organisations, the private sector and other major global players."*

During Bonn 2011, the original WEF Nexus framework was presented by Hoff (2011)[ix], presented in Figure 2. This and subsequent WEF frameworks (Conway et al., 2015; Karabulut et al., 2016)[x,xi] have recognised the environment and ecosystems as important drivers of the WEF Nexus. However, ecosystems are seldom recognised as a fourth pillar within the nexus.

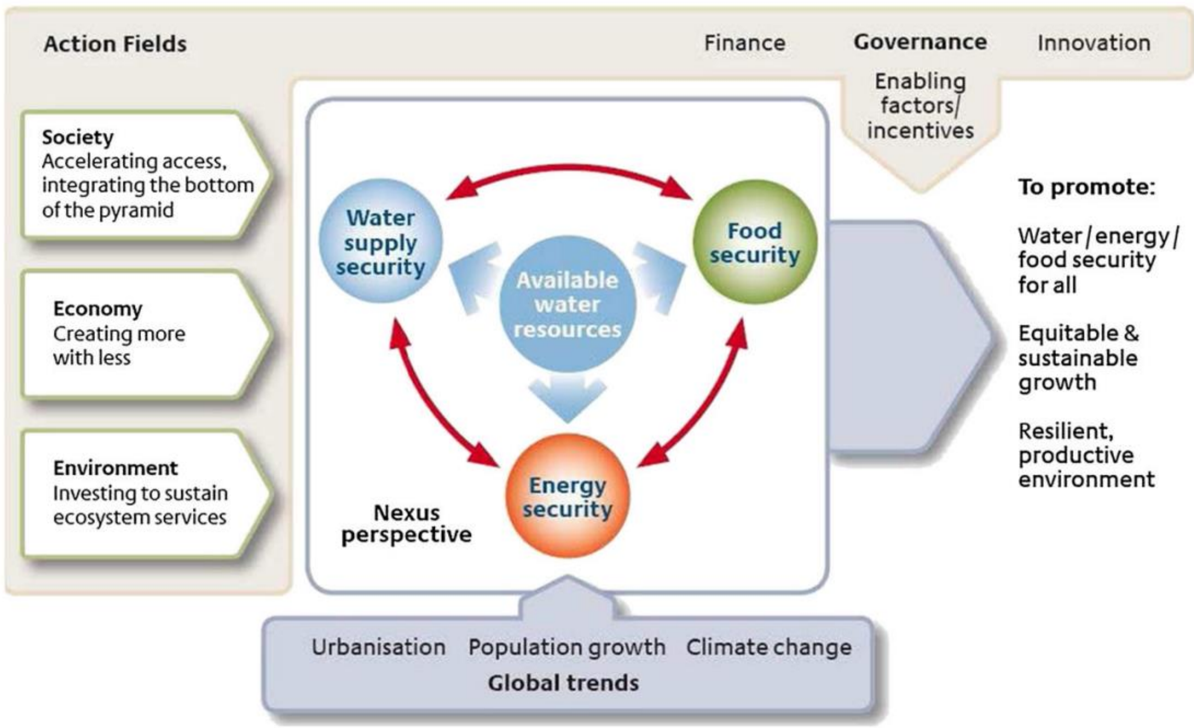

Figure 2: Bonn 2011 Nexus Framework (Liu et al., 2017)[xii]

In the conceptualisation of the NXG project, due to the importance of ecosystems and their interlinkages with the three pillars of the WEF Nexus, it was decided that ecosystems would be considered a fourth pillar within the water, energy, food, and ecosystems (WEFE) nexus. The framework incorporating ecosystems into the nexus is indicated in Figure 3.

The project schematic (including the WEFE Footprint), depicted in Figure 4 was developed during the first NXG Project Annual General Meeting (AGM) held in Riga on 28 September 2022. The schematic was developed in collaboration with the Nexogensis project's Work Package (WP) leaders and stakeholders from the five CSs. It was further presented and discussed during the initial stakeholder engagement sessions held by the CSs. The process details how the policies are integrated into the SDMs and NEPAT and how their impacts on the WEFE Footprint are considered at a river basin level.

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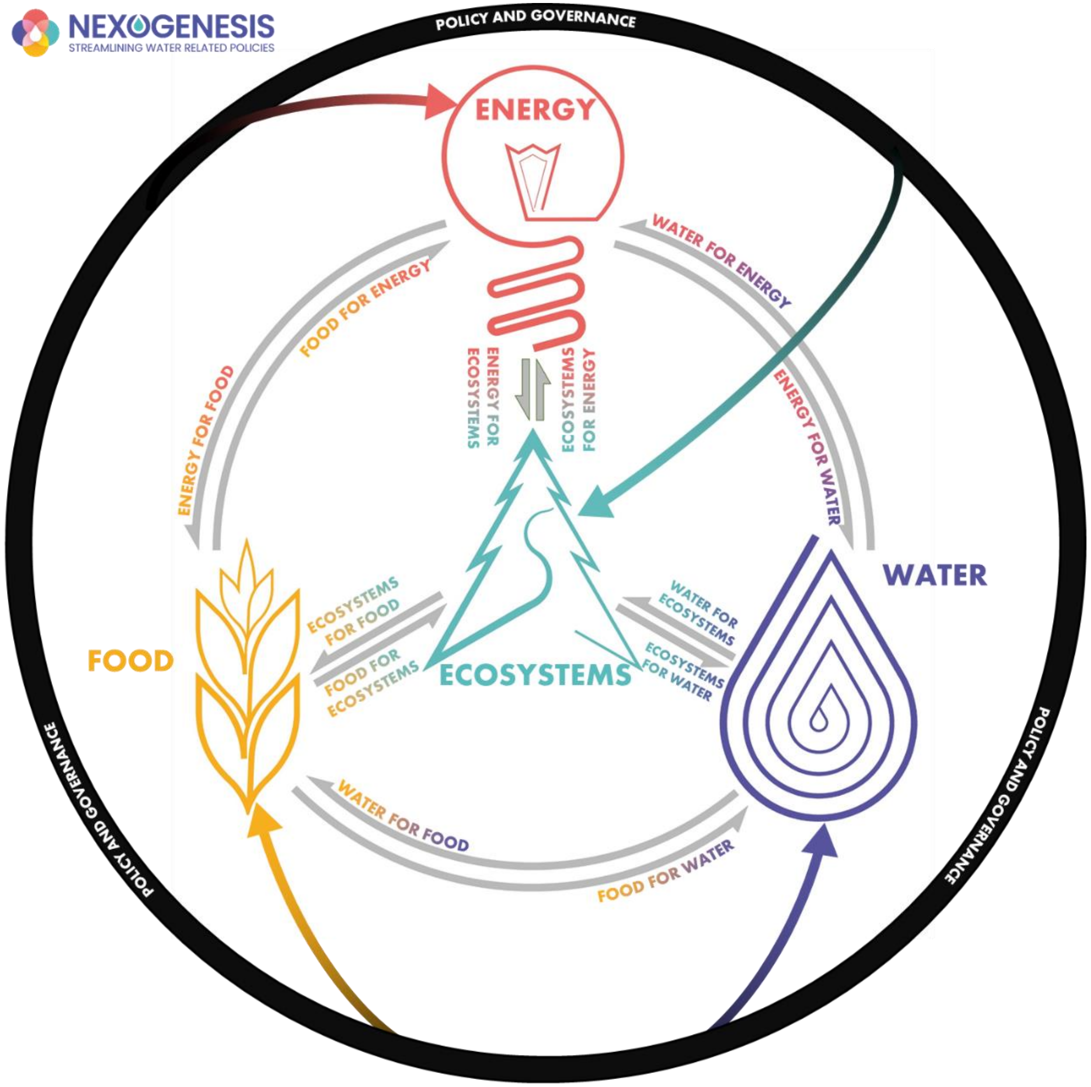

Figure 3: Nexogenesis WEFE Framework.

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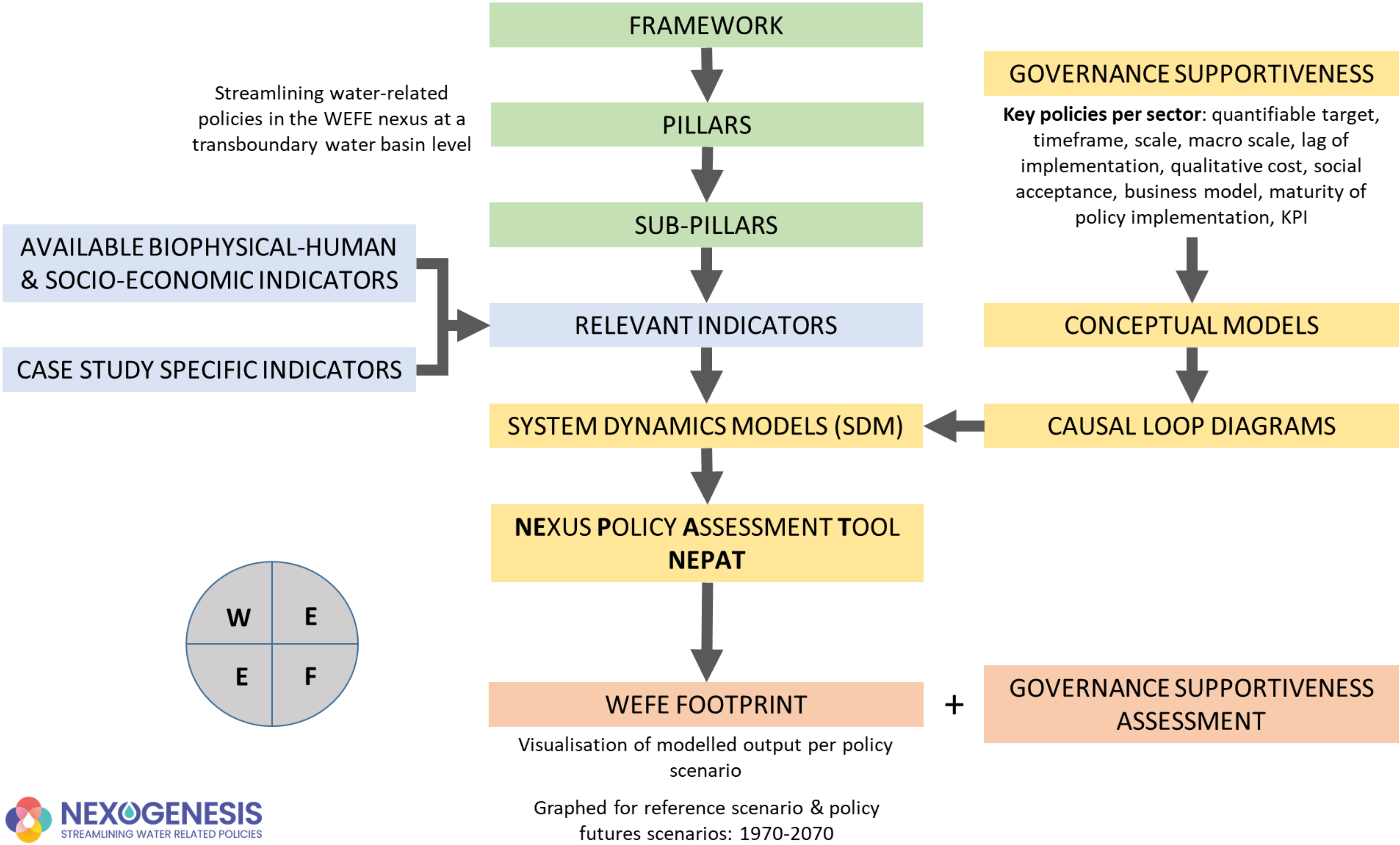

Figure 4: Project schematic developed at the Riga NXG Workshop following the WEFE Footprint focus session

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Due to humanity's exponentially increasing demand for natural resources underpinning the nexus pillars, Simpson et al.[vii] proposed an anthropocentric framework. Inherently linked to humanity's demand for resources is their attempt to manage these natural resources effectively through governance and policy implementation. The process depicted in Figure 4 indicates the approach adopted to incorporate such policies into the SDM and, ultimately, into the NEPAT.

The process began with developing conceptual maps and causal loop diagrams for each CS. Parallel to this, WP2 modelled the biophysical and socio-economic indicators relevant to each CS and each CS, in collaboration with WP1, identified and validated policy packages from each sector that would be implemented into the SDMs and NEPAT.

Following this, WP3 assisted the CSs in developing the SDMs. The SDMs were populated with the data provided by WP2, supplemented with local data from the CS where required. Under the guidance of WP3, each CS quantified the impacts of the validated policy instruments on SDM variables. WP3 incorporated the validated policy instruments into the SDMs using these impacts, which were then provided to WP4. WP4 used the SDMs to develop the NEPAT and its associated Decision Support System (DSS).

The relevant WEFE indicators were included in the SDMs for each CS, and the WEFE Footprint determination, including its visualisation, was incorporated into the NEPAT. The WEFE Footprint visualisation is an output of the NEPAT, which can be used to assess the trade-offs and impacts of alternative policy scenarios.

The following sections of this document detail the process followed to select the sub-pillars and indicators, process the relevant data to develop the composite indicator, and develop the visualisation of the WEFE Footprint.

Pillar, Sub-Pillar, Indicator Selection

Waas et al. (2014) defines an indicator as:

> *"… the operational representation of an attribute (quality, characteristic, property) of a given system, by a quantitative or qualitative variable (for example numbers, graphics, colors, symbols) (or function of variables), including its value, related to a reference value."*[v]

Pillars of the WEFE Footprint

As described in the WEFE Footprint Framework and shown in Figure 3, the WEFE Footprint has four key pillars: Water, Energy, Food, and Ecosystems. Each is considered an equally important pillar of the NEXUS. Under each Pillar, Sub-Pillars and Indicators were selected.

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Sub-Pillar and Indicator Selection Process

The section of indicators, and the aggregation of these indicators into sub-pillars, is a key step in the development of the WEFE footprint. The selection of indicators can be a subjective process and therefore it was important that the process be as rigorous as possible, and involve as many stakeholders as possible.

The selection of indicators to define the WEFE Footprint followed the process described in the following sections.

Review of available variables

The available data was reviewed to identify potential indicators to be included in NXG's WEFE Footprint. This included:

- A list of available modelled socio-economic and biophysical variables (provided by WP2).
- Existing globally available sector-specific indicators from the World Bank and the United Nations.
- Indicators included in existing global composite indicators, such as the WEF Nexus Index.

Workshop 2: WEFE Footprint (Virtual)

The second workshop on the WEFE Footprint was held virtually on 7 September 2022. Using the available variables, representatives of the various WPs and the five CSs identified potential indicators to be included in the WEFE Footprint. One of the workshop's outcomes was a mind map of the potential indicators, Figure 5.

In addition to the mind map, stakeholders attending the workshop highlighted the spatial differences between the globally available indicators and those developed within the NXG project by WP2. Globally available indicators are typically at a country level. NXG and the associated WP2 variables have been derived at a river basin level. Including globally available indicators into the SDM posed a challenge as many were unavailable at a river basin level.

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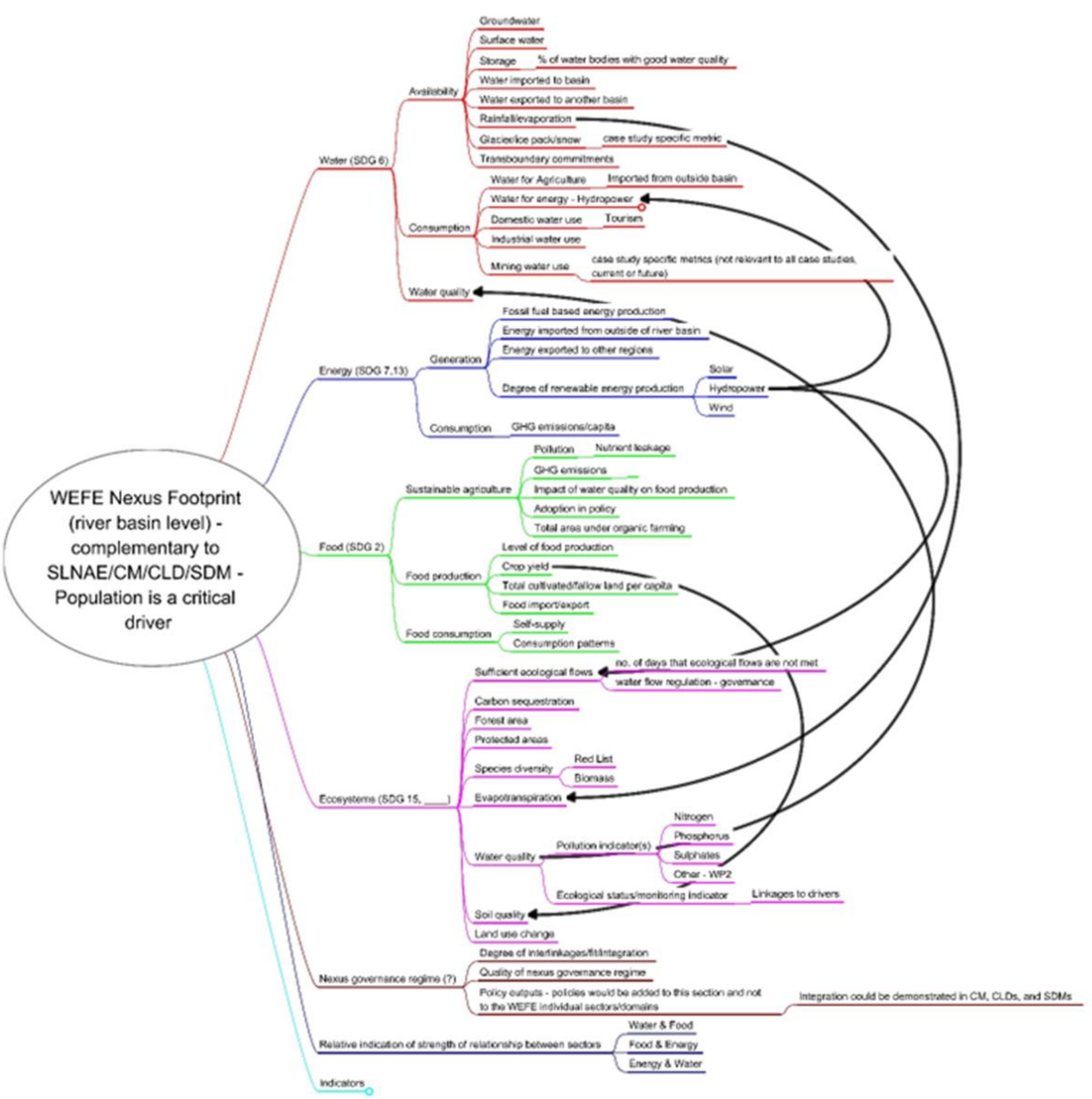

Figure 5: Mindmap of potential indicators (Outcome of Workshop 2)

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Workshop 3: WEFE Footprint (Riga)

A third workshop on the WEFE Footprint was held during the first NXG AGM (27-29 September 2022) in Riga, Latvia. A representative from each CS and WP attended the workshop. In addition to defining the goals of the WEFE Footprint, the potential sub-pillars were identified for each pillar, namely:

- Water
  - Quality;
  - Quantity; and
  - Accessibility.
- Energy
  - Generation;
  - Consumption; and
  - Demand.
- Food
  - Production;
  - Consumption; and
  - Sustainable agriculture.
- Ecosystems
  - Ecological flows;
  - Carbon sequestration;
  - Forestry;
  - Protected areas;
  - Species diversity;
  - Evapotranspiration;
  - Soil quality;
  - Land use;
  - Gross Primary Productivity; and
  - Net Primary Productivity.

The mind map developed during the second workshop was revisited, and potential indicators were linked to the sub-pillars mentioned above. A ‘wish list’ of variables was sent to WP2 for consideration. Including potential sub-pillars and variables in determining the WEFE Footprint would depend on data availability and relevance to the five CSs.

Common SDM variables

Parallel to developing the WEFE Footprint, CSs and WP3 finalised the conceptual maps and causal loop diagrams. Using these as a basis, CSs and WP3 developed the SDMs. Each CS was required to link the SDM variables to the final list of socio-economic and biophysical variables modelled by WP2 during the SDM mapping process.

These SDM maps were used to identify common variables across at least three of the five case studies, with the potential to include the variables in all five CS’s SDMs. The potential sub-pillars defined above were redefined and linked to common indicators, as shown in Figure 6. The common indicators and redefined sub-pillars were presented in a fourth workshop during the second AGM in Tours, France (19-21 September 2023).

Workshop 4: WEFE Footprint (Tours)

During the final workshop on the WEFE Footprint held in Tours on 20 September 2023, the indicators and sub-pillars outlined in Figure 6 were discussed. During the meeting, representatives from the five CSs and various WPs provided inputs into the proposed indicators and sub-pillars. An interactive presentation using Mentimeter software allowed stakeholders to identify potential gaps in indicators and sub-pillars. The results of the Mentimeter presentation are shown in Figure 7.

The outcomes from the interactive presentation informed a final wish list of WEFE Footprint indicators submitted to WP3 SDM modellers.

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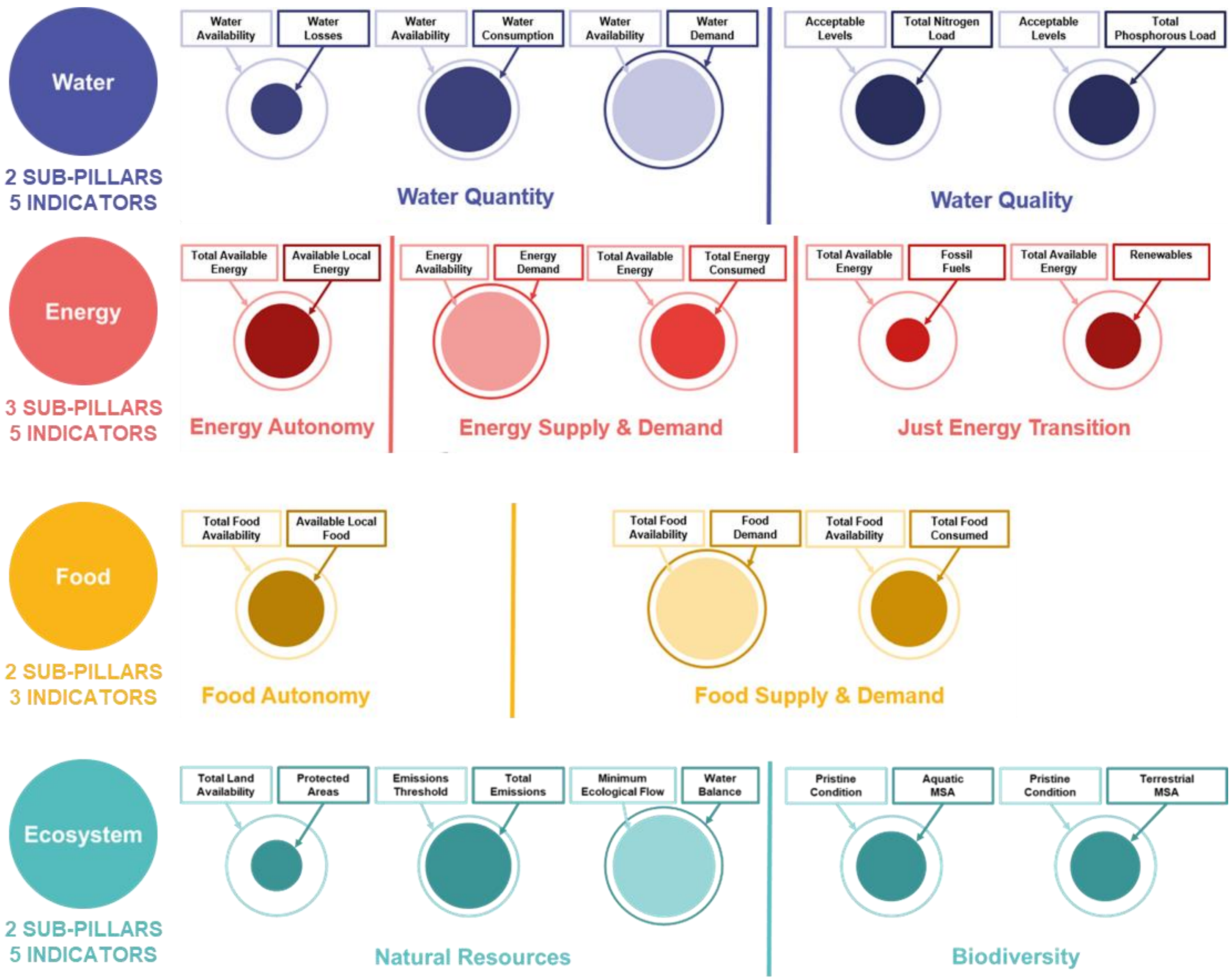

Figure 6: Proposed indicators and sub-pillars following comparison of all five CSs' SDM variables

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Figure 7: Results from Workshop 4 interactive presentation on WEFE indicator gaps.

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Final 'wish list' of WEFE Footprint indicators

The final 'wish list' of indicators determined during the Fourth Workshop and provided to the WP3 SDM modellers is shown in Table 1.

Table 1: Final WEFE Footprint "wish list"

Water		
Water Quantity	**Water Quality**	**Water Access**
Ground water availability	Nitrogen concentration	Access to water
Surface water availability	Phosphates concentration	Access to Sanitation
Water consumption	PH	
Water demand	Total dissolved solids/ electrical conductivity	

Energy	
Energy Quantity	**Energy Access**
Energy supply (Electricity)	Renewable energy consumption
Energy consumption (Electricity)	Emissions (CO_2 equivalents)
Energy demand	Access to energy
Energy imported	

Food	
Food Quantity	**Food Access**
Food production	Prevalence of undernourishment
Food consumption	Prevalence of obesity
Food demand	
Food imports	
Crop per drop	

Ecosystems		
Land Use	**Ecosystems Health**	**Ecosystem Services**
Wetland area	Ecological flows	Wetland Quality
Forest area	Alien species	Aboveground Carbon Mass
Protected area	Aquatic MSA	
	Terrestrial MSA	

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The 'wish list' of indicators was considered during a meeting held in Delft with WP3 and the five CS SDM modelling teams on 11 October 2023. The outcome of the discussions was that the indicators in red in Table 1 were excluded from the WEFE Footprint based on the following reasons:

- Insufficient data to include the indicator in the SDMs of more than one CS;
- No proxy variable available in SDMs to represent the indicator;
- Indicator not applicable to more than one CS.

Final WEFE Footprint

Based on the outcome of the meeting held with the WP3 and SDM modellers, the indicators that would form part of WEFE Footprint were selected and reframed into the sub-pillars indicated in Figure 8.

The Indicators in Figure 8 are not necessarily a true representation of the indicator value for every CS in the entire river basin. However, the Indicators represent the variables included in the SDM for each CS. As an example, the indicator "Emissions CO_2 equivalents" does not include emissions from transportation.

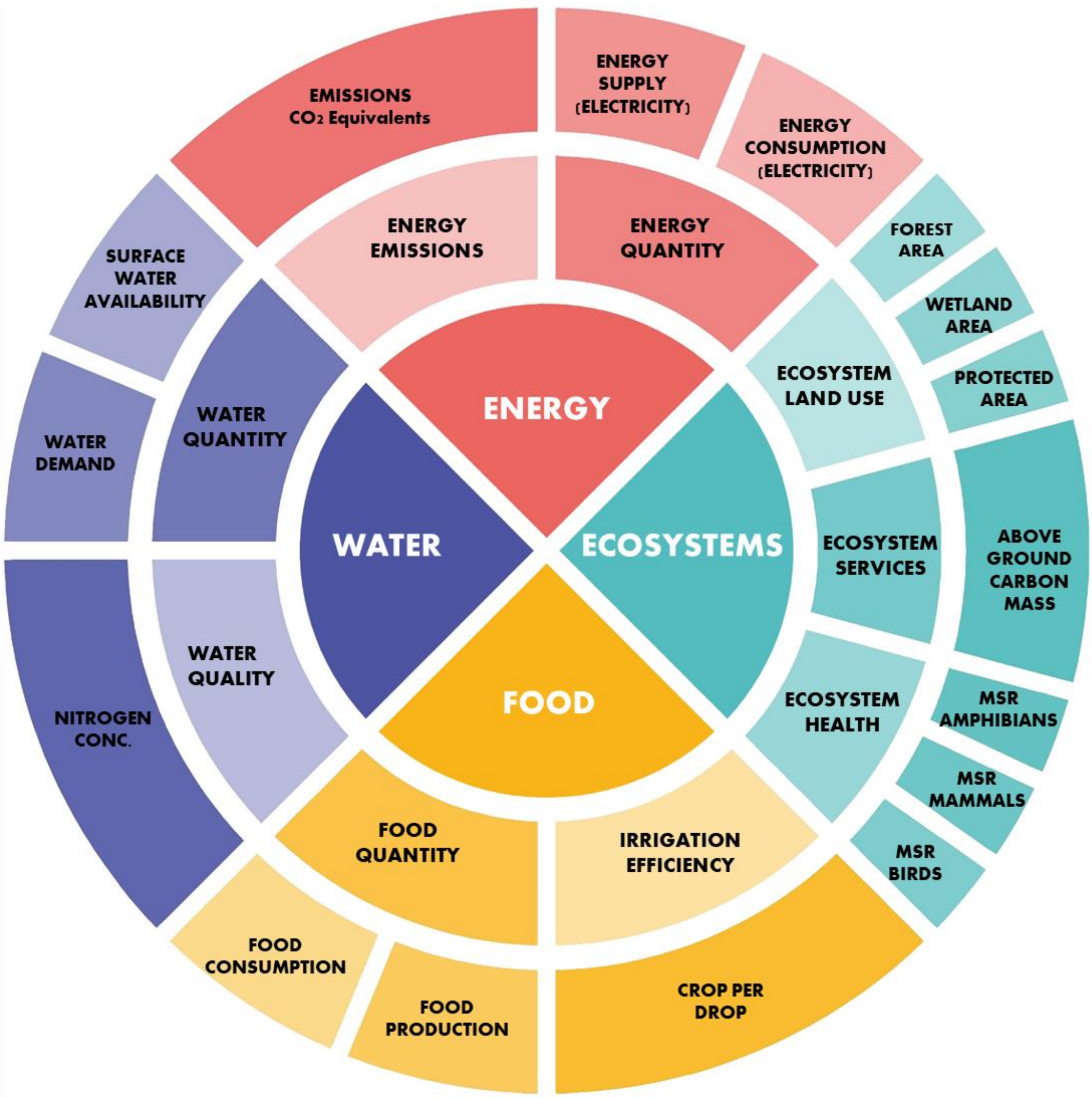

Figure 8: Final WEFE Footprint pillars, sub pillars and indicators

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The selected indicators in Figure 8 can be linked to various Sustainable Development Goals (SDGs). The multi-disciplinary nature of NXG, the multi-stakeholder partnerships being formed, and the technologies being applied within the NXG project align well with SDG 17: Partnerships for the goals. The NXG project is developing tools to assess and communicate the trade-offs and synchronicity between the nexus Pillars as measured by the indicators. Each indicator can be linked to SDGs, and the stakeholder engagement workshops seek to form partnerships to achieve policy outcomes that will positively impact indicators and the nexus. The main SDG associated with each indicator is presented in Table 2.

Table 2: Indicators linked to SDGs

Indicator	Sustainable Development Goal
Surface water availability	SDG 6: Clean water and sanitation – Surface water availability directly influences clean water for consumption, sanitation and irrigation (agriculture). Other related SDGs: 2, 3, 7, 11, 13, 14 and 15.
Water demand	SDG 6: Clean water and sanitation – Responsible water demand management will minimise water scarcity and ensure equitable access to clean water and sanitation. Other related SDGs: 2, 3, 7, 11, 12, 13, 14 and 15
Nitrogen concentration	SDG 6: Clean water and sanitation – Nitrogen concentration within water bodies, impacted by agricultural runoff and wastewater discharge, directly impacts the availability of clean potable water. High nitrogen concentration levels can result in eutrophication, depleting the available oxygen in water, impacting water quality and aquatic life (strong link to SDG 14) Other related SDGs: 2, 3, 12, and 15.
Energy supply (Electricity)	SDG 7: Affordable and clean energy – Energy Supply is directly related to universal access to electricity. A continuous, sustainable, clean energy supply is critical to increasing the standard of living. Increasing energy supply from clean sources is critical to achieving SDG 7. SDG 7 is not necessarily entirely encompassed by this indicator. However, "Energy supply (Electricity)" coupled with "Emissions (CO_2 equivalents)" provides a reasonable representation of SDG 7. Other related SDGs: 1, 3, 4, 6, 8, 9, 10, 11, 12, and 13.
Energy consumption (Electricity)	SDG 7: Affordable and clean energy – Energy consumption indicates access to affordable and clean energy and living standards. However, efficient energy consumption management is critical to reducing costs and ensuring equitable access to energy. Other related SDGs: 1, 3, 4, 6, 8, 9, 10, 11, 12, and 13.
Emissions (CO_2 equivalents)	SDG 13: Climate action – CO_2 emissions are one of the core drivers of climate change. Effective emissions management through the use of clean energy sources is critical to minimising climate change. Other related SDGs: 3, 7, 11, 12, 14, and 15.

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Indicator	Sustainable Development Goal
Food production	SDG 2: Zero hunger – Food production provides an indication of food security. Sustainable food production practices help maintain long-term food security by preserving natural resources, such as soil and water. Other related SDGs: 1, 3, 8, 10, 12, and 15.
Food consumption	SDG 2: Zero hunger – Food consumption indicates of access to nutritious food, thus reducing hunger. Other related SDGs: 1, 3, 4, 8, 10, 12, and 15.
Crop per drop	SDG 12: Responsible consumption and production – Crop per drop indicates sustainable production and optimal resource use. Producing more food with less water reduces environmental impact, promoting sustainable agriculture through responsible food production and water consumption. Other related SDGs: 1, 2, 6, 10, 11, and 15.
Wetland area	SDG 6: Clean water and sanitation – Wetlands improve water quality and regulate flows, contributing to clean water and sanitation. Additionally, wetlands contribute to groundwater recharge, increasing the availability of freshwater resources. Other related SDGs: 1, 2, 11, 13, 14 and 15.
Forest area	SDG 15: Life on land – Forests play a critical role in habitat for terrestrial species, ensuring ecosystem biodiversity and health. Effective forest management and protection are essential to maintaining life on land. Other related SDGs: 1, 2, 3, 6, 11, and 13.
Protected area	SDG 15: Life on land – Protected areas ensure the maintenance of terrestrial ecosystems and biodiversity, Thus preserving terrestrial life by protecting natural landscapes and critical ecosystems. Other related SDGs: 6, 11, 13, and 14.
Mean Species Richness (MSR): Mammals	SDG 15: Life on land – MSR: The Richness of mammals, birds and amphibians indicates terrestrial ecosystem health and biodiversity. Other related SDGs: 2, 3, 4, 6, 11, 13, and 14.
MSR: Birds	
MSR: Amphibians	
Aboveground Carbon Mass	SDG 13: Climate action – Aboveground carbon mass contributes to carbon sequestration, mitigating climate change as carbon sinks. Vegetation stores carbon reducing the concentration of greenhouse gases thus reducing climate change. Other related SDGs: 2, 3, 6, 11, and 15

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Development of Composite Indicator

The previous chapters focussed on the first two steps associated with JRC Coin's ten-step process. This chapter focuses on the following four steps of the process[iii]:

- Analyse and treat the data, where necessary;
- Bring all indicators onto a common scale;
- Weight the indicators and dimensions;
- Aggregate the indicators and dimensions;

Data analysis and treatment

Data was available for the four Reference Scenarios for four of the five CSs at the time of the WEFE Footprint's development. However, data was only available for one of the four Reference Scenarios for the fifth case study. The data was provided in monthly timesteps over the 35 years.

The data was plotted using histograms and scatter plots to understand the information provided. Due to the variability in data such as water availability, nitrogen concentration and mean species richness, it was decided to aggregate the data into yearly values. The approach for aggregating monthly data into yearly data is indicated in Table 3.

Table 3: Indicator's monthly to yearly aggregation approach

Indicator	Aggregation Approach	Indicator	Aggregation Approach
Surface water availability	Sum	Water demand	Sum
Nitrogen concentration	Weighted Average*	Energy consumption (Electricity)	Sum
Energy supply (Electricity)	Sum	Emissions (CO_2 equivalents)	Sum
Food production	Sum	Food consumption	Sum
Crop per drop	Average	Wetland area	Average
Forest area	Average	Protected area	Average
MSR: Mammals	Average	MSR: Birds	Average
MSR: Amphibians	Average	Aboveground Carbon Mass	Average

* For nitrogen concentration, the average value was skewed by monthly values that were orders of magnitude higher than the median, 75th, and 90th percentiles. This was investigated further. It was noted that the months with significantly higher nitrogen concentration occurred in months with orders of magnitude lower surface water runoff. As such, the nitrogen concentration was aggregated by determining the average weighted by surface water runoff.

Due to the nature of the modelled data from WP2, there was no need for data imputation for a given indicator. However, there are cases where a given indicator was not included in a CS's SDM. The handling of indicators not included in a given CS's SDMs is explained further in the "Indicator and dimension aggregation" section below.

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Outliers were identified following the aggregation of monthly data to yearly data. This was done per CS and for the four Reference Scenarios, where possible. The check for outliers was based on the approach outlined in the COIN Tool, where skewness and kurtosis were checked using a threshold of 2 and 3.5, respectively, to identify if a given indicator for a given CS and Reference Scenario contained any outliers.

Based on the check for outliers, the number of outliers per indicator did not exceed five in any of the five CSs and four Reference Scenarios. As a result, the approach selected for treating the data for outliers was Winsorisation. Due to the number of combinations of policy future scenarios, it was not feasible to check the number of outliers for each scenario. Furthermore, each policy future scenario would be based on one of the four Reference Scenarios, and data was only available for some of them when the WEFE Footprint was being developed. As a result, it was assumed that the available Reference Scenarios would provide a reasonable representation of Policy Future Scenarios, and the approach selected for treating the data for outliers was Winsorisation.

Data directions

The next step after treating the data is giving the Indicator a direction. The direction associated with each indicator is provided in Table 4. The directions selected in Table 4 are based on the approach outlined in JRC-COIN's "Coin Tool User Manual" (JRC-COIN, 2015)[xiii] where:

> *"A value of 1 means that higher values of the indicator are associated with higher values of the index/concept (e.g. higher values of the indicator "income" indicate higher values of index "quality of life"). A value of -1 means that higher values of the indicator are associated with lower values of the index/concept (e.g. higher values of indicator "deforestation" are associated with lower values of index "environmental performance")".*

Table 4: Indicator directions

Indicator	Direction	Indicator	Direction
Surface water availability	1	Water demand	-1
Nitrogen concentration	-1	Energy supply (Electricity)	1
Energy consumption (Electricity)	1	Emissions (CO_2 equivalents)	-1
Food production	1	Crop per drop	1
Food consumption	1	Wetland area	1
Forest area	1	Protected area	1
MSR: Amphibians	1	MSR: Birds	1
MSR: Mammals	1	Aboveground Carbon Mass	1

As indicated in Table 4, three of the 16 Indicators were assigned a negative direction:

- Water demand: An increase in water demand could result in an increase in standard of living, however there is a tradeoff to the environment that should be

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considered. The increase in water demand would result in a decrease in the water available to maintain the necessary ecological flows, thus reducing the functioning of downstream wetlands and ecosystems reliant on the flows.

- Nitrogen concentration: Significant increases in nitrogen concentration could result in nitrogen levels rising beyond the threshold of potable water, globally accepted as 10 mg/L, with associated impacts on downstream water users. Furthermore, increases in nitrogen concentration result in eutrophication and, ultimately, algal blooms with associated negative environmental impacts on aquatic ecosystems. Both high concentrations of ammonium and Cynobacterial algal blooms (blue-green algae) can cause mortality in aquatic and exposed terrestrial species
- Emissions (CO_2 equivalents): Increases in CO_2 emissions increase the greenhouse effect, ultimately contributing to climate change.

Data normalisation

After applying the directions to the data, the data is then normalised. During the third WEFE Footprint workshop in Riga, it was proposed that the indicators be divided by the indicator value in "Year Zero" 'y_0' to normalise the data. This approach was adopted as the preferred approach:

$$\tilde{x}_n = \frac{x_n}{x_0}$$

When formulating the WEFE Footprint using this approach, it was noted that some indicators, such as water availability, would influence the footprint more than indicators, such as mean species richness. This was due to the nature of the indicator. Water availability varied significantly from 0.3 to 3.5 times the initial value, whereas Mean Species Richness only varied from 0.6 to 1.5 times the initial value.

As such, other possibilities of normalising the data were investigated. The methodologies from the OECD and JRC's "Handbook on Constructing Composite Indicators" (OECD, 2008)[xiv] were considered:

1. Ranking
2. Standardisation (or z-scores)
3. Min-Max
4. Distance to reference country
5. Categorical scales
6. Indicators above or below the mean
7. Cyclical indicators (OECD)
8. Balance of opinions (EC)
9. Percentage of annual differences on consecutive years

The selected approach for normalising the data was a variation of the "Distance to reference country". The approach used was adapted from Bekker[xv] (2022):

$$\tilde{x}_{I,n} = 1 - \frac{x_{I,0} - x_{I,n}}{\max(x_I) - \min(x_I)}$$

Where:

$\tilde{x}_{I,n}$: *Normalised value of indicator I in year n*

$x_{I,0}$: *Value of indicator I in year 0*

$x_{I,n}$: *Value of indicator I in year n*

$\min(x_I)$: *Minimum value of indicator I for all reference and policy future scenarios*

$\max(x_I)$: *Maximum value of indicator I for all reference and policy future scenarios*

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One of the essential requirements for the WEFE Footprint is to compare the footprints for different Reference Scenarios and Policy Future Scenarios for a given CS. To facilitate this, the minimum and maximum values for a given indicator "I" are determined by obtaining the minimum and maximum values for a given CS for all the Reference Scenarios and Policy Future scenarios. The maximum and minimum values for each indicator "I" are fixed for a given CS.

The advantages of the selected approach for normalising the data are:

- All indicators are brought to a common scale, between zero and two:
    - "Zero" represents the furthest point away from the T_0 value in the negative direction, and
    - "Two" represents the furthest point away from the T_0 value in the positive direction
    - "One" represents when an indicator is equal to the T_0 value
- For a given CS, indicators are on a common scale across the four Reference and all Policy Future Scenarios, allowing for comparisons between different scenarios.
- This approach therefore addresses the challenge previously identified where some indicators influenced the Footprint more than others due to the magnitude of changes in the indicator value relative to other indicators where changes in the value are more moderate.

Indicator and dimension weightings

The WEF Nexus is multi-centric (Allouche et al., 2015)[xvi], treating water, energy, and food with equal importance. The multi-centricity of the WEF Nexus has been applied to the WEFE Footprint, with the Ecosystem Pillar allocated equivalent weighting to Water, Energy, and Food. Similarly, each sub-pillar within the four pillars and each indicator within its sub-pillar were given equal weightings. The weightings of the pillars, sub-pillars and indicators within their respective supra-dimensions are shown in Table 5. Furthermore, their contributions to the WEFE Footprint are shown in Table 6.

Table 5: Pillar, Sub-pillar and indicator weights within supra-dimensions.

Pillar	Sub-Pillar Weight	Sub-Pillar	Indicator Weight	Indicator
Water	**0.5**	**Water quantity**	**0.5**	Surface water availability
			0.5	Water demand
	0.5	**Water quality**	**1**	Nitrogen concentration
Energy	**0.5**	**Energy quantity**	**0.5**	Energy supply (Electricity)
			0.5	Energy consumption (Electricity)
	0.5	**Energy emissions**	**1**	Emissions (CO_2 equivalents)

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Pillar	Sub-Pillar Weight	Sub-Pillar	Indicator Weight	Indicator
Food	0.5	Food quantity	0.5	Food production
			0.5	Food consumption
	0.5	Irrigation efficiency	1	Crop per drop
Ecosystems	0.333	Ecosystem Land Use	0.333	Wetland area
			0.333	Forest area
			0.333	Protected area
	0.333	Ecosystem Health	0.333	MSR: Amphibians
			0.333	MSR: Birds
			0.333	MSR: Mammals
	0.333	Ecosystem Services	1	Aboveground Carbon Mass

Table 6: Pillar, Sub-Pillar and Indicator contributions to the WEFE Footprint.

Pillar	Contribution to the WEFE Footprint
Water	0.2500
Energy	0.2500
Food	0.2500
Ecosystems	0.2500

Sub-Pillar	Contribution to the WEFE Footprint
Water quantity	0.1250
Water quality	0.1250
Energy quantity	0.1250
Energy emissions	0.1250
Food quantity	0.1250
Irrigation efficiency	0.1250
Ecosystem Land Use	0.0833
Ecosystem Health	0.0833
Ecosystem Services	0.0833

Indicator	Contribution to the WEFE Footprint
Surface water availability	0.0625
Water demand	0.0625
Nitrogen concentration	0.1250
Energy supply	0.0625
Energy consumption	0.0625
Emissions (CO_2 equivalents)	0.1250
Food production	0.0625
Food consumption	0.0625
Crop per drop	0.1250
Wetland area	0.0278
Forest area	0.0278
Protected area	0.0278
MSR: Amphibians	0.0278
MSR: Birds	0.0278
MSR: Mammals	0.0278
Aboveground Carbon Mass	0.0833

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Indicator & dimension aggregation

The two most commonly applied methods when aggregating indicators into a composite indicator are:

- Weighted Arithmetic Mean

$$Composite\ Index = \frac{1}{\sum_{i=1}^{d} w_i} \sum_{i=1}^{d} x_i w_i$$

- Weighted Geometric Mean

$$Composite\ Index = \left(\prod_{i=1}^{d} x_i^{w_i} \right)^{1/\sum_{i=1}^{d} w_i}$$

For the WEFE Footprint, the arithmetic mean was selected due to its simplicity. Furthermore, the normalisation process and the selected technique result in normalised indicators that are unitless and on the same scale, varying between 0 and 2.

When aggregating the indicators into the subpillars, if no data is available for a given indicator, the indicator is excluded from the aggregation process, and the weightings of the remaining indicators within the sub-pillar are distributed equally. Should no data be available for all indicators within a given sub-pillar, the sub-pillar is excluded from the aggregation process, and the weightings of the remaining sub-pillars within the pillar are distributed equally.

Data visualisation

WEFE Footprint Visualisation

The WEFE Footprint represents the nexus at a given point in time for a given CS and Reference/Policy Future scenario. It is represented by three different radar plots, similar to The City Blueprint[xvi]. The visualisation of the WEFE Footprint is depicted in Figure 9. The composite index value is provided in the centre of the plot. Blue, red, yellow, and cyan represent water, energy, food, and ecosystems, respectively. The three radar plots are split into segments representing the pillars, sub-pillars and indicators. The percentage of the circle covered by the pillar, sub-pillar or indicator is representative of its contribution to the WEFE Footprint. For example, in Figure 9 “Crop per Drop” and “Emissions (CO_2 equivalents)” contribute equally to the Footprint (0.1250), while “MSR: Birds” contributes less (0.0278). The score in the centre of the footprint represents the overall index score, where a value of one represents the case where the overall WEFE Footprint in “Year n” is equivalent to the score in “Year Zero”. A score between zero and one indicates that the WEFE Footprint has moved in a Negative direction from “Year Zero”, and a score between one and two indicates that the WEFE Footprint has moved in a positive direction since “Year Zero”.

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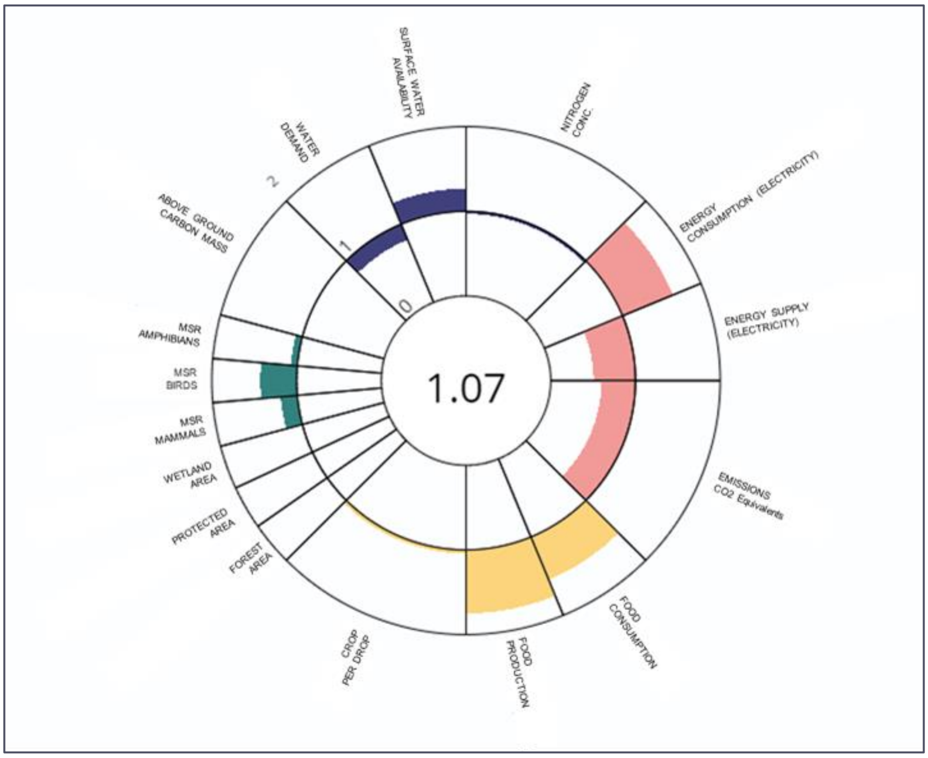

Figure 9.a) WEFE Footprint – Indicator Level (Jiu River Basin Policy Future Scenario – RCP8.5, SSP2, 2030)[1]

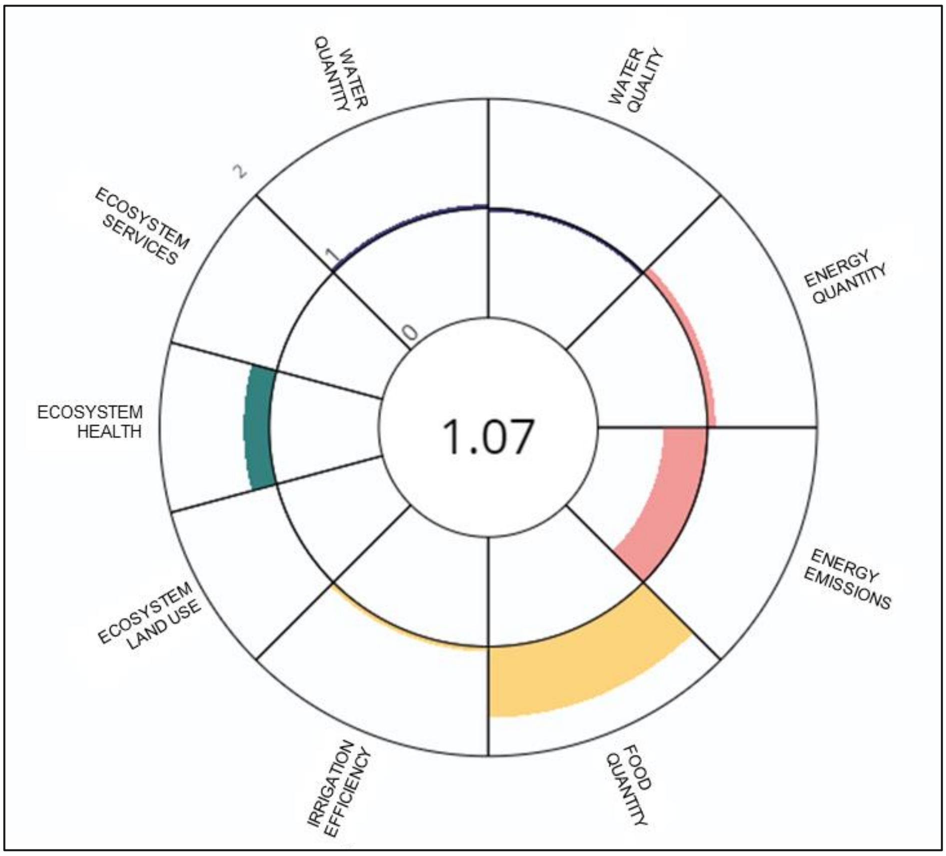

Figure 9.b) WEFE Footprint – Sub-Pillar Level (Jiu River Basin Policy Future Scenario – RCP8.5, SSP2, 2030)[1]

1 For demonstration purposes only. Not to be used for any decision making or scientific research.

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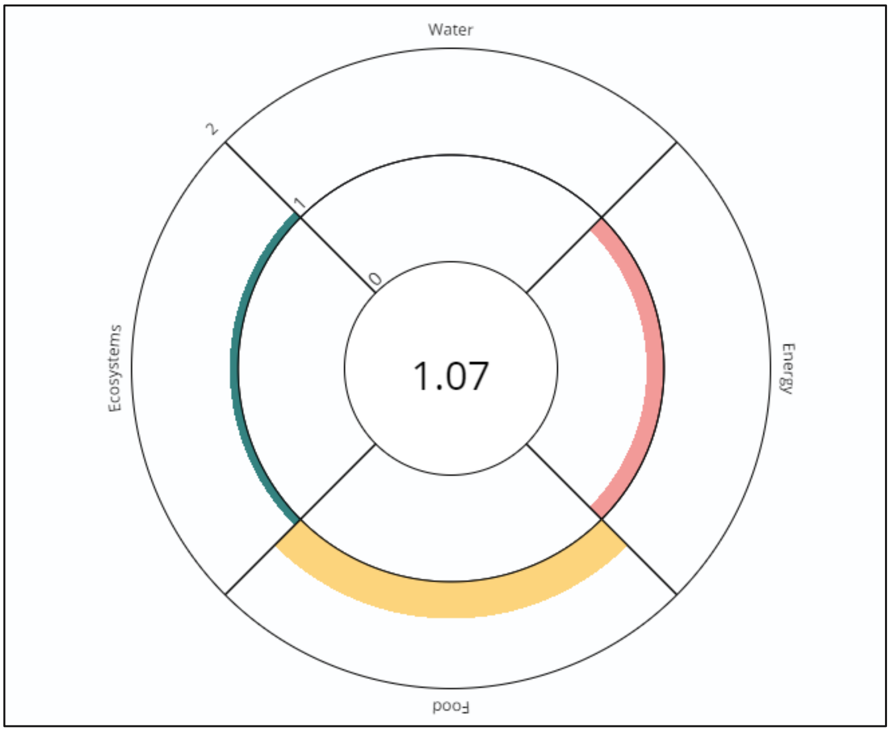

Figure 9.c) WEFE Footprint – Pillar Level (Jiu River Basin Policy Future Scenario – RCP8.5, SSP2, 2030) [2]

Figure 9: Visualisation of the WEFE Footprint

A normalised indicator value of zero represents the case where the value of the indicator is a maximum in "Year Zero", and the indicator value in "Year n" is a minimum, i.e. the furthest away from the "Year Zero" value in the negative direction for a given CS. Therefore, where a segment plots towards the centre of the radar plot, it has moved in the negative direction from the initial indicator value. For example, in Figure 9.b), the Energy Emissions sub-pillar has moved in the negative direction (primarily driven by increased "Emissions (CO_2 equivalents)"), leading to an associated negative impact on the index value.

Similarly, a normalised indicator value of two represents the case where the value of the indicator is a minimum in "Year Zero", and the normalised indicator value in "Year n" is a maximum, i.e. the furthest away from the "Year Zero" value in the positive direction for a given CS. Where the segment plots towards the circumference of the radar chart, it has moved positively from the initial indicator value. For example, in Figure 9.c), the Food Pillar has improved relative to the starting value, primarily driven by increased Local food availability and demand. If a segment of the WEFE Footprint visualisation is blanked out, no data is available for that footprint segment.

A normalised indicator value of one represents the case where the indicator value in "Year n" is equal to the indicator value in "Year Zero".

WEFE Footprint Comparison Visualisations

In addition to the WEFE Footprint visualisation, a method of comparing the Reference Scenario to a Policy Future Scenario is proposed. The visualisations in this section were not included in the NEPAT at the time of writing this. They are supplementary to the WEFE footprint and are

[2] For demonstration purposes only. Not to be used for any decision making or scientific research.

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under consideration for inclusion in the NEPAT to allow ease of comparison between Reference and Policiy Future Scenarios.

The proposed comparison visualisation is depicted in Figure 10. Each bar represents a different Reference or Policy Future Scenario. The different colours in each bar represent different pillars/sub-pillars/indicators.Each segment in the bar indicates the indicators contribution to the WEFE Footprint, with the total length of the bar representing the overall WEFE Footprint score

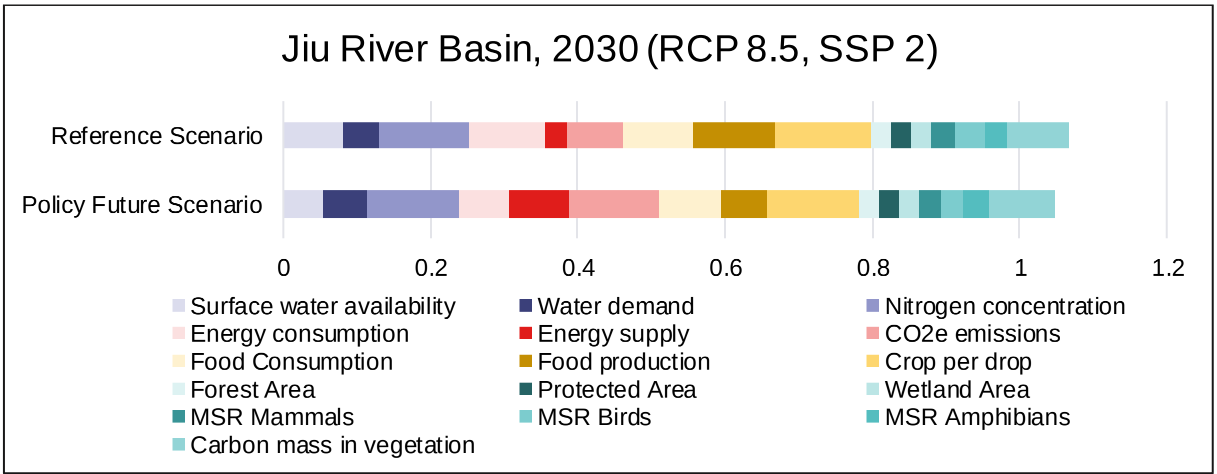

Figure 10: Visualisation for comparing WEFE Footprints across Reference and Policy Future Scenarios[3]

The final visualisation tracks the WEFE Footprint, pillars, sub-pillars, and indicators over time. Additionally, it allows for comparison between Reference and Policy Future Scenarios. The visualisation is presented in Figure 11.

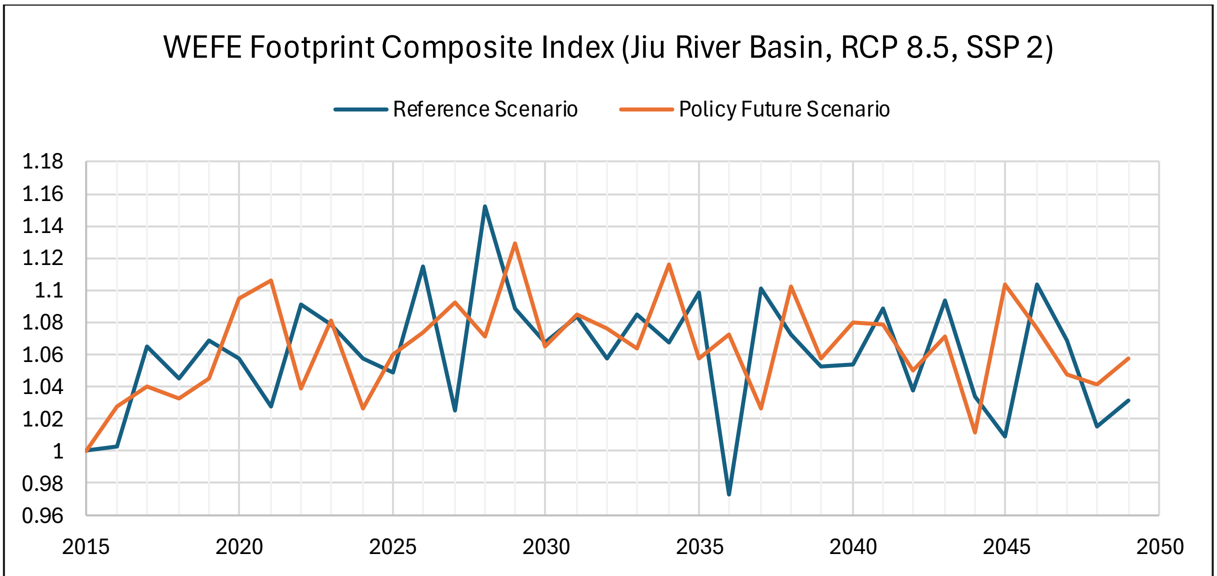

Figure 11: Visualisation of the WEFE Footprints' composite index over time[3]

WP4, led by Eurecat, assisted with incorporating the WEFE Footprint determination and visualisations into the NEPAT.

3 For demonstration purposes only. Not to be used for any decision making or scientific research.

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Conclusion and Way Forward

The development of the WEFE Footprint started with the first workshop in July 2022. Throughout the process, the footprint has undergone various iterations regarding its definition, goals, framework, indicators, and visualisation. The final representation of the WEFE Footprint is the outcome of inputs from stakeholders and representatives of the five Case Studies and various Work Packages.

The WEFE footprint indicates the status of each resource sector at a given year by aggregating indicators into sub-pillars, pillars and a composite indicator. Furthermore, it visualises the impacts and trade-offs of policy on the sectoral indicators.

The development has involved continuous analysis and interpretation of the available data to make sense of the data and the resulting WEFE Footprint. However, while developing the WEFE Footprint, the NEPAT and some SDMs were still in development. Going forward, once finalised, the NEPAT's outputs and resulting WEFE footprints will be further analysed in terms of correlations between indicators, sub-pillars, pillars, and the WEFE Footprint, as well as sensitivity analysis.

Additionally, the two proposed visualisations for ease of comparison of the WEFE Footprint across different Reference and Policy Future Scenarios will be considered for incorporation into the NEPAT.

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