DEPARTMENT OF INTERNATIONAL AND EUROPEAN ECONOMIC STUDIES

ATHENS UNIVERSITY OF ECONOMICS AND BUSINESS

Sustainable WEF Nexus Management: A Conceptual Framework to Integrate Models of Social, Economic, Policy and Institutional Developments

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Working Paper Series

21-07

June 2021

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Abstract: Despite being host to an extensive amount of natural resources, Africa is experiencing the acute impacts of a population explosion, rapid economic growth and climate change; all exacerbated by poor management. This has taken its toll on precious resources, water in particular, driving the need for innovative tools to support integrated WEF nexus management. This paper presents a framework for the integrated management of water resources, which brings together the socio-anthropological aspects of the WEF nexus under for separate models. The developed framework provides insight into the human element as part of the wider ecosystem; in terms of socio-cultural and economic activity, the laws and policies that govern these activities as well as the potential impacts and consequences of said activities. This paper outlines each individual model, before going on to present a conceptual framework for integrating the various models. The framework, which is grounded in systems thinking, adopts the principles of sustainable development as structural foci in order to position the various models and harmonize their inputs as well as outputs.

1. Introduction

A continent rich in natural resources, both renewable and non-renewable, Africa is endowed with an abundance of mineral reserves, biodiversity, water, and arable land. It contains 8% of the world's natural gas, 12% and 30% of global oil and mineral reserves respectively, 40% of global gold ore and up to 90% of chromium and platinum. In addition, the continent holds 10% of the world's internal fresh water, while 65% of all arable land lies in Africa. With projections estimating a total population of 2billion by the year 2050, Africa also possesses vast human capital (UNEP, 2021).

Despite this wealth of natural resources, the 'triple threat' (Walker, 2020) of unprecedented population growth, exceedingly rapid economic growth as well as climate change (coupled with poor and ineffective natural resource management) has seen water and food security issues on the rise, with Africa being the only continent on which the number of undernourished people witnessed an increase in recent decades (Plaizier, 2016). Given the fact that more than 70% of the Sub-Saharan African population depends directly on these natural resources, with natural capital accounting for 30%-50% of total wealth on the continent (UNEP, 2021), the socio-economic impact of these threats is disproportionately higher in the region. Already, there has been an increase in both conflict and migration in the region, driven by climate-induced water stress is being observed; subsequently creating a ripple effect around the globe (Iceland, 2017).

On a global scale, water consumption is increasing at a rate of 1% annually, and an even greater strain on water resources is anticipated over the next 20 years with the development of the domestic, industrial, energy and agricultural sectors (see Figure 1) expected to drive a significant increase in demand (United Nations, 2018; Boretti and Rosa, 2019). Thus, there is need for a greater understanding of these drivers of water demand, and the relationships that bind them.

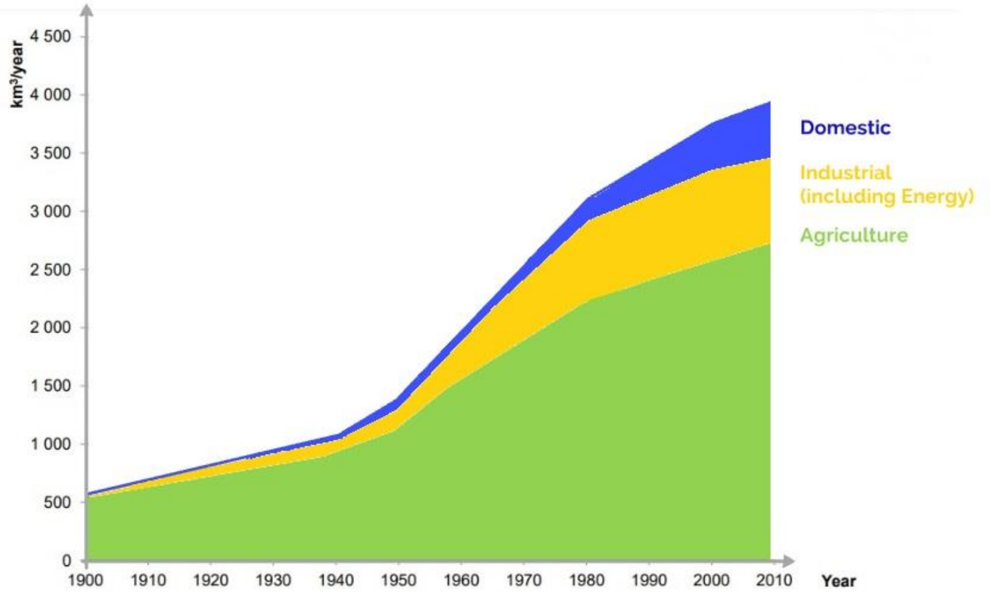

Figure 1. Global trends in water consumption per sector (Source: FAO, 2021)

The need for an integrated approach that considers these complex issues holistically is met by the Water-Energy-Food (WEF) Nexus framework (Hellegers et. al., 2008; Bazilian, 2011; UN-Flores, 2017; Fernandes Torres et. al., 2019; Katz et. al., 2020). The WEF Nexus describes the confluence of the issues related to water, energy and food, taking into account synergies and trade-offs with regards to resource allocation. Historically, disaggregated and siloed approaches to natural resource management and allocation have led to inequitable distribution and prioritization of resources (Mabhaudhi, et. a., 2019); rather than considering the development of each sector in isolation, the WEF Nexus approach analyses cross-sectoral issues simultaneously (Rasul and Sharma, 2016; Mabhaudhi, 2016; Nhamo, 2018). This type of 'systems thinking' (Sterman, 2000) is integral to the delivery of sustainable development (Albrecht et. al, 2018; Liu et. al., 2018), as it acknowledges the complexities and interdependencies between the various environmental and societal challenges and developmental issues. As such, WEF nexus approaches are not just crucial tools for resource management but also for the implementation of developmental policies (Boas, Biermann and Kanie, 2016) and agendas such as the Sustainable Development Goals (United Nations, 2015) (See figure 2).

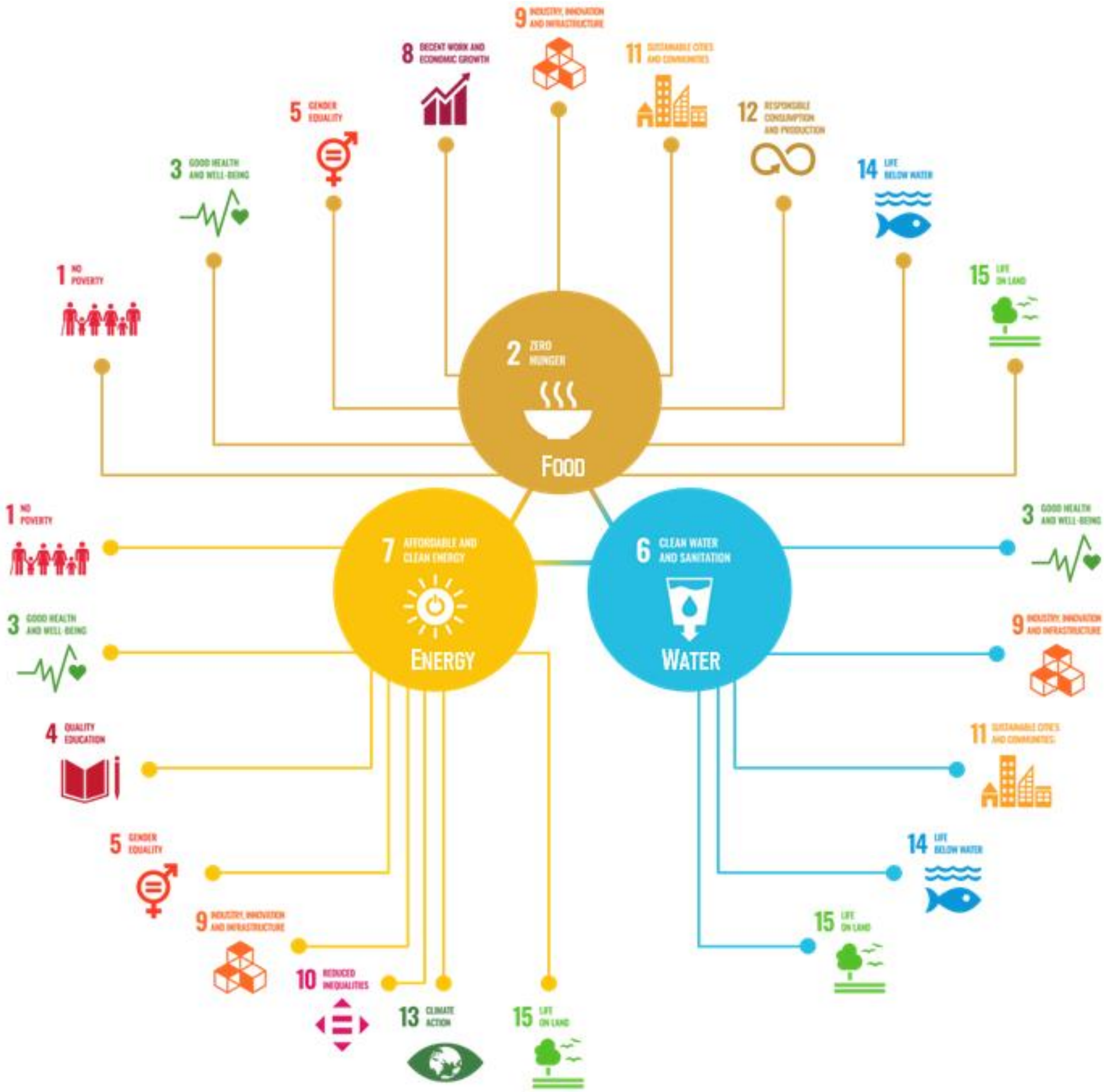

Figure 2. Sustainable Development Goals in the context of the WEF Nexus.

While climate change, as well as economic and population growth are major contributing factors driving global water stress, in Africa in particular, inefficient water resource and service management poses the biggest challenge (UNDP, 2006; Ngaira, 2009; Mason, Nalamalapu and Corfee-Morlot, 2019). In effect, the adoption of a WEF Nexus approach within the African context has the potential for a transformational impact –

targeting the most vulnerable populations to provide access to clean water, improving sanitation, reducing health issues and associated mortality, improving energy access, supporting job creation, alleviating poverty and essentially acting as a foundation for sustainable development in the region. Walker (2020) suggests three pillars of effective WEF Nexus management; firstly, good governance and strong institutions led by empowered and informed decision-makers; secondly, good cooperation which promotes regional and cross-sectoral coordination; and finally, accessible knowledge on the basis of enhanced data and information collection, management, analysis and sharing. The 'knowledge' pillar serves to underpin the first two, by creating models which use locally available data, as well as providing a shared understanding of the WEF Nexus amongst key stakeholders and decision makers in order to inform planning, investment and development decisions.

This paper presents research[1] conducted as part of the EC-H2020 DAFNE (Decision-Analytic Framework to explore the water-energy-food NExus in complex and trans-boundary water resources systems of fast-growing developing countries) project. The project developed a Decision Analytic Framework (DAF) to support stakeholders in effectively managing shared (transboundary) water resources. The DAF is an integrated decision support tool which is informed by a bio-physical modelling component (hydrological and environmental models) as well as a socio-anthropologic modelling component (modelling social, economic and institutional developments). While several studies in recent years (Welsch *et al*, 2014; Webber, 2016; Anghileri, 2017; Albrecht et. al, 2018) have explored the use of bio-physical models in the context of WEF Nexus management, the socio-anthropologic models which deal with the 'human element' of the equation, are yet to be investigated to the same extent; in particular, how such models can be integrated into a wider decision support system. These socio-anthropologic models focus on the behaviours and interactions of the human actor within the ecosystem and explore the human responses to environmental stimuli as well as the influence of the human agent on the development of the system. Furthermore, they explore the constraints imposed by policy, regulation and the roles of the institutional structures which govern the interactions of the various actors in the context of the WEF nexus.

Grounded in two case study river basins (RB), the Zambezi River Basin (ZRB) and the Omo-Turkana River Basin (OTB), this paper will first present an overview of the four individual models:

- Model of Economic Development (Stochastic Game Model)
- Model of Environmental Policy (Model of Legal Principles and Norms)
- Model of Demographic, Cultural and Social Development (Systems Dynamics Model)
- Model of Water Governance Principles (Law/Policy Classification and Expectation Matrix)

The paper will then proceed to outline a unifying sustainable development framework for the integration of the four models by mapping the relationships and providing an analytical description of the system of the interrelated models. Finally, the paper elaborates on the connections (input and feedback) between the socio-anthropologic models and both the bio-physical model, as well as the wider DAF

[1] H2020 DAFNE Deliverable4.5: Integrated framework of models for social, economic and institutional developments

2. Modelling the anthropological ecosystem of the WEF Nexus

The first model is the economic development model, the objective of which is to describe the economic development of the regions or countries of each case study, describing the use of water and its value to the functioning of their economies (Koundouri, Catarina and Englezos, 2017). From energy production to sanitation, hygiene, and food production, water plays a crucial role in the development of a nation as a whole. Therefore, water is central to such a model, given that all parts of an economy utilise water whether directly or indirectly. The model of economic development is formulated as a *Stochastic Game Model* in a transboundary setting (Kim et. al., 1989; Bhaduri et. al., 2011) produced from a WEF Nexus perspective, and takes into consideration the Total Economic Value of water. As multiple countries share water resources, the likelihood of conflicts over the allocation of water resources increases; particularly under the effects of climate change (Homer-Dixon, 1999; Barnes, 2009; Miguel and Satyanath, 2011; Koundouri and Papadaki, 2020). Thus, the model aims to identify the optimal economic development pathways and their dependence on water resource availability. The model takes into consideration five key sectors as they relate to each of the case study countries, namely:

- agricultural sector
- energy sector
- mining sector
- residential sector
- tourism sector

While the relationship between the agricultural and the energy sectors, and the WEF nexus are clearly discernible, the WEF nexus link with the latter three sectors (mining, residential and tourism) is less so. However, these three sectors are considered as they have a substantial impact on water use within the case study areas (World Bank, 2018); tourism and mining in particular constitute anchor income generating sectors for the local economies of the case study areas (World Bank, 2010, EORA, 2017; Oqubay, 2018). These sectors not only impact the availability of water in the region in terms of consumptive demand for drinking, sanitation (linked to demographic trends of the local populations and seasonal tourist numbers) and industrial processes as is the case in mining (EORA, 2017; ZAMCOM, 2016; World Population Review, 2018); but also depend on water to provide the natural habitat on which the local tourism industry relies (Shela, 2000). The model captures the influence of water resources on transboundary water management within each of the above sectors, following a multistage dynamic stochastic game approach (Kim et. al., 1989; Bhaduri et. al., 2011). The indices used for the estimation of the production functions for each sector (representing the ecosystem services), were constructed using measures of natural resources and landscapes. In this case, it is only possible to estimate the joint value of the ecosystem services, given that a particular ecosystem service may relate to various landscapes and resources, while a given natural resource could potentially provide more than one ecosystem service.. Thus, for each sector common variables which describe the main types of the ecosystem services were chosen (such as raw materials, forest, natural-cultural-mixed heritage sites, biodiversity and habitats, terrestrial protected areas, water quality, annual freshwater withdrawals, and uses, gas emissions (CO_2 and NO_2) and floods/droughts events). Furthermore, the Sustainable Development Goal Indicators (SDGIs) were considered in the selection of the chosen variables as presented later in this paper.

The second model is the model of environmental policy. The adoption of a comprehensive policy framework is critical for transboundary environmental resources; environmental degradation must be carefully managed, particularly in Africa, due to the importance of ecosystems for the provision of a range of services. So far, little work has been done to assess the strength of the policy frameworks in transboundary basins, in order to identify how best to modify them to create an improved policy framework for environmental conservation.

The model of environmental policy is a *Model of Legal Principles and Norms* (Lautze et. al., 2017; Lautze and Mukuyu, 2019), and operates on the premise that comprehensive, coherent legal and policy coverage to environmental issues is presumed to result in a conducive and effective policy context for environmental sustainability. Conversely, policy limitations, gaps and misalignment across countries and sectors are presumed to result in environmental vulnerability. The model was applied in order to gauge the suitability of existing legal and policy frameworks based on:

- the degree to which they cover key environmental issues
- the degree to which they are harmonized across countries in basins, and
- the degree to which they are coherent across sectors.

A review of literature on environmental issues within the OTB and ZRB led to the identification of several major environmental concerns. While the order of importance of environmental issues did not necessarily match across the two basins, the main environmental issues were largely the same. Five key environmental issues for investigation were used as the focus of the work:

- Fisheries and aquaculture
- Forests
- Wetlands
- Biodiversity
- Wildlife

Environmental law and policy texts from each of the basin countries formed the primary data utilized. The review targeted legal and policy documents covering water, energy and agriculture, and the laws and policies collected were classified according to a set of basic and technical parameters. The basic parameters provide the general information about the legal and policy documents such as the name of the document, year, country, sector, etc., while the technical parameters cover a range of more specific elements in the context of each of the five key issues. While the model of environmental policy does not specifically make use of indicators or variables in the traditional sense, the classified laws and policies were assessed against three criteria:

- Extent of coverage to five identified environmental issues in the two basins
- Degree of institutional alignment within basins
- Congruity between laws and policies in environment vs. non-environmental sectors

Efforts were made to ensure that the selection of the criteria was harmonised both with the variables considered by the other socio-anthropologic models, as well as the SDGIs

Outcomes of model application led to the identification of several areas that are in need of strengthening, which in turn led to a proposal of three policy alternatives aimed at addressing some of these areas

The third model focusses on Demographic, Cultural and Social Development. It is a *System Dynamic Model* (Vennix 1996) showing how socio-economic phenomena and environmental aspects interact, which represents important information for resource-related decisions in the WEF nexus (Lumosi, Pahl-Wostl, and Scholz, 2019). The model identifies relationships between different natural resource and societal factors in the case study areas; examining the system interactions (links and feedbacks) and the impact (both intended and unintended) of trends such as population growth on the system. In doing so, demographic development as well as related drivers and responses could be given special consideration. By displaying balancing or reinforcing feedback loops, the model helps to identify system responses and behavior. Furthermore, it enables to reconsider whether important influences have been considered sufficiently as well as general system responses that might follow the change in elements of the system (e.g., population grow). Such models are able to support long-term decision-making by capturing knowledge gaps within the system as well as highlighting trade-offs and synergies. The model of Demographic, Cultural and Social Development is a qualitative model which does not use quantitative data about relationships. It may be used to identify:

- critical issues in the respective social-ecological system
- links between socio-economic and resource-related factors, and
- the influence they have on each other

The model was developed in a participatory manner by interviewing a representative set of stakeholders from the case-studies and subsequently integrating their perspectives (Scholz et al 2019). During the interviews, causal loop diagrams (CLDs) displaying the links between cause and effect within the system were developed together with the interviewees. Such causal loop diagrams can be used to gain insights into complex, dynamic and interconnected issues, and to communicate those insights (Vennix, 1996; Tip, 2011). The individual maps were subsequently analysed and combined into a joint model (Scholz et al 2019). Variables adopted within the social model (such as population growth, access to water and/or food, displacement, urbanisation and agricultural practices), were suggested by the interviewed stakeholders. A set of suggestions for variables was identified during the stakeholder workshops to help the process. Stakeholders were asked for demographic, cultural and social issues in relation to the WEF Nexus. Hence, the variables inherently address each of the three main WEF Nexus domains and relate to the SDGIs, thereby providing a basis for integration with the other models.

The fourth and final model examines the principles of water governance. The water governance model seeks to understand the developments and challenges of applying substantive and procedural legal principles in the context of transboundary watercourses, by presenting a *Law and Policy Classification Matrix*. The modelling exercise indicates the level of legal expectation with regards to a number of key legal principles across both the ZRB and the OTB (see Yihdego and Gibson, 2020, with relation to findings in the ZRB). Transboundary watercourses fulfil a number of roles in relation to social and economic development across a number of sectors such as energy and agriculture. They can also present several risks such as floods, droughts and environmental challenges. It is therefore challenging for these complex and often competing uses to be balanced, particularly across multiples countries. Governance structures developed through legal, political and organisational institutions aim to manage the nature of the actions occurring within these competing uses in order to ensure that resulting implications are within the boundaries of legal principles derived from international watercourse law. This was further developed to a Law, Nexus Goals (LNG) framework which proposed integrating international watercourses law, the WEF nexus and the SDGs (Yihdego & Gibson, 2020).

The WEF nexus approach within the model is based on the premise of attributing equal importance to all three of its domains. It does not determine the shape of governance arrangements, but rather seeks the formation of a cooperative arrangement. In this sense, a WEF nexus approach is not explicitly found within the key legal principles used within the model, however it can be related to the factors used to determine equitable and reasonable use listed within Article 6 of the United Nations Watercourses Convention which takes into consideration *inter alia* socio-economic need, ecological need and conservation, protection, development, and economy of use of water resources.

An in-depth literature review of international and national legal and policy documents relating to the WEF nexus was conducted, and qualitative analysis carried out. The search targeted the water sector in particular, but also included National Development Plans and sectoral strategies relating to energy and agriculture. The collection of legal and policy documents led to the identification of a number of key legal principles which set out duties and obligations in relation to the use of transboundary water resources. While a list of legal principles cannot be exhaustive due to the wide scope and constant evolution of the law, 13 broad categories of principles relevant to both basins were identified to underpin the model. These are:

1. Equitable and Reasonable Use[2]
2. No Significant Harm[3]
3. Ecosystem Protection[4]
4. Pollution Prevention[5]
5. Intergenerational Equity[6]

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[2] *See* UN Convention on the Non-navigational Uses of International Watercourses (UNWC) (36 ILM 700; signed 21 May 1997; in force 17 August 2014). (UNWC), Article 5 and Article 6 with relation to relevant factors to be taken into consideration.

[3] UNWC, Article 7

[4] UNWC, Article 20

[5] Within the Water Governance Model, the principle of pollution prevention is derived from no significant harm. The principle can however also be related to the polluter pays principle which is detailed in Principle 16 of the Rio Declaration on Environment and Development, UN Doc.A/CONF.15/26 (vol.1); 31 ILM 874 (1992)

[6] The principle of intergeneration equity is found within a number of international Conventions, including the UNECE Convention on the Protection and Use of Transboundary Watercourses and International Lakes (1936 UNTC 269; signed 17 March 1992; in force 06 October 1996) (UNECE Water Convention) (Article 2(5)(c), UN Convention on Biological Diversity (CBD), 1760 U.N.T.S. 79 (in force 29 December 1993), Preamble and the United Nations Framework Convention on Climate Change 1992 31 ILM 849, Article 3(1)

6. Precautionary Principle[7]
7. Environmental Impact Assessment[8]
8. Transboundary Impact Assessment[9]
9. Provision for Establishment of Joint Body/Mechanism[10]
10. Information/Data Exchange[11]
11. Notification[12]
12. Consultation[13]
13. Dispute Settlement[14]

In order to identify the level of legal expectation each document was given two scores: the first on the level of legal force dependent upon the legal status of the document (ie. from absence of a legal document to fully ratified legislation); and the second on the language used dependent on whether the key principle was found within the document (Yihdego and Gibson, 2020). Once these scores had been ascribed, both values were multiplied to give an overall score for that principle within the specific law or policy.

3. Sustainable Development as a foundation for model integration

In principle, each of the different models seek to reflect a particular aspect of human and institutional interactions within the conceptual boundaries of the WEF Nexus; while useful in isolation, complementarity is required to provide a holistic view of the socio-anthropologic workings of the WEF Nexus. Disciplinary silos created primarily methodology and terminology had to be transcended using a common framework and *lingua franca* (asking fundamental questions such as *"what is understood by the term 'model'?"*). To achieve this, dedicated effort was made towards gaining an understanding of the various disciplinary perspectives and approaches towards developing their respective models.

While the economic and social models are distinctive in their scope, the environmental policy and governance models share an overlap in terms of thematic focus. It was concluded that the two models are complementary; while the environmental model aims to identify extent to which relevant laws and policies of riparian countries

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[7] Stipulated in Principle 15 of the UN Conference on Environment and Development, "Rio Declaration on the Environment and Development" (Rio Declaration) UN Doc. A/CONF.151/26 (vol.I); 31 ILM 874 (1992)

[8] Environmental Impact Assessments are now recognised as part of the customary obligation not to cause significant transboundary harm, as stated in Pulp Mills on the River Uruguay, Argentina v Uruguay, Order, Provisional Measures, ICJ GL No 135, [2006] ICJ Rep 113, (2006) 45 ILM 1025, ICGJ 2 (ICJ 2006), 13th July 2006, International Court of Justice [ICJ], para 204

[9] UNWC, Article 11 requires states to exchange information, consult and if necessary, negotiate the possible effects of planned measures on the condition of an international watercourse.

[10] The UNWC suggests that watercourse states may consider the establishment of joint mechanisms (Article 8.2). Stronger obligations regarding the formation of such institutions are found in the UNECE Article 9.

[11] The obligation to exchange information and data flows from the general obligation to cooperate under Article 8 of the UNWC, more specific provisions relating to the exchange of information are found in Articles 9 and 11.

[12] UNWC, Article 11

[13] UNWC, Article 17

[14] UNWC, Article 33

in ZRB and OTB take into consideration and address critical environmental issues and propose ways in which responses to environmental issues can be improved, the governance model focuses on the application of these laws within the context of global and regional frameworks. Furthermore, while the environmental policy model strictly addresses legislation relating to the environment, the governance model considers broader themes to do with how states conduct processes (harmonization of national laws and developmental strategies, approaches and processes) developed to manage water resources.

The first phase of the integration process, initiated during at the early stages of the development of the individua models, involved the definition of a foundational framework for the model integration. The concept of Sustainable Development (SD) was adopted as unifying element, which would essentially provide the conceptual scaffolding upon which the model integration process could be constructed; with the Sustainable Development Goals (SDGs) and the SDGIs serving as touchstones for each of the models, offering a common basis for the examination of model variables. Traditionally, SD is founded upon the three pillars of sustainability; environment, society and economy, commonly referred to as the '3 Ps'; i.e. planet, people and profit (Elkington, 2004). Over the years, this characterization has evolved into other iterations that highlight aspects of SD seemingly left out of the 3-pillar conceptualisation. An example is the '5 Ps' model: planet, people, prosperity, peace and partnership (United Nations, 2015), which seeks to capture the roles that freedom, equity, justice and strong global partnerships play in ensuring sustainability. It is with a view to make explicit the underlying role that is played by governance and policy in the implementation of SD, that the team adopted a '4 Ps' characterisation of the concept (Figure 3), whereby 'policy' forms a fourth pillar of SD.

Figure 3. – Sustainable Development Represented as '4Ps'.

The 4Ps of SD constitute the fundamental building blocks for the SD integration framework, which translate into four key domains namely:

- Social profiles
- Economic characteristics
- Environmental status
- Policy landscape

These four domains represent key elements of the socio-environmental ecosystem of the case study areas and reflect the separate focal areas of each of the four models. This not only served to contextualise each model within the scope of SD, but the relevant domains helped inform the indicators adopted within each of the models. Furthermore, the SD framework was a useful tool in order to crystallise the distinction between the focus and approach of the Environmental Policy and Water governance models. The indicators and variables adopted by each model constitute a vital component of the respective models, as well as the integration process. The model variables and indicators were utilised as another tether to connect individual models, by incorporating the SDGIs into the SD framework. The SDGIs[15] are a set of 232 indicators adopted by the UN in order to monitor global progress on the SDGs[16] (a collection of 17 global goals and 169 targets set out under the UN 2030 Agenda[17], geared towards the advancement of sustainable development across the globe by 2030). The full list of SDGIs was reviewed and edited down to a reduced list of indicators considered by each of the models (Table 1). In total, 59 SDGIs and 15 SDGs were taken into account in some form or another by the four models.

Table 1. – Socio-Anthropologic Model Variables and Indicators in the Context of the SDGs and SDGIs (Developed from: United Nations Statistics Division, 2020)

SDGs and Relevant SDG Indicators		Model			
SDG	INDICATORS	Econ.	Env.	Soc.	Gov.
	1.1.1 Proportion of population below the international poverty line, by sex, age, employment status and geographical location (urban/rural)			✓	✓
	1.2.1 Proportion of population living below the national poverty line, by sex and age			✓	
	1.2.2 Proportion of men, women and children of all ages living in poverty in all its dimensions according to national definitions			✓	
	1.4.1 Proportion of population living in households with access to basic services	✓		✓	
	1.4.2 Proportion of total adult population with secure tenure rights to land, (a) with legally recognized documentation, and (b) who perceive their rights to land as secure, by sex and type of tenure			✓	
	1.5.2 Direct economic loss attributed to disasters in relation to global gross domestic product (GDP)			✓	
	2.1.1 Prevalence of undernourishment			✓	
	2.1.2 Prevalence of moderate or severe food insecurity in the population, based on the Food Insecurity Experience Scale (FIES)			✓	
	2.3.2 Average income of small-scale food producers, by sex and indigenous status			✓	

[15] SDG Indicators https://unstats.un.org/sdgs/indicators/indicators-list/

[16] Sustainable Development Goals https://www.un.org/sustainabledevelopment/sustainable-development-goals/

[17] UN 2030 Agenda https://sustainabledevelopment.un.org/post2015/transformingourworld

	2.4.1 Proportion of agricultural area under productive and sustainable agriculture			✓	✓
	2.5.2 Proportion of local breeds classified as being at risk, not at risk or at unknown level of risk of extinction			✓	
	3.1.1 Maternal mortality ratio			✓	
	3.1.2 Proportion of births attended by skilled health personnel			✓	
	3.2.1 Under-5 mortality rate			✓	
3 GOOD HEALTH AND WELL-BEIN	3.2.2 Neonatal mortality rate			✓	
	3.3.1 Number of new HIV infections per 1,000 uninfected population, by sex, age and key populations			✓	
	3.9.2 Mortality rate attributed to unsafe water, unsafe sanitation and lack of hygiene (exposure to unsafe Water, Sanitation and Hygiene for All (WASH) services)			✓	
	4.5.1 Parity indices (female/male, rural/urban, bottom/top wealth quintile and others such as disability status, indigenous peoples and conflict-affected, as data become available) for all education indicators on this list that can be disaggregated			✓	
	4.6.1 Proportion of population in a given age group achieving at least a fixed level of proficiency in functional (a) literacy and (b) numeracy skills, by sex			✓	
4 QUALITY EDUCATION	4.7.1 Extent to which (i) global citizenship education and (ii) education for sustainable development, including gender equality and human rights, are mainstreamed at all levels in (a) national education policies; (b) curricula; (c) teacher education; and (d) student assessment			✓	
	4.a.1 Proportion of schools with access to (a) electricity; (b) the Internet for pedagogical purposes; (c) computers for pedagogical purposes; (d) adapted infrastructure and materials for students with disabilities; (e) basic drinking water; (f) single-sex basic sanitation facilities; and (g) basic handwashing facilities (as per the WASH indicator definitions)			✓	
	6.1.1 Proportion of population using safely managed drinking water services	✓		✓	
	6.3.2 Proportion of bodies of water with good ambient water quality	✓		✓	✓
	6.4.1 Change in water-use efficiency over time	✓		✓	
6 CLEAN WATER AND SANITATIO	6.4.2 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources	✓		✓	✓
	6.5.1 Degree of integrated water resources management implementation (0–100)		✓	✓	✓
	6.5.2 Proportion of transboundary basin area with an operational arrangement for water cooperation		✓		✓
	6.6.1 Change in the extent of water-related ecosystems over time	✓		✓	✓

	6.b.1 Proportion of local administrative units with established and operational policies and procedures for participation of local communities in water and sanitation management				✓
	7.1.1 Proportion of population with access to electricity	✓		✓	✓
	7.1.2 Proportion of population with primary reliance on clean fuels and technology			✓	
	7.2.1 Renewable energy share in the total final energy consumption	✓		✓	
	8.1.1 Annual growth rate of real GDP per capita	✓		✓	
	8.2.1 Annual growth rate of real GDP per employed person	✓		✓	
	8.3.1 Proportion of informal employment in non-agriculture employment, by sex	✓		✓	
	8.4.2 Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP	✓			
	8.5.2 Unemployment rate, by sex, age and persons with disabilities			✓	
	8.9.1 Tourism direct GDP as a proportion of total GDP and in growth rate	✓		✓	
	8.9.2 Proportion of jobs in sustainable tourism industries out of total tourism jobs			✓	
	9.2.1 Manufacturing value added as a proportion of GDP and per capita	✓			
	9.2.2 Manufacturing employment as a proportion of total employment	✓		✓	
	9.3.1 Proportion of small-scale industries in total industry value added				
	9.4.1 CO_2 emission per unit of value added	✓			
	10.5.1 Financial Soundness Indicators	✓		✓	
	10.b.1 Total resource flows for development, by recipient and donor countries and type of flow (e.g. official development assistance, foreign direct investment and other flows)	✓			
	11.1.1 Proportion of urban population living in slums, informal settlements or inadequate housing			✓	
	11.3.1 Ratio of land consumption rate to population growth rate			✓	
	11.4.1 Total expenditure (public and private) per capita spent on the preservation, protection and conservation of all cultural and natural heritage, by type of heritage (cultural, natural, mixed and World Heritage Centre designation), level of government (national, regional and local/municipal), type of expenditure (operating expenditure/investment) and type of private funding (donations in kind, private non-profit sector and sponsorship)	✓			
	13.2.1 Number of countries that have communicated the establishment or operationalization of an integrated policy/strategy/plan which increases their ability to adapt to the adverse impacts of climate change, and foster climate resilience and low			✓	

13 CLIMATE ACTION	greenhouse gas emissions development in a manner that does not threaten food production (including a national adaptation plan, nationally determined contribution, national communication, biennial update report or other)				
	13.3.2 Number of countries that have communicated the strengthening of institutional, systemic and individual capacity-building to implement adaptation, mitigation and technology transfer, and development actions			✓	
14 LIFE BELOW WAT[illegible]	14.1.1 Index of coastal eutrophication and floating plastic debris density			✓	
	14.4.1 Proportion of fish stocks within biologically sustainable levels	✓		✓	
	14.b.1 Progress by countries in the degree of application of a legal/regulatory/policy/institutional framework which recognizes and protects access rights for small-scale fisheries		✓		
15 LIFE ON LAND	15.1.1 Forest area as a proportion of total land area	✓			
	15.1.2 Proportion of important sites for terrestrial and freshwater biodiversity that are covered by protected areas, by ecosystem type	✓	✓	✓	
	15.6.1 Number of countries that have adopted legislative, administrative and policy frameworks to ensure fair and equitable sharing of benefits		✓		✓
	15.9.1 Progress towards national targets established in accordance with Aichi Biodiversity Target 2 of the Strategic Plan for Biodiversity 2011–2020			✓	
16 PEACE, JUST[illegible] AND STRONG[illegible] INSTITUTION[illegible]	16.6.2 Proportion of population satisfied with their last experience of public services			✓	
17 PARTNERSH[illegible] FOR THE GO[illegible]	17.1.1 Total government revenue as a proportion of GDP, by source			✓	

The second phase of the integration process involved the mapping of the relationship between the models from the WEF-Nexus perspective. The integration illustrates the linkages and interconnections between each of the models as well as their conceptual location in relation to one another. Adopting methods rooted in systems thinking and systems dynamics modelling, (Deaton and Winebrake, 2000; Sterman, 2000; Hovmand, 2014) the integration map was developed, and refined over multiple iterations in order to create the final iteration as presented in figure 4. The map comprises of three separate elements namely:

- The Case Study Scope
- The SD Domains
- The models

These three elements are connected by three types of relationships listed below:

- Nested
- Input
- Feedback

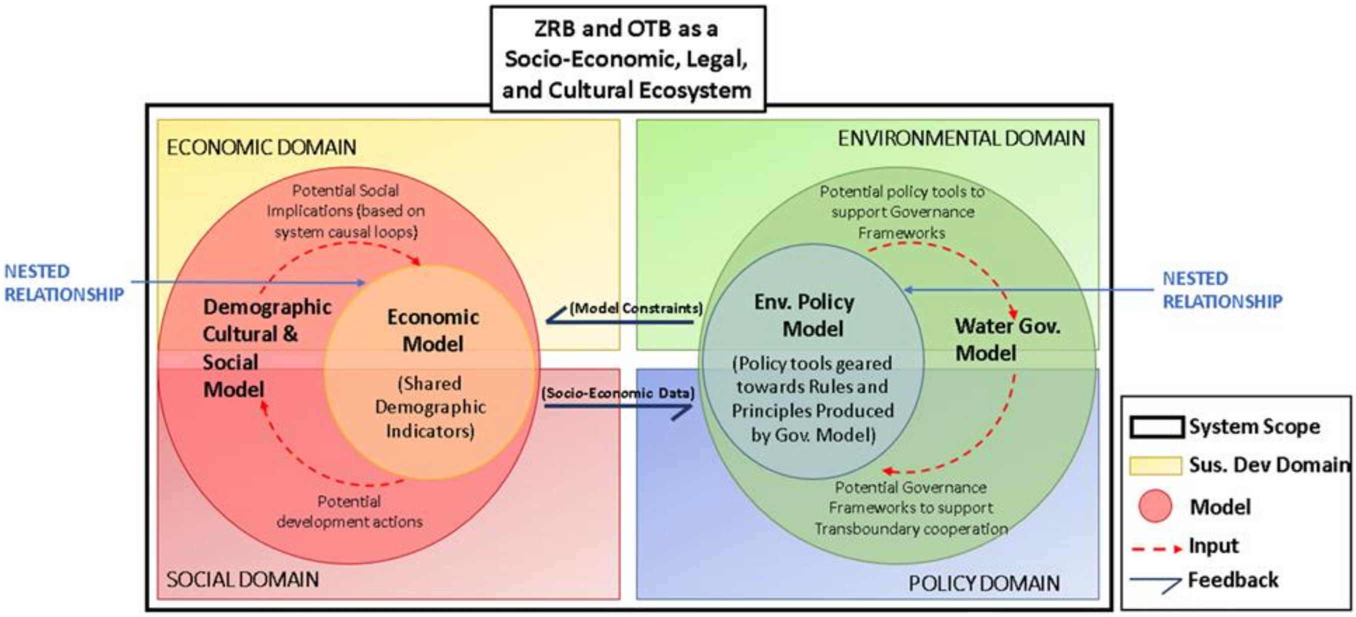

Figure 4. –Map of interconnected relationships between the individual models under Sustainable Development Framework.

The *Case Study Scope*, refers to the scope of ZRB and OTB as a Socio-Economic, Legal and Cultural Ecosystem. In keeping with the systems approach, this element provides the conceptual system boundary of the study and hence the mapping. The Case Study Scope has a nested relationship with both the SD Domains and the individual models, as both elements lie within the system boundary of the study. With the concept of SD providing an underpinning framework for the integration, the *SD Domains*, represent the four pillars of SD, and their respective focal areas within the System Scope.

The four *Models* themselves are grouped into two pairs; socio-economic models (Economic Development Model and Demographic, Cultural and Social Development Model), and institutional models (Environmental Policy Model and Water Governance Model). Each of these pairs are nested within the Economic and Social Domains, and the Environmental and Policy Domains respectively; reflecting the primary domains of activity addressed by the models. A further nested relationship is shared between each of the model pairs; with the Economic Model nested within the Demographic, Cultural and Social Development Model, while the Policy Model is nested within the Water Governance Model. Within the first pair, the *Model of Economic Development* addresses what is considered a niche aspect of the wider *Model of Demographic, Cultural and Social Development*. While in the latter pair, the *Model of Environmental Policy* reflects legal tools which may be adopted to implement the over-arching *Models and Principles of Water Governance*. Furthermore, the nested relationship between the pairs of models also reflects shared variables between each of the two models within the pair; shared demographic indicators as well as shared policy tools and principles.

Within each of the model pairs, *input relationships* exist in both directions. Between the Socio-economic models, the Economic model generates inputs for the Social model in the form of potential developmental actions; while the Social model in turn produces potential social implications of those actions within the system (based on the causal loops of the systems dynamics model). With respect to the institutional pair of models, the Water Governance model generates potential governance frameworks to support transboundary cooperation as inputs for the Environmental model; which goes on to provide inputs into the Water Governance model in the form of recommendations for potential policy tools to support proposed governance frameworks.

The left-hand (socio-economic) side and the right-hand (institutional) side of the map are connected via *feedback relationships*. These relationships represent the exchange of data and information which serves to fine-tune the operation of the models to better reflect the workings of the system scope, and thereby support the production of more robust model outputs. In this case, the institutional models provide constraints for the application of the socio-economic models; which simultaneously provide socio-economic data outputs (such as the data, findings and trends compiled by the economic, demographic and environmental models which have been utilised and incorporated by the governance model) to support the refinement of the institutional models.

4. Linking Societal Developments and Environmental Responses

As previously mentioned in this paper, the main purpose of working towards the integration of individual models is to present a clearer overarching picture of activity within the WEF Nexus. In other words, the integrated socio-anthropologic models described in the previous section of this paper, work hand-in-hand with traditional environmental research and planning tools such as hydrological, climate change and land-use models (bio-physical WEF models) as illustrated in figure 5. In addition to these models, scenarios driven by the global Representative Concentration Pathways (IPCC, 2007) and Shared Socio-economic Pathways (Kriegler et al., 2012; Kriegler et al., 2013; O'Neil et. al., 2013) are used in order to frame potential future trends in terms of climate change, water demand and availability, energy consumption and production, demographic and economic development.

While the socio-anthropologic models present societal developments, the bio-physical models are able to reflect the environmental responses as a consequence of these actions. Conversely, when the bio-physical models present given environmental states, the socio-anthropologic models can produce outputs to inform decision making. In the case of the DAFNE project, this process is embodied within a decision support tool known as the DAF. The DAF model (Burlando et.al., 2018) screens potential WEF management actions (eg. Dam construction or reservoir operation policy) under various scenarios, sequencing them in different combinations to form candidate developmental pathways (Bertoni et. al., 2017).

In the context of the DAF, bio-physical WEF models provide preliminary input for the socio-anthropologic models in the form of hydrological time series (which is of particular importance for the development of the economic model), while the model outputs support the development of the future scenarios, as well as provide input to the WEF Model in the form of model constraints which may be applied when running simulations (E.g. policy-based constraints such as limits on abstraction). Similarly, the models not only outline model constraints for the DAF simulations, but also contribute to the development of the DAF pathways by supporting the identification of candidate actions. A stakeholder working group (SWG) made up of representative WEF nexus stakeholders in the case study areas provides an avenue for validation of the model outputs as both preliminary and final model outputs can be fed back to the stakeholders. The SWG also supports the identification and selection of variables as part of the model development process.

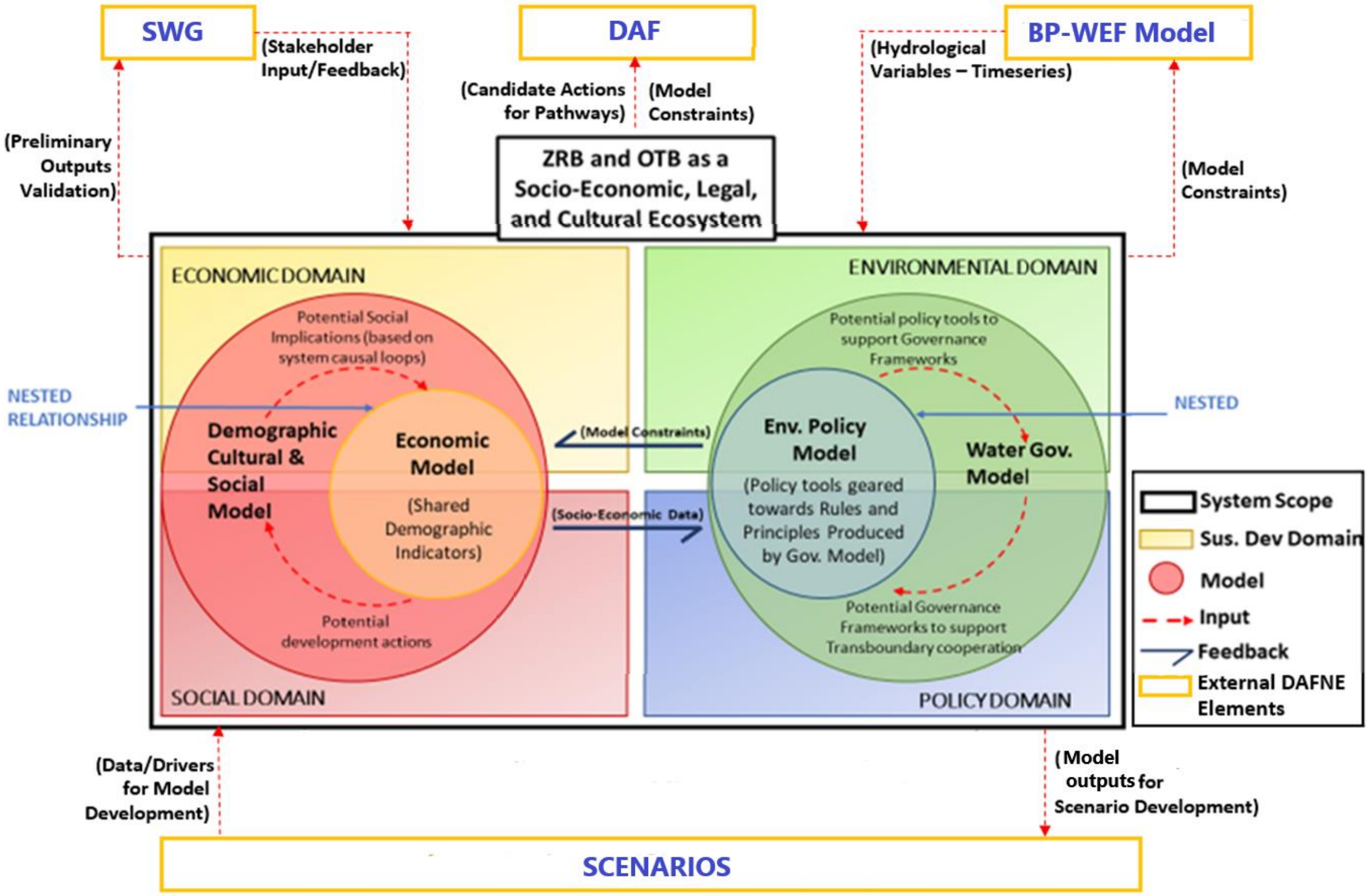

Figure 5. –Conceptual Integration of Socio-anthropologic models in with bio-physical models under the WEF Nexus DAF.

The developed framework goes some way to meet the current need for interdisciplinary approaches which seek to combine both quantitative as well as qualitative assessment methods in WEF nexus modelling (Fernandes Torres et. al., 2019). The framework adds to the emerging literature (Wu, et. al., 2015; Lischka, et. al., 2018; Olvera- Alvarez, et. al., 2018) seeking to promote interdisciplinarity within model integration for the exploration of various sectors such as ecology, healthcare and socio-technical systems. Additionally, it extends previous forays towards integration within WEF Nexus studies (McCarl, et. al., 2017; Hussein, et. al., 2017) by making explicit the role of policy and governance in understanding the WEF Nexus; thereby placing just as much emphasis on these aspects as on hydrology or land-use within the modelling process. While in the case examined in this paper, the framework is applied to a set of models that explore the WEF Nexus from a transboundary perspective, the framework is flexible enough to be applied at various other scales (national, regional, and local). By defining a structure for the interactions between different types of models, the framework has the potential to be a particularly useful tool in WEF nexus management. Furthermore, the framework embeds the concept of sustainable development into the integration structure, by mapping the individual models onto the SDGIs. Thus, making it a valuable aid for decision makers working towards the implementation of the SDGs.

Conclusions

With inefficient management of natural resources recognized as the biggest obstacle to achieving sustainable WEF nexus management, accessible knowledge and data to inform evidenced-based decision making have been identified as crucial to ensuring effective natural resource management in the WEF context. This necessitates the availability of innovative tools to both support understanding of the WEF nexus as well guide decision making; tools which are dynamic enough to provide a holistic picture of the workings of the various elements at play within the WEF nexus.

Based on the results of each model as outlined in prior sections of this paper, along with the integration approach detailed, it is possible to analyse key WEF issues from multiple perspectives. For example, when the Economic model produces potential actions (e.g. prioritisation of agriculture, or energy production), while the WEF model presents the environmental responses, the Socio-Cultural model produces the potential implications of these actions (e.g. more food production leads to less poverty, or a higher demand for energy causes deforestation). The policy and governance models are then able to present policy tools and governance frameworks that can either support development in line with the proposed actions, or mitigate against potential environmental impacts that could result from a certain course of action. This shows the complementarity and overlapping relations between the governance and environmental models.

While environmental models are useful decision-making tools, considering them in conjunction with socio-economic and policy-based models provides a more holistic overview of the ecosystem. The greatest environmental impacts are arguably as a result of human activity. Furthermore, shifts in the dynamics around the WEF nexus and subsequent trends are equally stimulated by human activity. In the case of the DAFNE DAF, which focuses on the WEF Nexus and as such the dynamics (trade-offs and synergies) between each of the issues which converge at the nexus, obtaining an inclusive perspective is of even greater importance. As such, while each of the models provide an in-depth view into a unique slice of the nexus, incorporating outputs from all the models brings various pieces of the puzzle together, providing a richer picture and making any subsequent decision-making process more robust and more effective.

Acknowledgements: This work is supported by the Decision Analytic Framework to explore the water-energy-food nexus in complex transboundary water resource systems of fast developing countries (DAFNE) project, which has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 690268.

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