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

Ebun Akinsete [1]*, *Phoebe Koundouri* [2], *Xanthi Kartala* [2], *Nikos Englezos* [3], *Jonathan Lautze* [4], *Zeray Yihdego* [5], *Julie Gibson* [6], *Geeske Scholz* [7], *Caroline van Bers* [7] and *Jan Sodoge* [8]

[1] International Centre for Research on the Environment and the Economy (ICRE8), Maroussi, Greece, [2] Department of International and European Economic Studies, Athens University of Economics and Business, Athens, Greece, [3] Department of Banking and Financial Management, University of Piraeus, Piraeus, Greece, [4] International Water Management Institute, Pretoria, South Africa, [5] School of Law, University of Aberdeen, Aberdeen, United Kingdom, [6] Centre for Environmental Law and Governance, University of Strathclyde, Glasgow, United Kingdom, [7] Institute of Environmental Systems Research, Osnabrück University, Osnabrück, Germany, [8] Institute for Analytical Sociology, Linköping University, Linköping, Sweden

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***Correspondence:**
Ebun Akinsete
ebun.akinsete@icre8.eu

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Rapid population growth along with increased rates of economic growth around the globe are placing valuable natural resources, water in particular, under unprecedented stress; this in turn drives the pursuit of innovative tools to support integrated Water-Energy-Food (WEF) nexus management. This paper presents a framework for the integrated management of the WEF nexus, which brings together four separate models that address the less well-examined socio-anthropological aspects of the nexus. The proposed framework provides insight into the human element as part of the wider ecosystem in terms of socio-cultural and economic activities, the laws and policies that govern these activities, as well as their potential socio-economic impacts and consequences. This paper outlines each individual model, before going on to present a conceptual framework for the integration of the various models for the purpose of supporting more robust decision-making. The framework, which is grounded in systems thinking, adopts the principles of sustainable development as structural foci in order to position the various models in relation to one another; harmonizing their inputs as well as outputs.

Keywords: sustainable resource management, Sustainable Development Goals (SDGs), WEF nexus, integrated water resource management, decision support system (DSS)

INTRODUCTION

Water is a precious resource which not only plays a central role in supporting life on earth, but also exists as a social and economic good. Over the years, rising levels of scarcity have drawn attention to the increasing pressures on global water resources; as 52% of the global population is predicted to live in water-stressed nations by 2050 (Schlosser et al., 2014). In addition, decision-makers are tasked with addressing the challenge posed by sustainably managing the resource in the face of often competing user needs (such as drinking, irrigation, industrial production, leisure, tourism, energy and ecosystem functions). In fact, the scale and complexity of this challenge and the resultant inefficiency in managing water resources, is acknowledged as the greatest threat to global water resources (UNDP, 2006; Ngaira, 2009; Mason et al., 2019). Historically, disaggregated and siloed approaches to natural resource management and allocation, which consider the development of each sector in isolation, have led to the inequitable distribution and prioritization of resources (Mabhaudhi et al., 2019). As such, the community of practice around water has responded with a wave of support for Integrated Water Resource Management (IWRM), which promotes a coordinated approach toward managing water and related resources in a manner that ensures equitable socio-economic and environmental welfare (Perry, 1999; Agarwal et al., 2000; United Nations, 2002; Biswas, 2004; Jønch-Clausen, 2004; Lenton and Muller, 2012). While IWRM serves as a broad foundation for practitioners and researchers alike to address water-related issues from a more holistic perspective, the framework is not without its critics; citing the inherent vagueness in terms of its definition, consideration of what resources and/or sectors ought to be integrated and the implementation of the framework itself (Moench et al., 2003; Biswas, 2008). In addition, despite efforts to promote a more comprehensive view on natural resource management, IWRM is still to a large extent weighted toward the water sector as the primary focus; with other sectors such as land-use planning, energy, agriculture etc. considered as *de facto* secondary sectors (Biswas, 2008; Savenije and Van der Zaag, 2008; Giordano and Shah, 2014).

"Nexus thinking" has emerged as an alternative paradigm which considers sets of interrelated sectors, addressing the complexity of associated issues holistically, in order to tackle relevant problems (Muller, 2015). The Water-Energy-Food (WEF) Nexus describes the confluence of the issues related to water availability (both in terms of quantity and quality), energy generation and food production; taking into account synergies and trade-offs with associated with resource allocation (Hellegers et al., 2008; Bazilian et al., 2011; UN-Flores, 2017; Fernandes Torres et al., 2019; Katz et al., 2020). Crucially, while the IWRM framework focuses on a comprehensive approach from a mono-sectoral (water sector) perspective, the WEF nexus approach places emphasis on engaging with multiple sectors and analyzing cross-sectoral issues simultaneously (Mabhaudhi et al., 2016; Rasul and Sharma, 2016; Nhamo et al., 2018; United Nations, 2021). With this embedded "systems thinking" (Sterman, 2000), the WEF nexus approach lends itself to the examination of other complex challenges such as sustainable development (Albrecht et al., 2018; Liu et al., 2018), since it acknowledges and addresses the complexities and interdependencies between the various environmental and societal challenges, as well as developmental issues such as poverty reduction and gender equality (Kundzewicz, 1997; Jønch-Clausen, 2004). Therefore, WEF nexus approaches are not just crucial tools for resource management, but also for the implementation of developmental policies (Hering and Ingold, 2012; Boas et al., 2016) and agendas such as the Sustainable Development Goals[1] (United Nations, 2015) (see **Figure 1**).

In recent years, several studies (Welsch et al., 2014; Webber, 2016; Anghileri et al., 2017; Albrecht et al., 2018) have explored the use of integrated models in the context of WEF Nexus management. For the most part these models have focused on environmental management, with the integration of traditional Climate, Land-use, Energy and Water Strategy (CLEWS) models, which are epistemologically rooted in the natural sciences; such as climate change models, hydrological models, and agricultural or crop models (Allwood et al., 2013; Howells et al., 2013; Daher and Mohtar, 2015; Daher et al., 2017, 2018; FAO, 2018; Dargin et al., 2019). A few combine aspects of hydrological modeling with economic modeling (Jalilov et al., 2015; Bekchanov and Lamers, 2016; Yang et al., 2016); and while cross-disciplinary, these integrated tools primarily employ quantitative approaches. Even integration frameworks which acknowledge the importance of adequately representing system elements (McCarl et al., 2017), fall short when it comes to capturing societal interactions. Instead, they place more emphasis on bringing together energy models, crop models and hydrological models. Mixed-methodological tools drawing on different disciplines and combining both quantitative and qualitative approaches are few and far between; and while most support stakeholder engagement (Karlberg et al., 2015; de Strasser et al., 2016; Smajgl et al., 2016; Wolfe et al., 2016) as well as inform policy development (Endo et al., 2015; Soliev et al., 2015), they fail to incorporate anthropo-centric models which address the human element of the system (modeling governance and socio-cultural aspects of the system). Although Givens et al. (2018) acknowledges key challenges in bridging the disciplinary and philosophical divides necessary to integrate anthropo-centric considerations and models within the traditional WEF Nexus structures, Molajou and Afshar (2021) reassert the importance of social models in this anthropogenic age where human intervention increasingly impacts WEF processes. This gap hampers the effectiveness of such integrated models, limiting their role as tools for development which incorporate not just the physical characteristics of the WEF Nexus challenge, but also its political and socio-economic characteristics in order to balance stakeholder viewpoints and better support decision-making processes (Rahaman and Varis, 2005; Grigg, 2008). As a consequence, the impacts of anthropogenic systems within the WEF nexus are not adequately represented, resulting in unsuccessful attempts to tackle environmental challenges as well as strategies and interventions which do not yield the expected results (Dang and Konar, 2018; Kuil et al., 2019; Panahi et al., 2020).

[1]Sustainable Development Goals: The SDGs are a collection of 17 global goals and 169 targets set out under the UN 2030 Agenda, geared towards the advancement of sustainable development across the globe by 2030 https://www.un.org/sustainabledevelopment/sustainable-development-goals/.

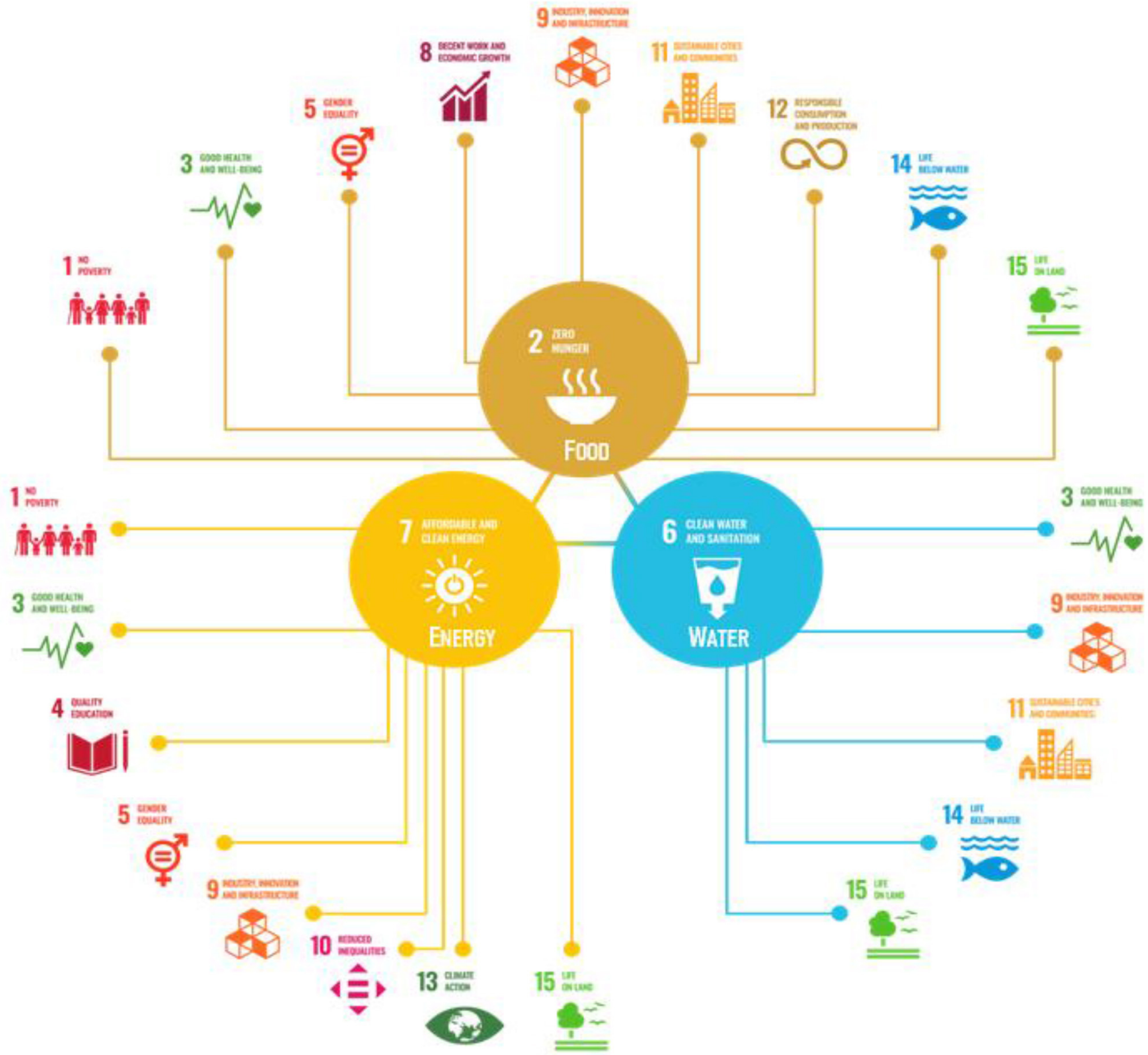

FIGURE 1 | Sustainable development goals in the context of the WEF nexus (author's own).

This article presents research[2] conducted as part of the European Commission funded Horizon2020 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 modeling component (hydrological and environmental models), as well as a socio-anthropologic modeling component (modeling social, economic and institutional developments). The latter set of models includes four separate models which account for different aspects of the socio-ecological interactions within the WEF nexus. These are models of:

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

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

The socio-anthropologic models examined within this paper are centered around the behavior and interactions of the human actors 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. This paper focuses on these socio-anthropologic models, conceptualizing a theoretical approach toward harmonizing model outputs within an integrated framework. It provides a broad overview of the four individual socio-anthropologic models, as each of the models are examined in detail within other publications (Koundouri et al., 2017; Lautze et al., 2017; Lautze and Mukuyu, 2019; Lumosi et al., 2019; Scholz et al., 2019; Yihdego and Gibson, 2020). The article then proceeds to outline a unifying sustainable development framework for the integration of the four models, by mapping their 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 the other WEF Nexus analytical tools developed by the project; including the bio-physical models and the broader DAF.

MODELING THE ANTHROPOLOGICAL SPHERE OF THE WEF NEXUS

The first step toward analyzing the anthropological sphere of the WEF Nexus, and indeed any WEF nexus analysis is the identification of the system boundaries; be that river basin, watershed, national or regional boarders etc. In the case of the DAFNE project, the models are developed in the context of two transboundary river basins in southern and eastern Africa, considering the international implications of the various WEF nexus issues. While the economic and social models are distinctive in their scope, the environmental policy and governance models share a thematic focus. The latter set of models are complementary; the environmental model aims to identify the extent to which relevant laws and policies of riparian countries consider and address critical environmental issues (proposing ways in which responses to environmental issues can be improved), while 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 carry out processes (harmonization of national laws and developmental strategies and approaches) developed to manage water resources in the context of WEF nexus-related activities.

The first model is the economic development model, the objective of which is to describe the economic development of the riparian region, describing the use of water and its value to the functioning of the economy (Koundouri et al., 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 utilize 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 (TEV) of water. As multiple countries share water resources, the likelihood of conflicts over the allocation of water resources increases; particularly with 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 the key WEF-related economic sectors within the river basin countries, namely:

- agricultural sector
- energy sector
- industrial/mining/extractive sector
- residential sector
- tourism sector

While the relationship between the agricultural and the energy sectors within the WEF nexus is clearly discernible, the link with the latter three sectors (industrial/mining/extractive, residential and tourism) is less so. These sectors impact the availability of water within in the river basin in terms of consumptive demand for drinking, sanitation (linked to demographic trends of the local populations and seasonal tourist numbers) and industrial processes such as mining and the extractive sector as a whole (ZAMCOM, 2016; EORA, 2017; World Population Review, 2018). In addition, they depend on water to provide the natural habitat on which the tourism industries of the river basin countries rely (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 indicate the function of 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]. The main output of the model is an estimation of the derived demand for water use, as well as the optimal economic WEF nexus scenario in environmental terms. In other words, the model aids in the identification of the scenario where WEF nexus resources provide are utilized to provide the greatest economic benefit with the least environmental impact.

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, 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 (Lautze et al., 2017).

The model of environmental policy is a *Model of Legal Principles and Norms* (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 two river basins 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 areas of concern were largely the same. Based on this, five key environmental issues were adopted as the focus of the investigation:

- 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, with the laws and policies 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: (i) Extent of coverage to five identified environmental issues in the two basins, (ii) Degree of institutional alignment within basins, (iii) Congruity between laws and policies in environment vs. non-environmental sectors. The assessment subsequently identifies key areas in need of strengthening, which are translated into policy alternatives aimed at addressing these areas.

The third model focuses 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 et al., 2019). The model identifies relationships between different natural resource and societal factors within the river basin; 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 are given special consideration. By displaying balancing or reinforcing feedback loops, the model helps to identify system responses and behavior. Furthermore, it allows the decision-maker to consider whether important influences have been sufficiently taken into account, as well as general system responses that might result from changes in elements of the system (e.g., population growth). 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 rely on quantitative data about relationships between factors. 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 river basins and subsequently integrating their perspectives (Scholz et al., 2019). While a set of suggested variables (based on demographic, cultural and social issues related to the WEF Nexus) was identified during stakeholder workshops to facilitate the modeling process, the variables adopted within the social model (such as population growth, access to water and/or food, displacement, urbanization and agricultural practices) were suggested by the interviewed stakeholders. During the interviews, causal loop diagrams (CLDs) displaying the links between cause and effect within the system were developed together with 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 analyzed and combined in a joint model which demonstrates the key linkages between elements and their potential impacts (Scholz et al., 2019).

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 modeling exercise indicates the level of legal expectation with regards to a number of key legal principles within the river basin countries. Transboundary watercourses fulfill a number of roles in relation to social and economic development across a number of sectors such as energy and agriculture. They can also pose several risks such as floods, droughts and environmental challenges. It is therefore challenging to balance these complex and often competing uses, particularly across multiples countries. Governance structures developed through legal, political and organizational 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 laws concerning international watercourses, the WEF nexus and the SDGs (Yihdego and 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 the economy of water resource use.

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 review 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[3]
2. No Significant Harm[4]
3. Ecosystem Protection[5]
4. Pollution Prevention[6]
5. Intergenerational Equity[7]
6. Precautionary Principle[8]
7. Environmental Impact Assessment[9]
8. Transboundary Impact Assessment[10]
9. Provision for Establishment of Joint Body/Mechanism[11]
10. Information/Data Exchange[12]
11. Notification[13]
12. Consultation[14]
13. Dispute Settlement[15]

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 (i.e., from absence of a legal document to fully ratified treaties); 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. The assessment and analysis reveal potential areas of improvement regarding the coherence of implementation of such principles across the riparian region.

While it is recognized that each of the above models generates insightful findings about the WEF nexus in the context of their respective foci (economic, environmental, social and legal), complementarity is required to provide a holistic view of the socio-anthropologic workings of the WEF Nexus and potentially generate richer and more valuable results. As such, a key ambition of the DAFNE project from the very beginning, was to address this integration by developing a framework that could bring together these various models; efficiently harmonizing their inputs and outputs.

SUSTAINABLE DEVELOPMENT AS A FOUNDATION FOR MODEL INTEGRATION

In principle, each of the different models seeks to reflect a particular aspect of human and institutional interactions within the conceptual boundaries of the WEF Nexus. Differences in

[3] *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.

[4] UNWC, Article 7.

[5] UNWC, Article 20.

[6] 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).

[7] 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).

[8] 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).

[9] 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.

[10] 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.

[11] 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.

[12] 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.

[13] UNWC, Article 11.

[14] UNWC, Article 17.

[15] UNWC, Article 33.

methodology and terminology between the disciplines, brought about by a traditionally siloed approach, have created barriers (Givens et al., 2018) which 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, a dedicated effort was made toward gaining an understanding of the various disciplinary perspectives and approaches in developing their respective models.

The first phase of the integration process, initiated during at the early stages of the development of the individual models, involved the construction of a foundational framework for the model integration. As the ultimate outcome of sustainable WEF Nexus management (Hering and Ingold, 2012; Boas et al., 2016; Bleischwitz et al., 2018; Hülsmann and Ardakanian, 2018; Caucci et al., 2020). Sustainable Development (SD) was adopted as unifying element, which would essentially provide the conceptual scaffolding upon which the model integration process could be constructed. While the Sustainable Development Goals (SDGs) and the Sustainable Development Goals Indicators (SDGIs) serve 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 conceptualization. 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 making explicit the underlying role that is played by governance and policy in the implementation of SD, that the team adopted a "4 Ps" characterization of the concept, including "policy" as a fourth pillar of SD; in addition to the original planet, people, and profit.

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 dimensions of the river basin being modeled and reflect the separate focal areas of each of the four models. This not only serves to contextualize each model within the scope of SD, but the relevant domains helped inform the indicators adopted within each of the 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 act as another tether to connect individual models (Koundouri et al., 2017; Lautze et al., 2017; Lautze and Mukuyu, 2019; Lumosi et al., 2019; Scholz et al., 2019; Yihdego and Gibson, 2020), by incorporating the SDGIs[16] into the SD framework. The full list of SDGIs was reviewed and edited down to a reduced list of indicators considered by each of the models (see **Appendix 1**). In total, 59 SDGIs and 15 SDGs were taken into account in some form or another by the four models.

The second phase of the integration process involves 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 modeling (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 2**.

The map comprises of three separate elements namely:

- The Study Scope
- The SD Domains
- The models

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

- Nested
- Input
- Feedback

The *Study Scope*, refers to the area of study examined by the models (river basin, watershed, country, region, etc.) 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 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

[16]SDG Indicators: The SDGIs are a set of 232 indicators adopted by the UN in order to monitor global progress on the SDGs. *https://unstats.un.org/sdgs/indicators/indicators-list*.

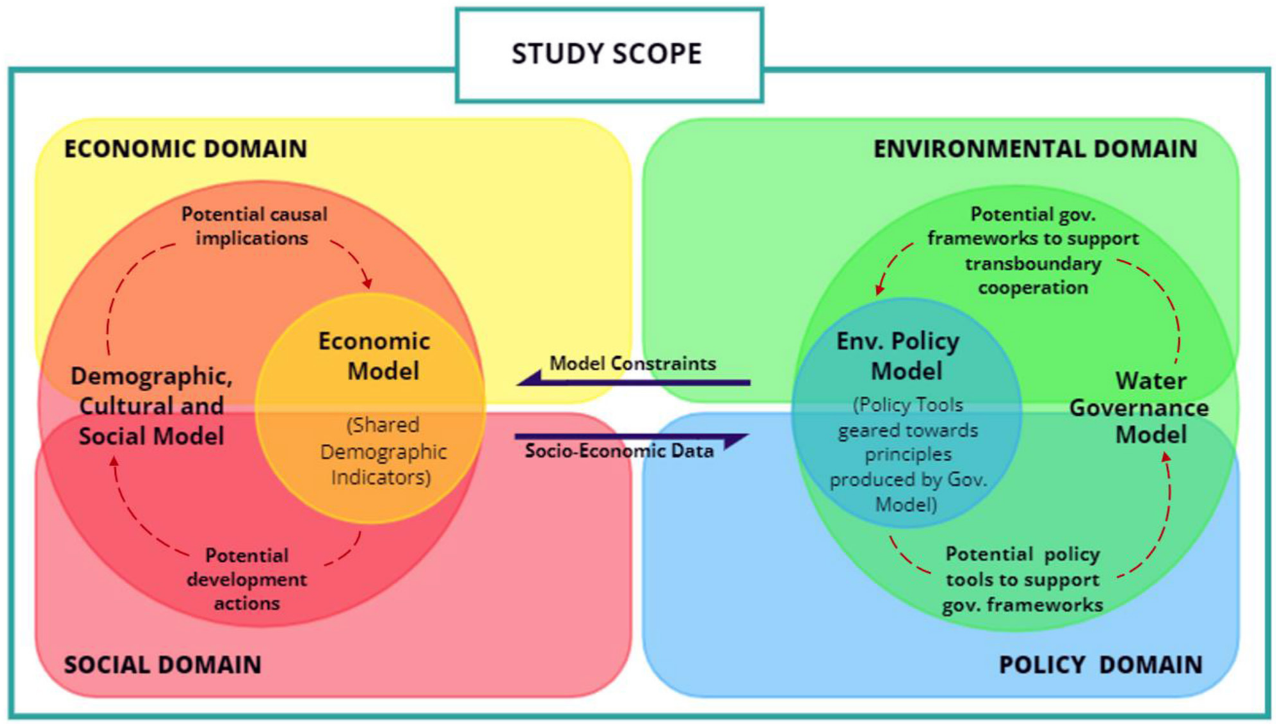

FIGURE 2 | Map of interconnected relationships between the individual models under sustainable development framework.

Model of Environmental Policy reflects legal tools which may be adopted to implement the overarching *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; i.e., 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 **Figure 2** 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 utilized and incorporated by the governance model) to support the refinement of the institutional models.

LINKING SOCIETAL DEVELOPMENTS AND ENVIRONMENTAL RESPONSES

As previously mentioned, the main purpose of working toward 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 article, 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 3**. In addition to these models, scenarios driven by the global Representative Concentration Pathways (IPCC, 2007) and Shared Socio-economic Pathways (Kriegler et al., 2012, 2013; O'Neill et al., 2014) 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. These scenarios also seek to address uncertainty within the systems being examined and modeled (Bertoni et al., 2017). Due consideration of uncertainty within the framework

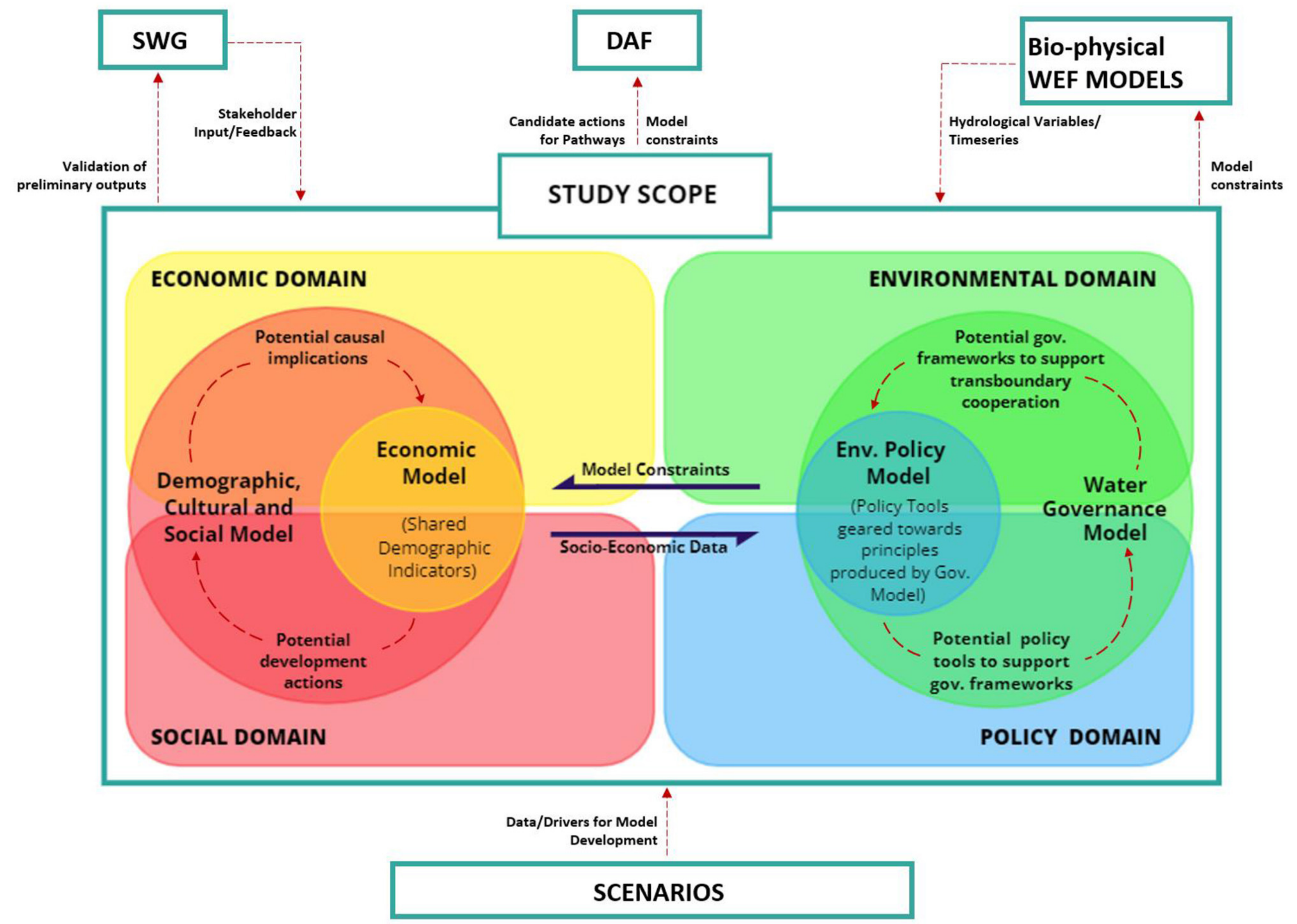

FIGURE 3 | Conceptual integration of socio-anthropologic models with bio-physical models under the WEF nexus DAF.

is critical, and is characterized firstly in terms of long run uncertainty based on the alternative scenarios for population growth, energy, GDP, climate change, etc. (McCarl et al., 2017), as well as within the quantitative models (economic and bio-physical models) which take into account the uncertainty posed by climate change (Bhaduri et al., 2011).

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 (Burlando et al., 2018) screens potential WEF management actions (e.g., 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 socio-anthropologic model outputs support the development of management actions, as well as provide input to the bio-physical WEF models 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 from the 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.

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 modeling (Fernandes Torres et al., 2019); adding to the emerging literature (Wu et al., 2015; Lischka et al., 2018; Olvera-Alvarez et al., 2018), and seeking to promote interdisciplinarity within model integration for the exploration of various sectors such as ecology, healthcare and socio-technical systems. However, despite the advances put forward by the framework, the predominantly qualitative nature of the socio-anthropologic models poses a challenge in the framework's consideration of uncertainty. While uncertainty is embedded within the various scenarios run by the DAF, it is not explicitly addressed within the framework itself (with the mathematically-based economic model being the only socio-anthropological model to internalize uncertainty). Furthermore, although the DAF can be run within a stakeholder workshop to facilitate decision making, the integrated framework itself does not offer concrete solutions to address pluralism amongst stakeholder views and working toward consensus. Both of the aforementioned areas offer avenues for further research and refinement of the integrated framework in the future.

That said, the framework extends previous forays toward integration within WEF Nexus studies (McCarl et al., 2017; Wa'el 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 modeling process. While in the case examined in this article, 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 other scales (national, regional 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 toward the implementation of the SDGs and SD in general.

Each of the models outlined in this paper, along with the integration approach presented, make it possible not only to analyze key WEF issues from multiple perspectives but to merge their outputs in order to generate a more complete view of the WEF nexus interactions. For example, when the Economic model produces potential actions (e.g., prioritization of agriculture, or energy production), while the bio-physical WEF models present 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 leads to 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 demonstrates the complementarity between the models, and the utilization of outputs across models and disciplines.

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. A majority of the environmental impacts observed today 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 Decision Analytic Framework, which focuses on the WEF Nexus and therefore, 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 provides an in-depth view into a unique slice of the WEF nexus, incorporating outputs from all the models brings various pieces of the puzzle together; providing a richer picture and enhancing the robustness and effectiveness of any subsequent decision-making process.

CONCLUSIONS

> *Water should be recognized as a tool for community development, peace building, and preventive diplomacy. Water can have an overreaching value capable of coalescing conflicting interests and facilitating consensus building among societies. To incorporate all of the physical, political, and economic characteristics for a river basin, a process for cooperative watershed management is vital.*
> - Rahaman and Varis, 2005

With the 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 a deeper 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. In particular, tools which place adequate importance on the human agent within the WEF nexus, and reflect the intervention of society and institutions.

AUTHOR CONTRIBUTIONS

EA: conceptualization, investigation, methodology, visualization, writing—original draft, and writing—review and editing. PK, XK, NE, JL, ZY, JG, GS, CB, and JS: conceptualization, investigation, methodology, and writing—review and editing. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2022.727772/full#supplementary-material

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