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The nexus across water, energy and food (WEF): Learning from research, building on evidence, strengthening practice

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Abstract

While water-energy-food (WEF) Nexus is one of the most important, and widely investigated, environmental topics of our time, previous stock taking efforts possess notable limitations, namely (i) their focus is restricted to research articles, and (ii) there is less focus on nexus permutations that begin with energy and food. This paper assembled more than 900 documents and systematically categorized them according to more than 10 key parameters (e.g. scale, methods, limitations), to characterize approaches, achieved outcomes and presence of variables likely to support on-the-ground change. Our results reveal that WEF Nexus activities are often driven by the water sector, undertaken at global and national scale and authored by experts from diverse backgrounds. Among the utilized methods, modelling and review (i.e. systematic) are the most common. While climate change and governance are routinely considered in WEF Nexus documents, gender, stakeholders and capacity are not. These findings highlight areas for improvement in the design of WEF Nexus initiatives.

KEYWORDS
conceptual framework, multi-sectoral, systems thinking, water-energy-food nexus

1 | INTRODUCTION

1.1 | The water-energy-food (WEF) Nexus is intrinsically important

The WEF Nexus (just 'Nexus' in the following) across energy, food and water is intrinsically important as these sectors are all dependent on one another (Keulertz et al., 2016). Energy is important to access water, and water is a key means to generate energy. Equally, water is essential for food production but food production can compromise water quality. Reflecting the importance of these interlinkages, the German Government organized a widely-heralded conference in 2011 on the *Water, Energy and Food Security Nexus-Solutions for the Green Economy* (Hoff, 2011). Subsequently, the concept experienced a rapid rise in prominence and captures interconnection between multiple goals of Agenda 2030 of the Sustainable Development Goals (OFID, 2017; Ortigara et al., 2018; United Nations, 2018) and is reflected in strategies of key development agencies such as the Asian Development Bank (Panella, 2021).

1.2 | Nexus provides practical value in an inter-connected world of growing risk

As countries emerge from a global pandemic only to face more intense manifestations of climate change (IPCC, 2022; World Economic Forum, 2022), there is growing urgency to pursue integrated and resilient approaches to resource management (Smith et al., 2019) to maximize their beneficial uses. The coronavirus disease (COVID-19) related risks of interruptions to the supply of and demand for resources, particularly for the WEF resources (Al-Saidi & Hussein, 2021) accentuate the need to rebuild our society differently. For instance, Kazakhstan, one of the biggest global wheat flour exporters, suspended exports as a result of COVID-19 (Harvey, 2020), resulting in supply shortages and price increases in importing countries like Tajikistan (FAO, 2021) that has plenty of water resources and is investing heavily in hydropower while running on grain deficit.

1.3 | The Nexus has been extensively investigated, and also practically implemented

Recognition of the value of Nexus approaches has driven ubiquitous research investigation, and thorough interrogation, of the nexus concept. A past search of Google Scholar (Lautze et al., 2020) suggested more than 8000 articles have been written on the nexus, while a range of review articles (Albrecht et al., 2018; Shannak et al., 2018; Simpson & Jewitt, 2019a) have identified the lower but still voluminous body of Nexus literature. Lost at times among the widespread nexus literature are emerging experiences in the practical implementation of Nexus projects, particularly in the developing world. For example, using seawater for aquaculture and utilizing nutrient-rich outflow from aquaculture to grow halophyte plants that are used for biofuel production (UAE and Qatar) (Halalsheh et al., n.d.). While there has been growing emphasis on stock-taking Nexus activities (Albrecht et al., 2018; Shannak et al., 2018; Simpson & Jewitt, 2019a), it is not clear whether such efforts merely review research endeavours or extend to include practice.

1.4 | Taking stock of stock-takes

Stock-takes of literature pertaining to the Nexus of different permutations of W-E-F are in no short supply (e.g. Albrecht et al., 2018; Al-Thani & Al-Ansari, 2021; Botai et al., 2021; Hamidov & Helming, 2020; Kliskey et al., 2021; Kondash et al., 2021; Namany et al., 2019; Opejin et al., 2020; Proctor et al., 2021; Purwanto et al., 2021; Sarkodie & Owusu, 2020; Shannak et al., 2018; Simpson & Jewitt, 2019a; Urbinatti et al., 2020; Wahl et al., 2021). Some of this literature focuses only on a particular country or region (e.g. Botai et al., 2021; Kondash et al., 2021; Okumu et al., 2021), however, while other portions of this literature do not include analysis of article contents but focus mainly on the

frequency of keywords (Opejin et al., 2020; Proctor et al., 2021; Sarkodie & Owusu, 2020; Urbinatti et al., 2020). Still, other segments of this literature focus on the Nexus only in certain contexts such as urban areas (Wahl et al., 2021) or irrigation (Hamidov & Helming, 2020), or related to certain perspectives (Namany et al., 2019; Purwanto et al., 2021; Shannak et al., 2018) or particular objectives (Al-Thani & Al-Ansari, 2021). Finally, while some segments of this literature do attempt to review document content with few explicit constraints, the sample sizes utilized in such documents appear far from exhaustive. Albrecht et al. (2018) undertook a systematic review of WEF Nexus assessment methods employed in 245 articles. Simpson and Jewitt (2019a) undertook a review of 53 journal articles and documents from four grey literature. Kliskey et al. (2021) applied an assessment framework to 289 WEF Nexus articles. In any case, limitations that appear to cross-cut the existing set of Nexus stock-takes include: (i) they include research publications but exclude practically implemented nexus projects, and (ii) they are far from exhaustive, often examining a relatively small subset of available documentation.

1.5 | Value add of this paper

This paper is believed to constitute the most comprehensive Nexus stock-take undertaken assembling over 900 documents for full-text analysis. The paper addresses limitations of existing knowledge by extending the scope and broadening the focus of past Nexus stock-takes, in at least two ways:

- To extend the scope, we examine the literature on both research and practice.
- To broaden the focus, we include relevant literature regardless of the sectoral perspective from which it has emerged; sectors in Nexus acronyms can occur in any sequence.

We also present a redesigned conceptual framework oriented towards capturing key factors relevant for achieving Nexus outcomes. To help move from concept to practice, we assess the frequency of inclusion of these key factors—for example, scale, research or implementation methods and sectoral focus—in the Nexus literature.

1.6 | Objective, purpose, structure

This paper analyses the most voluminous set of Nexus documents to-date in order to characterize the depth and breadth of literature on the Nexus. Equally, the paper seeks to reveal status, trends and limitations in the body of work on the Nexus. The purpose of pursuing these objectives is to contextualize ongoing and future efforts, to encourage focus to be placed in areas that are (i) new, and (ii) likely to lead to positive, practical change. The paper first reviews the document collection process and develops an analytical framework in order to capture key aspects of Nexus documents. The paper then categorizes and synthesizes past research and implementation efforts. Key threads from past efforts are distilled, and recommendations are generated on priority areas of focus going forward.

2 | METHODS

2.1 | A framework encompassing water, energy and food

2.1.1 | Nexus origins

Nexus is defined as a connection or series of connections linking two or more things (Merriam-Webster, 2021). The term is widely-used across many sectors, but it would appear to have proliferated especially in technology[1] and

development, for example, GIZ et al. (2014). In the development sector, Nexus is most often applied to integration across sectors of environment, water, energy, agriculture, natural resources and biodiversity—all of these sectors comprise key areas of development programming.

2.1.2 | Permutations of nexus frameworks

A search of Nexus literature in the development community reveals frameworks that encompass various combinations of the three core sectors—that is, water, energy and food—as well as frameworks that include a focus on additional sectors. Hoff (2011) produced one of the first WEF Nexus schematics, in which water is situated at the centre of the triangle with water security, food security and energy security. SIM4NEXUS (n.d.) considered the nexus of climate, water, land, food, energy and ecosystems, with resources efficiency as the ultimate goal. Melo et al. (2021) advocate for forests to form an additional, foundational dimension of the water, energy, food, forest security nexus framework. Ultimately, while there are countless other examples, these documents serve to illustrate there are numerous permutations and indeed potential additions to the Nexus framings across energy, food and water. This paper focuses on W-E-F, in any order, as a common denominator of analysis.

2.1.3 | Limitations of nexus frameworks

An increasingly recognized limitation of W-E-F framings is that they often have not been put to practice. Leck et al. (2015) suggest efforts to conceptualize the Nexus have been too ambitious and sophisticated for practical application. Al-Saidi and Elagib (2017) assert that Nexus is a novel concept with few practically useful recommendations. Simpson and Jewitt (2019a) equally underline that more focus is needed on action and mention a number of WEF Nexus challenges including the complexity of temporal and spatial scales. Zarei et al. (2020) clarify that not only the proposed management for the WEF nexus but even the analysis are at the theoretical stage. Rasul and Neupane (2021) make the connection between a lack of a framework that can operationalize the concept as a decision-making or a planning tool and the scarcity of its practical applications. Factors explaining the lack of application include:

- Absence of appropriate institutional arrangements to handle the complexity (Rasul et al., 2021);
- Insufficient stakeholder interaction (Wahl et al., 2021);
- Insufficient understanding of the interlinkages of W-E-F systems due to knowledge and data gaps (Simpson & Jewitt, 2019a);
- Feasibility of science-policy integration, for example, mismatch of disciplines, views, topical areas and jurisdiction (Romero-Lankao et al., 2017);
- Cross-scale inequalities, for example, scalar considerations of which WEF systems should be considered, by whom and for whom they should be secured (Romero-Lankao et al., 2017) and
- Path dependency, for example, infrastructure and social practices adopted for individual WEF systems are difficult to change (Romero-Lankao et al., 2017).

2.1.4 | Synthesizing a nexus framework

While a review of the abundance of existing Nexus frameworks reveals substantial variation, certain common threads are also apparent. Synthesis of these core threads suggests a framing with water, food and energy at three points of a shared triangle (Figure 1), acknowledging that the points affect each other (biophysically) and related social and economic settings.[2] Reconciling diverse sectoral perspectives suggests that a particular sector should not feature at the

centre of this triangle, because the three sectors are interrelated and each is essential (Willis et al., 2016). Rather, at the heart of the triangle are sustainable and resilient societies and economies—that is, the overall aim is to achieve through informed interventions that consider interdependencies, synergies and trade-offs across the three sectors embedded in other environmental systems and climate change. Indeed, the aim of a Nexus is not simply to integrate different sectors but to achieve an outcome that is more beneficial than pursuing isolated sectoral goals and build resilience and sustainability. Finally, given that the Nexus interaction do not exist in isolation but are grounded in a contextual environment that includes issues such as biodiversity, ecosystems processes and functions and environmental and societal pressures (e.g. climate change, demographic change, land use change), the contextual environment and climate are depicted in a way that encompasses and circumscribes the WEF Nexus frame.[3]

2.1.5 | Holistic concepts are a tool to achieve holistic outcomes

Ultimately, as shown in the right portion of Figure 1, Nexus framings should be viewed as a means to achieve practical improvements for people and the environment. Practical improvements include examples such as improved water productivity that reduces energy consumption and greenhouse gas emissions but raises agricultural production, or using water retentions to simultaneously grow food and bioenergy crops. Importantly, the realization of Nexus outcomes depends on much more than the strength of the framework applied. Some of the key factors which may support or constrain the achievement of outcomes are shown in the centre of Figure 1, namely: the scale of Nexus intervention, sectors involved, available capacity, sectoral entry point and target, enabling conditions (e.g. governance, stakeholder engagement, capacity development) and type of research or implementation methods (e.g. review vs. tool development).

2.2 | Data collection and analysis

2.2.1 | Approach to document compilation and categorization

This paper takes stock of Nexus research and practice in order to understand the spectrum, and potential impacts, of Nexus approaches that have been employed. To take stock, an extensive document collection effort was undertaken

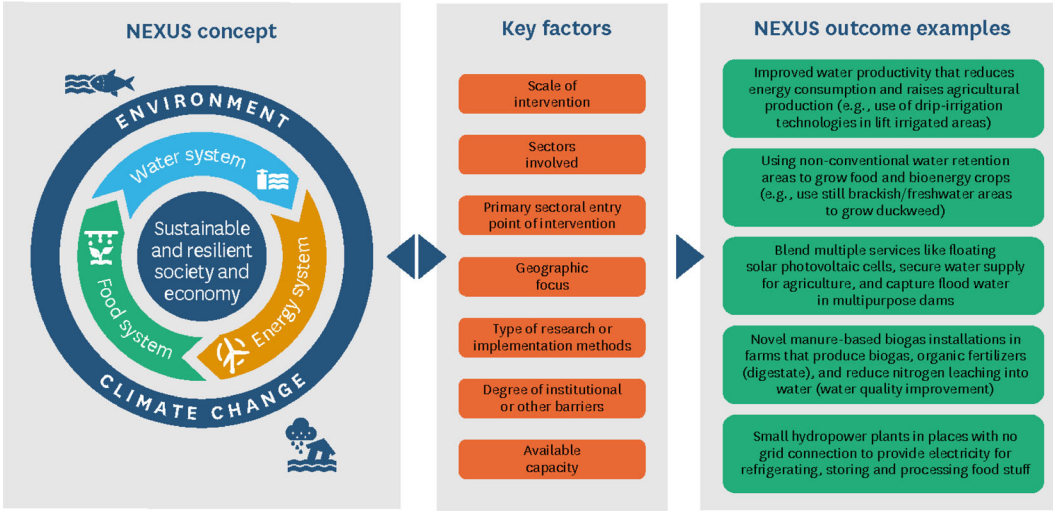

FIGURE 1 Nexus framework: From concept to outcome (Authors' elaboration).

in order to comprehensively capture relevant information on Nexus research and projects; the volume of articles initially compiled, coupled with the perceived limited relevance of some, in turn, motivated a filtering exercise. The set of documents was then categorized according to a system derived from the framework presented above. Finally, categorized documents were analysed.

2.2.2 | Document collection

We conducted a systematic search on Scopus and Web of Science (WoS) database platforms to collect documents that explicitly address a combination of *water*, *energy*, *food* and *nexus* terms from both the research and project literature domains. The following search terms were utilized to identify relevant documents 'water AND energy AND food AND nexus'. These keywords were selected as opposed to the other variations (e.g. water energy land) to be consistent with the original WEF Nexus concept which was assumed to be more inclusive. The year range was not specified in the search. In addition, we conducted a Google Scholar search to capture very recent research publications (i.e. published in 2021 excluding publications already captured by Scopus and WoS) that could have been omitted from Scopus and WoS results due to a potential indexing lag in the utilized database platforms. Therefore, the year range was limited to 2021. To ensure the incorporation of practice-oriented literature, we also searched websites of various UN organizations, development banks, donor agencies, research organizations and the Nexus Resource Platform (i.e. water-energy-food.org). In total, we scanned the websites of 16 organizations.[4]

2.2.3 | Document filtering

A list of some 3254 documents was initially produced, comprised largely of research publications. A total of 1084 documents in Scopus were also included in the WoS results, however. After removing the duplicate entries, the total number of documents was reduced to 2164 (Table 1). The resulting 2164 unique publications were then filtered to generate a list for a full-text review through the application of four criteria: (1) research documentation was limited to 'article' and 'review' publications; documents categorized as other types of publications including abstracts, call for papers, editorials, erratum documents were excluded; (2) research publications required a 'digital object identifier' number, in order to ensure that the publications are verifiable and accessible; publications lacking DOI were excluded; (3) research publications with fewer than five citations per year on average were excluded and (4) project documents which fail to focus on a specific case study were excluded.[5] Application of these four criteria yielded a progressive reduction in the total number of documents, resulting in 913 documents that satisfied all criteria for a full-text analysis. We could not obtain the full texts for three publications and the main texts of two publications were not in English, however. The full text of 908 documents was ultimately reviewed.

2.2.4 | Confirming inclusion of all W-E-F sectors

A full-text review of the 908 documents revealed that 169 did not capture the entire W-E-F Nexus and were excluded from further analysis. Most of the excluded cases captured only two of the W-E-F sectors (e.g. water and energy) and some captured one of the closely related W-E-F elements (e.g. water-energy-nutrients) but not the actual W-E-F. Removing the 169 documents resulted in a final total of 739 documents that were categorized for further analysis. Among these, 648 were research-oriented—with methods sections typically published in peer-reviewed journals—while 91 were project-oriented publications obtained from websites of development agencies that typically depict project approaches and highlights.

TABLE 1 Number of Nexus documents.[a,b,c]

Source	Scopus	Web of science	Google scholar	Websites of development organizations	Total
Initial number of documents	1514	1472	12[a]	256	3254
Removing duplicate entries	1512[b]	384[c]	12	256	2164
Limiting research publications to documents categorized as 'article' and 'review'	1146	320	7	256	1729
Removing research publications with missing 'digital object identifier'	1122	270	5	255	1652
Removing research publications with low (<5/year) citations	670	136	5	251	1062
Removing project documents without a case study	670	136	5	102	913
English text documents that were actually collected	666	135	5	102	908

[a]Refers to the Google Scholar results excluding duplicates captured by Scopus or Web of Science.
[b]One document had an internal duplicate which was removed (i.e. doi: 10.1007/978-3-642-36,143-2_30); and one document's doi referred to a different publication than indicated in the Scopus records (doi: 10.13031/TRANS.14134) and was removed.
[c]Four documents had internal duplicates which were removed (i.e. doi: 10.1080/02626667.2017.1353695; 10.1080/02626667.2018.1545094; 10.1080/02626667.2018.1545096; 10.1080/02626667.2018.1545097). In case of internal duplicates, we assumed that the duplicates with a later date referred to reprints and as such we kept earlier versions for analysis.

2.2.5 | Document categorization: Basic parameters

Building on previous efforts to categorize the voluminous research on Nexus (e.g. Albrecht et al., 2018; Botai et al., 2021; Purwanto et al., 2021), we coded the documents according to a predefined set of basic and advanced parameters (Table 2). Coding was done by the authors of this paper and an environmental specialist (referenced in the acknowledgements). Different categories of individual parameters were coded based on code descriptions, which were slightly expanded when unique cases emerged through discussion of new cases and mutual agreement. A randomly selected subset of coded publications was checked by a second coder to ensure consistency.

Four basic parameters—namely, sectoral background of author(s), sectoral focus of documents, scale and geographical focus—were utilized to contextualize the focus of each document.

- *Authors' stated sectoral affiliation* was categorized to capture the scope and type of primary sectoral perspectives included in research publications. Given the large variation of sectoral affiliations, the analysis was limited to capture affiliations with water (including marine environment), energy, food (e.g. agriculture, soil, fisheries), environment (e.g. environmental science, policy, engineering), sustainability (e.g. science, development), earth systems (e.g. Earth system science, observation), nature/natural resources (e.g. humanity and nature, natural resources) and other. It is possible for authors' affiliation to overlap (e.g. environmental engineering and agriculture) and in these cases, a document is counted in both.
- *Sectoral focus and scope* were categorized to understand the relative emphasis on different Nexus sectors and sectoral 'priority' as the selected order of sectors is assumed to imply emphasis as suggested by Liu et al. (2018).[6]
- *Scale* was categorized to capture the geographical extent of a document's focus. Scale is an important parameter, especially for WEF Nexus governance (Pahl-Wostl et al., 2021) and investment assessments (Rising, 2020) and

TABLE 2 Categorization Framework.

	Parameter	Categories
Basic	Sectoral focus and scope	Water, energy or food core sectors only, core sectors plus others (e.g. Biodiversity, Climate, Environment, Ecology, Ecosystem, Land, other)
	Author(s) stated sectoral affiliation	Water, energy, food (agriculture, soil, fisheries, livestock), environment, sustainability, earth systems, nature/natural resources, other
	Scale	Global, regional, basin, country, city/urban, sub-national (non-city), other
	Geographical focus	East Asia and Pacific, Europe and Central Asia, Latin America & the Caribbean, Middle East and North Africa, North America, South Asia, Sub-Saharan Africa and NA (e.g. unspecified, global, multi-regional)
Advanced	Type of methods (listed alphabetically)	Review and analysis (e.g. bibliometric; topical); Modelling (e.g. integrated; system dynamics; other); Mathematical approaches (e.g. optimization; statistical; machine learning); Supply chain calculations (e.g. LCA; footprint assessment; input–output); Qualitative methods (e.g. survey; interviews); Analysis (e.g. comparative, systematic excl. laboratory); Tool development (e.g. game; dashboard); Case study approach; Other methods (all others)
	Limitations	What were the limitations of the approach utilized?
	Outcome	Was there a practical outcome?
	Climate change	Reference to climate change
	Governance	Mention of the governance context
	Gender	Reference to gender
	Stakeholder engagement	Inclusion of community members, government representatives or other stakeholders
	Capacity development	Mention of activities to enhance skills or capacity of concerned actors

was a commonly analysed parameter in previous Nexus literature reviews (Albrecht et al., 2018; Al-Thani & Al-Ansari, 2021; Chang et al., 2021).

- *Geographical focus* was used to capture the region within which an article places focus. The geographical focus is important as it can highlight global regions most frequently captured by the Nexus studies. This analysis is different from 'country of origin' analysis because the authors of a study can be affiliated with an institution in one region (e.g. North America) but they can focus on Nexus in another region (e.g. East Asia and Pacific). The list of global regions was adopted from the World Bank classification of countries (The World Bank, 2021).

2.2.6 | Document categorization: Advanced parameters

Documents were also categorized according to eight advanced parameters, selected to facilitate the depiction of key aspects of a utilized approach. *Type of research or implementation methods* refer to the assessment approaches or tools utilized in considered studies. In this study, we differentiate methods into different categories derived from stratifications utilized in recent studies (Chang et al., 2021; Fouladi & Al-Ansari, 2021; Islam et al., 2021; Proctor et al., 2021; Yuan et al., 2021). When more than one method is used, that article was categorized based on the more detailed method, for example, when footprint and optimization are used, an article was categorized as optimization because footprint results can be used as an optimization parameter. *Limitations* refer to limitations (e.g. in research methods) or challenges (e.g. encountered in implementation). Limitations were explicitly stipulated by the authors; if none were stated, this was recorded as none stated. *Outcome* refers to any tangible change, for example, a new institution created for the management of WEF resources, change in WEF-related policies or a new project initiated to

validate study results. We applied a strict interpretation of an outcome to capture a practical outcome rather than an outcome in any shape or form.

2.2.7 | Remaining parameters categorized in binary system

Climate change and the WEF Nexus share a fundamental link. Greenhouse gas (GHG) emissions from energy (i.e. fuel combustion and fugitive fuel emissions) and agriculture (e.g. food) are the largest anthropogenic sources (IEA, 2019) driving climate change. In turn, the key risk of climate change that spans across regions is a risk to food and water insecurity (IPCC, 2014). This analysis helps reveal the frequency of climate change emphasis in WEF literature. *Governance* refers to whether the publication mentions a governance context. A governance context in this study is assumed a discussion on policies, involvement of government institutions, resource management or mentioning a combination of relevant words or phrases. This analysis helps reveal the frequency of consideration to the governance context in the WEF literature. Stakeholder engagement refers to whether a publication mentions engaging the community or other relevant stakeholders. *Capacity Development* refers to whether a publication mentions capacity or skill enhancement activities. Finally, *gender* captures whether a publication explicitly references gender or makes a distinction between male and female actors.

3 | RESULTS

3.1 | Sectoral sequence suggests water-centrism

Most of the publications analysed focused exclusively on the water-energy-food Nexus in some order (87%; Figure 2). In terms of the sectoral 'prioritization' as reflected in the sequence of Nexus presentations, water was mentioned first in 64% of publications. Food- and energy-centric nexus documentation is less common. Food was mentioned first in 25% of publications, and energy in 10% of publications. In six publications (1%), a different sector was mentioned first (i.e. land, climate, soil). For example, Wolde et al. (2021) focused on the land, water, energy and food (LWEF) nexus. In fact, 99 documents, reflecting approximately 13% of the total, considered sectors in addition to water-energy-food (+ other sector). The three most mentioned additional sectors beyond the water-energy-food were ecosystem (3%), environment (2%), land (2%) and climate (2%).

3.2 | Sectoral affiliations: More environment, water and food than energy

About 1/3 of research publications involved authors affiliated with the environment (e.g. environmental science, policy or engineering). Authors with a stated affiliation with water and food were each found among authors of 18% of publications (Table 3). 9% on energy and 9% on sustainability (e.g. sustainability science, development). 5% on Earth systems (e.g. Earth processes, observation), and nature/natural resources in 3%. Finally, the remaining 35% listed other backgrounds (e.g. ranging from health to machine learning).

3.3 | Nearly 1/3 of the documents have a global focus

The largest portion of WEF documents are focused at the global scale (29%; Figure 3). National scale was the next most common scale in the WEF publications, 159 (22%). The third most common scale was a sub-national

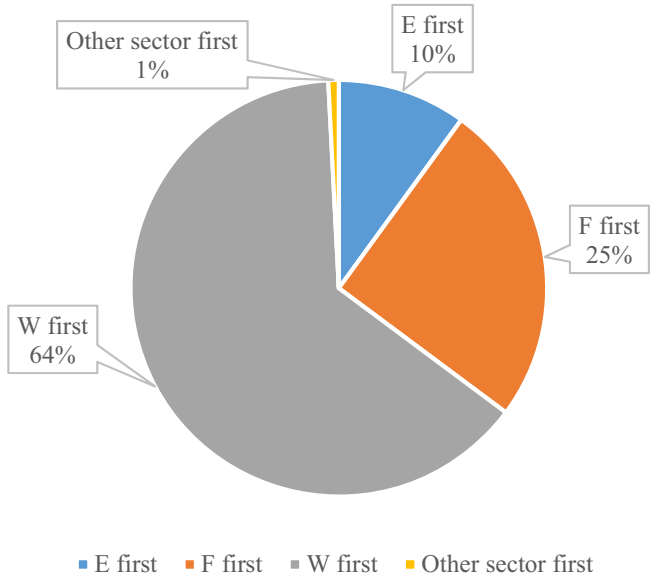

FIGURE 2 Relative prioritization of sectors in reviewed publications.

TABLE 3 Authors' stated sectoral affiliation in research publications.

Stated sectoral affiliation	Percent of
Environment (e.g. environmental science, policy, engineering)	33%
Water (e.g. water security, water systems engineering, water resources)	18%
Food (e.g. agricultural sustainability, soil sciences, food engineering)	18%
Energy (e.g. energy and environment, biofuel research, petroleum studies)	9%
Sustainability (e.g. sustainability science, development)	9%
Earth Systems (e.g. Earth system science, Earth observations)	5%
Nature/Natural Resources (e.g. humanity and nature, natural resources)	3%
Other (e.g. urban studies, planning, health)	35%

Note: The total adds up to more than 100% because some publications listed authors with multiple sectoral affiliations and were counted in all mentioned categories.

scale—encompassing any scale larger than a city and smaller than a country—with 18% of publications. Next, most common scale was the basin scale, 99 (13%) followed by the regional scale, 73 (10%). Thirty-eight WEF publications (5%) focused on the city scale. In 24 publications (3%), scale was not mentioned at all or was ambiguous, making the process of designating into one of the existing scales very difficult. An example of a study in this category is a study by Ozturk (2015) titled, Sustainability in the food-energy-water nexus: Evidence from BRICS (Brazil, the Russian Federation, India, China and South Africa) countries, which is in between the country and regional scale. Disaggregating research versus project publications suggests that almost a third of research (31%) is focused at the global scale, while only 9% and 11% of research is focused on regional and basin scales respectively. Conversely, only 13% of project documents focus on the global scale, while a comparatively higher proportion—18% and 30%—focus at regional and basin scales.

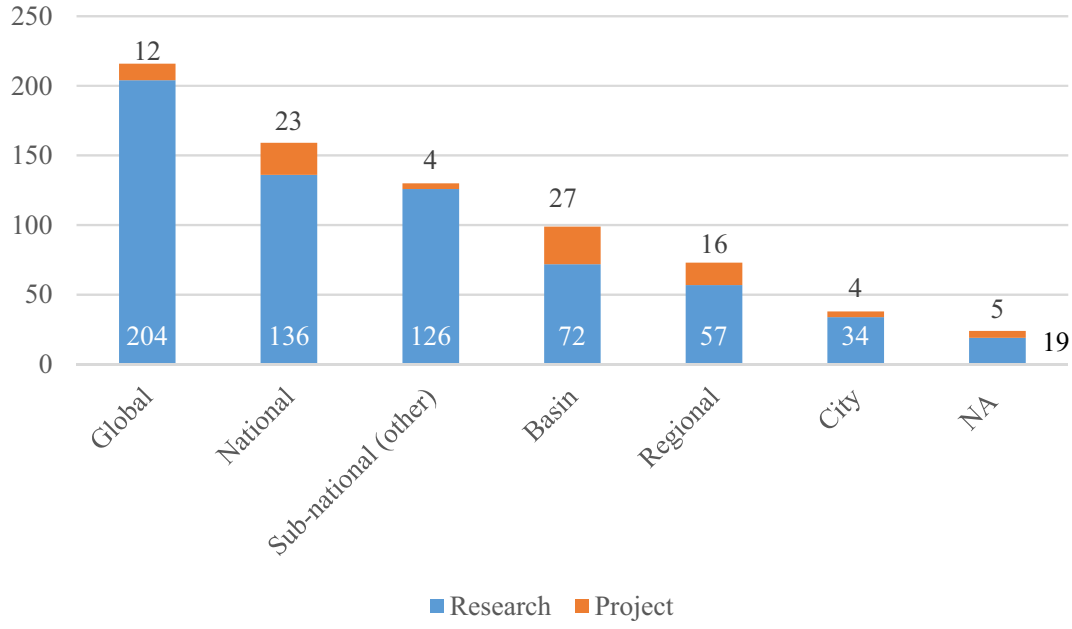

FIGURE 3 Frequency of WEF study scales in research and project publications.

3.4 | Substantial documentation on East Asia and Pacific, South Asia and Latin America less so

In terms of the geographical focus, East Asia and Pacific ranks as the most productive region, with 16% of publications considered in this study focusing on that region (Figure 4). Europe and Central Asia were covered by 12% of publications. Sub-Sahara Africa was the focus in 9% of publications and North America in 8%. Seven percent of publications focused on the Middle East and North Africa, and only 4% of publications focused on South Asia. The geographical focus of the remaining publications was either general, unclear or multi-regional.

3.5 | China, USA, Brazil are of the greatest national focus

WEF publications were the most concentrated in China (8%) and the United States of America (USA; 6%) (Figure 5a).[7] WEF publications focusing on Brazil (16), Qatar (12), Spain (14) and the United Kingdom (16), were alike, 2% each. Cities that received the most focus in WEF publications were located in the above-mentioned countries. Seven WEF publications focusing on the city scale mentioned two or more cities. An example of such publication is a study by Djehdian et al. (2019) who covered 69 cities in the USA (not shown on the map). Global and regional distribution of WEF publications are not shown because of ambiguity.

3.6 | Aral Sea, Mekong and Nile Basins receive the most frequent focus

A total of 36 different basins and aquifer systems were covered by the WEF publications (Figure 5b). The top three most targeted basins were the Mekong River basin, followed by the Aral Sea and Nile River basins. Next commonly targeted basins were the Columbia River basin, Danube River basin, Ganges-Brahmaputra-Meghna River basins, Indus River basin and the Zambezi River basin.

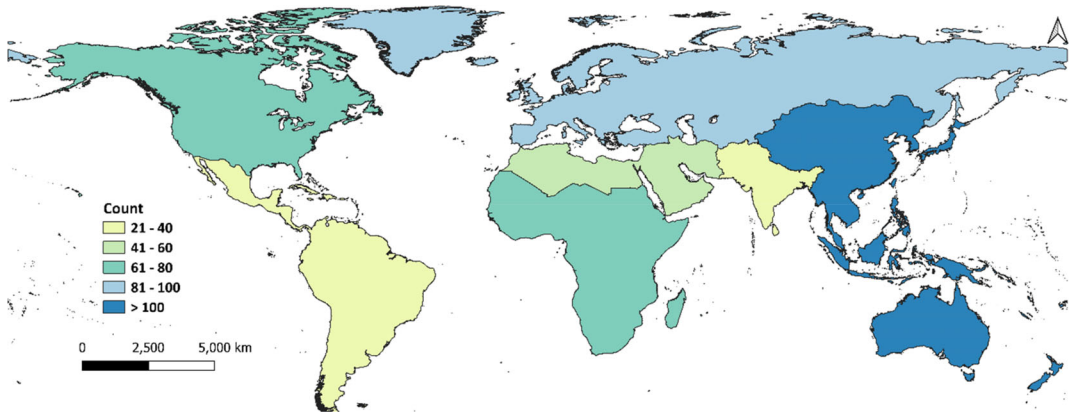

FIGURE 4 Geographical focus of WEF publications, Major World Regions.

3.7 | Methods are dominated by reviews and models

In general, we observed a large number of different methods utilized in WEF publications (Table 4). Among them, review and analysis was the most common method (28%) followed by modelling approaches (16%). The modelling approaches can be differentiated into different types (integrated, system dynamics, hydrologic, etc.) and we found that integrated modelling was the most common type detected in 10% of publications. Mathematical approaches were the next most common method detected in 12% of WEF publications. Methods involving supply chain calculations were used in 8% of publications. Qualitative methods were mentioned in 7% and other quantitative analysis (e.g. comparative, systematic excluding laboratory) in 6%. A few publications, making up 2% of the total also mentioned tool development (e.g. dashboard, game) and a similar number mentioned case study approach. A combination of all of the remaining methods was mentioned in 19% of publications. The less common methods were also very diverse ranging from multi-criteria analysis (e.g. decision-making; Analytical Hierarchy Process) mentioned by 1% of WEF publications to economic valuation methods mentioned by less than 1% of publications.

3.8 | Limitations of approaches in nexus articles

Approximately 42% of the WEF Nexus articles acknowledged limitations in approaches developed and applied (Figure 6), but the types of these limitations in Nexus studies have not been analysed before (Sušnik & Staddon, 2021). Of those indicating limitations, some 40% identified data limitations as constraining their approach. Approximately 19% acknowledged that a model that was developed, excluded certain key variables. Approximately 15% identified uncertainties and assumptions as a key limitation of the approach. Approximately 8% of articles acknowledged the lack of transdisciplinarity[8] as a key limitation; this was often a way to acknowledge the lack of social science approaches. Finally, a range of other more minor limitations—including finances, capacity, participation and representative—comprised a final group of other limitations. This final group collective accounted for about 19% of documents.

3.9 | Nexus outcomes are in short supply

Evidences on tangible changes that supported real Nexus outcomes—from policy adoption or shifts, to new infrastructure that enhances cross-sectoral efficiencies—are unfortunately not abundant. Nonetheless, 14 articles do

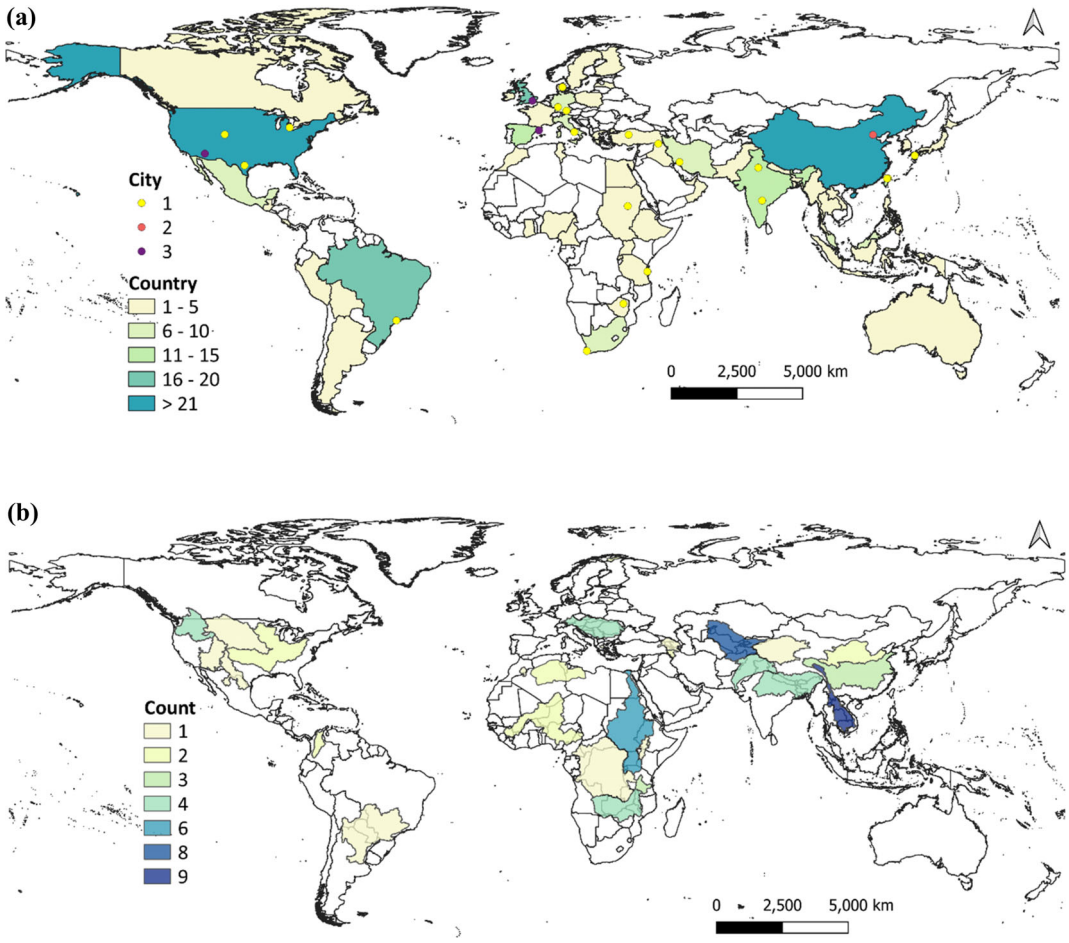

FIGURE 5 Focus of WEF documents on particular (a) countries and cities, and (b) basins and aquifers.

contain a focus on clear-cut Nexus outcomes, and several of these articles contain references to more than one outcome (Table 5). Outcomes range from general (e.g. enhanced Nexus benefits) to specific (e.g. water savings achieved, enhanced energy production and food availability). More interestingly, articles shed light on a range of key tools that were used to realize these outcomes. Tools ranged from solar steam irrigation to a hydropower mid-grid. Ultimately, a key way to realize Nexus outcomes going forward is to centre future projects on selecting and implementing one or more of these tools in conjunction with an analytic framework that ensures cross-sectoral benefits will be achieved.

3.10 | Climate change is routinely considered

Climate change was mentioned in the majority of WEF publications (66%; Figure 7). While climate change was most often considered in the general sense, there was equally substantial specific consideration to adaptation and mitigation. An example of general climate change reference is a publication by Adebiyi et al. (2021), where the word 'climate' comes in the title and is followed by more discussions in the text—'Water-food-energy-climate nexus and technology productivity: a Nigerian case study of organic leafy vegetable production'. Similarly, a study by Nasrollahi

TABLE 4 Methods used in the WEF studies.[a]

Method	Explanation	Count	Percent
Review and analysis (bibliometric; topical)	Involves reviewing literature and conducting some simple analysis of the findings.	208	28%
Modelling	Involves creating and simulating natural and anthropogenic processes.	119	16%
Mathematical	Groups methods that involve heavy mathematical computation (e.g. probability, statistics and optimization).	88	12%
Supply chain calculations (LCA; footprint; input–output)	Group of approaches that track inputs and outputs in the supply chain of products/processes.	58	8%
Qualitative	A group of data collection and analysis methods that are more qualitative than quantitative in nature.	50	7%
Analysis (e.g. quantitative excl. laboratory)	A group of approaches that mention general or comparative quantitative analysis.	43	6%
Tool development	Methods involving development of (interactive) tools for broader audience.	15	2%
Case study	Refers to studies that involve a case study design.	15	2%

[a]One hundred forty-three papers possessed methods that do not fall in any of these categories.

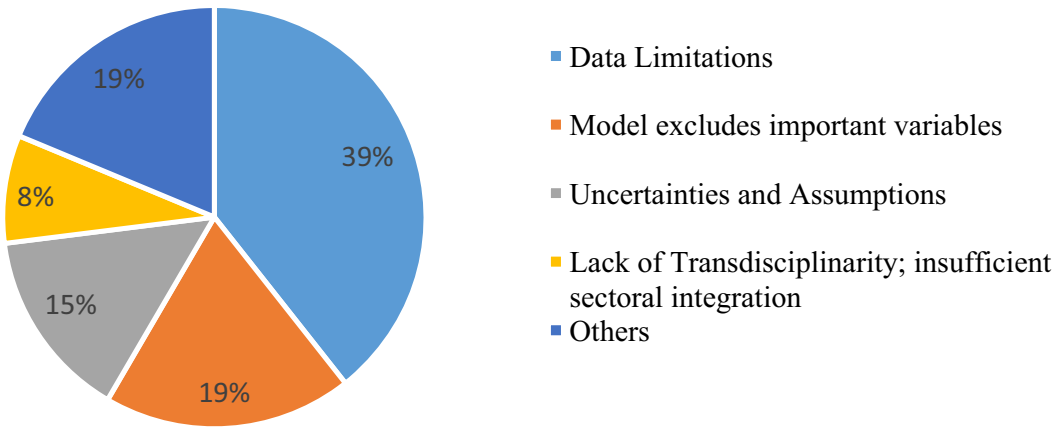

FIGURE 6 Limitations in Nexus documents.

et al. (2021) includes the word 'adaptation' in the title and proposes an adaptability analysis for the Urmia Lake basin—'Unraveling the Water-Energy-Food-Environment Nexus for Climate Change Adaptation in Iran: Urmia Lake Basin Case-Study'. An example of a reference to mitigation is a paper by Tan et al. (2021) who included GHG mitigation performance improvement indicator (among others) when comparing alternative settings.

3.11 | Governance is routinely considered, gender is not

Governance was mentioned in one form or another in most of WEF publications, 74% while the opposite was true for gender, which was mentioned in only 9% of WEF publications (Figure 8). An example of a WEF publication that mentioned governance is a publication by Sušnik et al. (2021), where they integrate policies, developed with relevant

TABLE 5 Nexus outcomes and tools to achieve them.

Outcome	Tool	Source
Enhanced water flux (168%, ~630.5 L m-2 h-1), excellent fouling resistance (~93.8%) and increased rejection to bovine serum albumin (94.1%).	The modified membrane with surface-enriched multifunctional zwitterionic nanoparticles	Sun et al. (2019)
Enhanced productivity across WEF sectors	(i) Solar steam irrigation, (ii) ethanol production, (iii) electricity subsidies, (iv) integrated hydropower, (v) forest management	FAO (2014)
Improvements in water savings, supported by infrastructure	Cross-institutional collaboration to implement a design process for resources efficient and productive service delivery	GIZ and ICLEI (2014)
Interstate agreement (Brazil), creation of water reserves (Peru), climate change adaptation plan adopted (Colombia)	GIZ nexus development projects	Bellfield (2015)
Improved production in and across WEF sectors	Biogas products (e.g. gasifier), micro-hydropower, cookstoves	Guta et al. (2015)
Improved production in and across WEF sectors	(i) solar-powered pumping, (ii) wind farm to pump GW, (iii) biomass-powered off-grid electricity system, (iv) solar-powered refrigeration, (v) off-grid electrification, (vi) solar hydro hybrid system for fish and eco-tourism	Bhattacharyya et al. (2015)
More energy, less-silted water, more sustainable agriculture	PES Fund for forests (natural infrastructure), that hydropower must pay into to incentivize famers to plant trees (which offsets silt)	Ozment et al. (2015)
Elevated income, elevated food security and resilience	Solar pumping for irrigation	IRENA (2016)
Energy savings and enhanced nexus benefits	Waste-to-energy plant, septage management	Never (2016)
Enhanced production within and across WEF sectors	(i) Power utilities work with farmers to improve water availability in France; (ii) renewable energy on farms in England and Italy, (iii) harnessing energy benefits of wastewater in Germany	UNECE (2017)
Enhanced energy, water availability and food production	Solar constructed and drip irrigation provided	Siala et al. (2017)
Leads to more electricity and water to residents (and more water leads to more food)	Hydropowered mini-grid	RES4Africa (2019)
Enhanced nexus benefits within and across sectors	(i) Reconstruction of dew mounds leads to greater livestock numbers in Tajikistan, (ii) decree in Uzbekistan, and electricity metering systems, leads to reduction in pumping and water use	CAREC (2019)
Range of positive nexus outcomes, from more benefits for communities and more sustainable resources use	Water fund	The Nature Conservancy (2020)

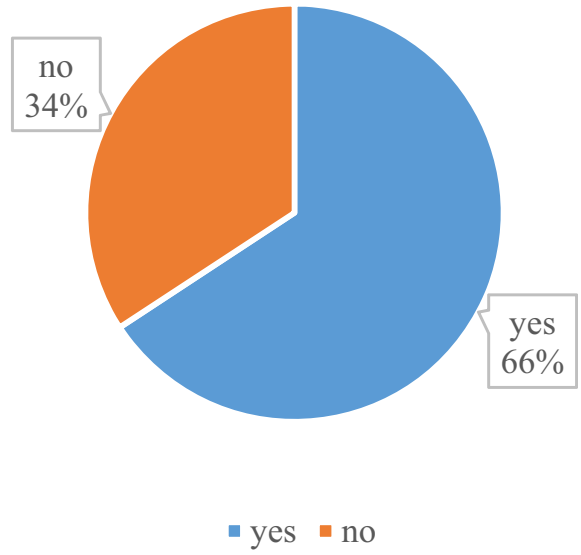

FIGURE 7 Reference to climate change in Nexus documents.

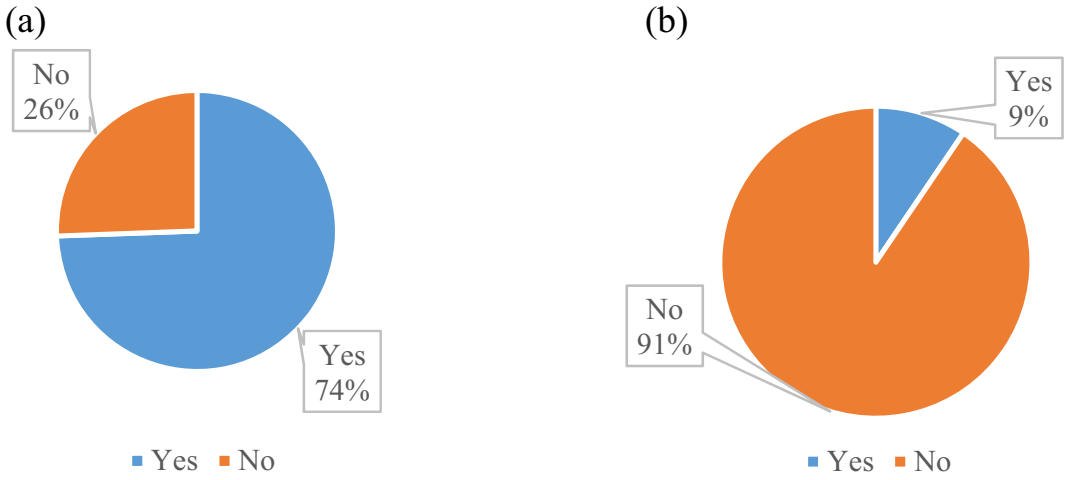

FIGURE 8 Inclusion of (a) governance and (b) gender in Nexus documents.

stakeholders to the model. An example of a WEF publication that captured gender is a publication by Wolde et al. (2021) who analysed the impact of land, water, energy and food Nexus degradation on socioeconomic characteristics (including gender).

3.12 | Stakeholder engagement and capacity development not widely considered

Stakeholder engagement and capacity development activities are mentioned in only 33% and 15% of WEF publications, respectively (Figure 9). A publication by Huntington et al. (2021) gives detailed account of engaging

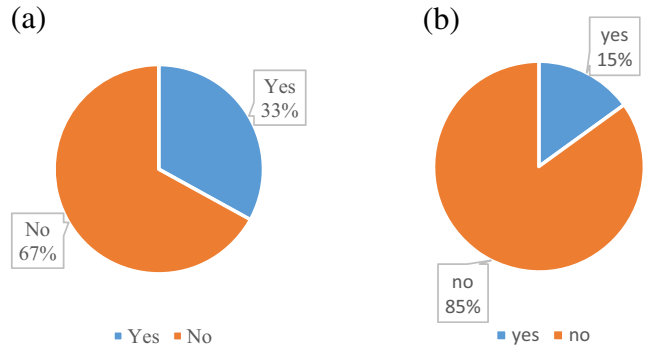

FIGURE 9 Reference to (a) stakeholder engagement and (b) capacity development in Nexus documents.

stakeholders through interviewing municipal and tribal leaders as well as people responsible for water, energy and food systems and holding a stakeholders workshop. In another example, Li et al. (2019) recruited experts from government departments, universities and companies to help with different assessments. An example of a capacity development reference is provided by Chaudhuri et al. (2021) who list lack of appropriate information, education and training (among others) as examples of the negative externalities associated with the Water Users Associations.

4 | DISCUSSION

Given growing resources scarcity and increasing need to pursue environmentally sustainable management approaches, WEF Nexus has emerged as one of the most important development concepts of the 21st century. While there is a clear need to expand roll-out of Nexus approaches given their benefits, it is equally relevant to capture and understand lessons derived from the body of existing activities on the Nexus. As such, this paper assembled more than 900 documents which were filtered and categorized according to more than 10 key parameters (e.g. scale, methods, limitations) in order to characterize approaches, outcomes and presence of variables likely to support on-the-ground change. This is believed to be the most comprehensive effort to-date to understand activities on the Nexus.

The major headline from this paper is that WEF documentation places insufficient focus on outcomes. This finding is consistent with assertions from existing work, like Simpson and Jewitt (2019b) found that the WEF Nexus research was mostly conceptual in nature and focused on macro-scale resource security. Similarly, Simpson and Jewitt (2019a), and Zarei et al. (2020) found that WEF Nexus analysis and management are mostly at a theoretical stage. In another study, Næss et al. (2021) stated Nexus is an evolving concept that requires multidisciplinary initiatives to achieve certain outcomes. These common findings lead to a bottom line that is—Nexus concepts need to start demonstrating practical value by achieving outcomes and fostering impact, in order to for this concept to secure a level of real-world legitimacy that will enable the concept to survive beyond fleeting prominence.

Underlying the scant outcomes in WEF documentation is the scarce attention to elements that are key to realizing outcomes. Indeed, capacity building and stakeholder engagement are not commonly found in Nexus documentation. This finding is consistent with more limited efforts to examine the same. For example, Kliskey et al. (2021) reported that only a small portion of the Nexus literature involved stakeholders as equal partners, a trend that they attributed partially to time-intensive nature of engaging with stakeholders. In another example, Magdanz (2021) found simulations to be most common studies in the WEF nexus literature as opposed to empirical studies. Ultimately, stakeholder engagement is key to adoption of Nexus solutions, and given the sophisticated nature of Nexus concepts, many stakeholders will require some capacity development. Failing to consider these aspects will limit chances for adoption of Nexus solutions.

Further constraining achievement of outcomes is that methods used in WEF activities—most commonly reviews and models—may have high data requirements that are often unmet. This link between the data availability and outcomes is consistent with the findings from Shannak et al. (2018) who emphasized lack of data availability and sharing as reasons for the failure of some promising models. Similarly, Huntington et al. (2021) struggled to include important variables (e.g. transportation, governance) in a systematic model that prevents capturing all relevant parts of the WEF system. At the same time, some studies call for further expanding the Nexus models despite the data availability challenges. For instance, Wang et al. (2021) call for further emphasizing material elements like ecological footprint and CO_2 emissions in the nexus models. Thompson et al. (2021) are working towards developing a complex, integrated model that requires large quantities of social and biophysical data. While achieving thorough characterization of Nexus interactions is clearly important and such efforts would clearly require immense quantities of data, it may be equally prudent to guard against overly circuitous processes—that is, sophisticated models that drive ambitious data collection which generate complex results that in turn require simplification for uptake—that prolong pathways to outcomes. Given the urgency of realizing Nexus solutions on the ground, it may be expedient to simplify pathways to outcomes by, for example, starting from simpler models for which data can be found or creating a platform that captures existing WEF (+ other sector) models and the description of their individual data requirements and potential sources.[9]

Unfortunately, distribution in the scale of focus found in Nexus documentation may further reflect a failure to adopt an outcome orientation. Consistent with the previous findings of Itayi et al. (2021) who found that Nexus research often focused on large (national, regional and global) scales and Chang et al. (2021) who found 34% out of about 100 analysed WEF articles focused on the global scale, our review found Nexus documents were most often focused at larger scales (e.g. global and national). While WEF Nexus approaches need to be scaled for different assessments because there is no one-size-fits-all model (Simpson & Jewitt, 2019a), there is some evidence to suggest that greater opportunity for practical outcomes could be achieved at smaller, more focused scales. To provide an example from a different field of transboundary waters, cooperation at smaller scales is more typically oriented towards development-oriented outcomes like hydropower development, whereas large-scale cooperation is more oriented towards facilitation and coordination (Holmatov & Lautze, 2016). Moreover, since qualitative analysis can be undertaken more easily at smaller scales (Itayi et al., 2021), a small-scale focus may serve as a constructive approach for engaging and co-producing knowledge and solutions with stakeholders representing different parts of WEF systems.

On a positive note, the finding that governance and climate change are both frequently mentioned in Nexus documentation suggests that Nexus approaches are reasonably robust as concerns these elements. More detailed content analysis of Nexus documents that mention governance and climate change can help map factors that enable their frequent occurrences. Such analysis can reveal opportunities to amplify involvement of infrequent elements like gender, capacity development and stakeholder engagement. We recommend a detailed content analysis of Nexus documents as an area for future work.

Further, there is fairly diverse sectoral participation in WEF activities. Similar to the results of Itayi et al. (2021) who determined water-centrism of WEF Nexus by analysing frequency of keywords in research papers and determined water as the most common keyword and energy as the least, our paper used a larger and diverse set of documents to confirm that Nexus activities are indeed more often driven by the water sector. Nonetheless, our paper was able to add considerable nuance by identifying that sectoral diversity in project teams is considerable regardless of sectoral driver—with the exception of the energy sector which may be somewhat underrepresented. This suggests that regardless of which letter comes first in the abbreviations, the process of developing Nexus approaches requires sectoral inclusivity. More effort could nonetheless be placed on (i) incorporating energy sector participation, and (ii) fostering Nexus efforts that are led by sectors other than water.

5 | CONCLUSIONS

This paper found that less than 15 documents in a voluminous knowledge base (>700 documents) on the WEF Nexus contain clear elucidation of concrete outcomes. Moreover, key elements to enable outcomes—such as stakeholder engagement, capacity development and gender—routinely remain unmentioned in Nexus documentation. Nexus documents do often focus on sophisticated models, which rely on extensive data. Efforts to obtain such data, however, are rarely successful. Ultimately, these findings provide an evidence-based point of reference that serves to temper postulation on theoretical benefits of the Nexus. Equally, despite some clear positives with the principles and concepts of the Nexus, this review of Nexus documentation points to clear opportunities for improving ways in which Nexus activities are designed. Such opportunities centre on formulating Nexus activities so they are more outcome-oriented.

Contextualizing the current state-of-play on the Nexus within the original aspirations of the Bonn2011 Nexus Conference undoubtedly gives one pause and generates questions on whether the pace of Nexus implementation is out-of-step with the urgency required to respond to pressing on-the-ground realities of resource scarcity and climate change. The original *Understanding the Nexus: Background paper for the Bonn2011 Nexus Conference* report, for example, mentioned numerous concrete examples of applying a Nexus approach along with a list of specific, recurring opportunities, for example, increasing resource productivity (in general) and desalinating water using renewable energy (as a concrete example). While the diffusion of innovation can often take long time, traditional timelines may need to be accelerated given unprecedented challenges such as climate change. Whatever the case, a more profound concern relates to the degree to which Nexus activities are in fact on a track for eventual implementation, even if the journey is a long one; or conversely, if the heavy focus on academically oriented journal articles and lack of outcomes will remain constant. Papers such as this one and the UNECE publication titled *Solutions and investments in the water-food-energy-ecosystems nexus: A synthesis of experiences in transboundary basins*[10] are certainly positive developments, to orient the Nexus community more towards on-the-ground examples. A key message emerging from both of these efforts is that changes can start small and inspire more profound transformation as we learn from what works and what does not in-practice.

Despite the new ground covered by this paper, there remain at least three notable areas on which future work can be conducted as a means to improve the strength and nuance of findings. First, research and project documents were mixed. While this intermingling allowed findings to reflect a broader and more diverse range of contexts, structural differences in the nature of documents at times presented challenges to categorization in a single template. Future research can focus on reviewing research versus project documents separately, each with its own template. Second, despite being the largest Nexus stock-take undertaken to date, the volume of documents is continuously expanding and, as such, this work should be updated in due course. Third, certain assumptions were made in document categorization, which is inherent when processing a set of secondary documents. Publications with mixed methods, for example, were categorized according to the more robust method based on our assessment. Application of more granular categorization, for example, which captured and categorized each method when several were employed, could reveal additional detail.

Before closing, we would like to acknowledge three potential sources of uncertainty in this work. First, filtering research publications based on the average number of citations may have omitted inclusion of relevant publications, for example, published in fields where Nexus is not a common topic but with relevant results and novel insights. Second, while we assumed that sequence of W E F sectors highlights sectoral emphasis in Nexus publications (based on assumptions in previous studies), the sequence may not always reflect sectoral prioritization but simply reflect the authors' choice to use a default WEF sequence. Third, while the coding system encompassed for a rich set of parameters, screening for additional parameters like industry may have added additional nuance to the results.

In closing, we offer five distilled recommendations for advancing the pursuit of the WEF Nexus:

- Focus on outcomes in new projects. It may be better to implement and evaluate-learn-adapt rather than investing heavy focus on esoteric data-intensive frameworks.
- Incorporate into WEF Nexus activity conceptualization and design, at a fundamental and upstream level, elements likely to enable realization of outcomes. Elements include things like capacity development and stakeholder engagement.
- Keep it simple—Steer clear of complex models unlikely to be understood or applied in target contexts. Equally, a challenge to academics is to balance rewards for those who can achieve more sophisticated, often data-intensive approaches with those who can achieve more accessible ones.
- Focus on smaller and more manageable scales like basin (or sub-basin/catchment), city, household rather than whole countries to limit complexity and achieve practical outcomes.
- Incorporate energy specialists to a greater degree into teams devising WEF Nexus approaches and solutions in order to balance sectoral perspectives. Energy is a key sector and, given financial returns on energy investments, a potentially catalytic one for outcomes. Nonetheless, energy was found to be the least common background among professionals from WEF sectors. It is critical to bring energy specialists into the fold.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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ENDNOTES

[1] For example, www.nexus.io, www.refx.com/nexus

[2] This is analogous to how Ostrom (2009) visualized that core sub-systems of social-ecological systems (i.e. resource systems, resource units, governance systems and actors) affect each other and linked social, political, economic settings and related ecosystems.

[3] From the systems thinking perspective, it is analogous to viewing the WEF as a new system composed of water, energy, food and ecosystems as its elements, that are interconnected with a purpose of meeting sectoral and intersectoral goals in an efficient and robust way. This would be consistent with the definition of a system by Meadows (1999) that has to have (a) elements; (b) interconnections and (c) purpose or a function.

[4] The full list of organizations is presented in Table A1.

[5] We adopted a broad definition of a case study to lower inclusion barrier. Specifically, a project-oriented publication was considered to focus on a case study if it met one of the following three criteria: (i) have a specific, sub-regional geographic focus (e.g. national, river basin, sub-national); (ii) explicitly use phrases such as 'case study', 'demonstration project' or similar or (iii) summarized, analyse or zoom on a specific external project. However, publications that only briefly mentioned names of case studies were not included.

[6] Captured variations in acronyms are similar to the 'nexus focus' parameter analysed by Chang et al. (2021).

[7] Figure 5a excludes publications containing multiple countries or cities as level of focus was not always in-depth. Figure 5b does not include some national basins and aquifer systems. Specifically, Neishaboor, Shazand and Zayandeh

basins, as well as Yazd-Ardakan Aquifer system (in Iran), Azraq groundwater system (Jordan), Tamar River basin (UK) and Cumbaza River basin (Peru) are not shown.

[8] Transdisciplinarity in this sense refers to transcending across approaches from different disciplines as oppose to interdisciplinary that would refer to transferring approaches from one discipline to another (Nicolescu, 2014).

[9] A platform similar to WEF Nexus Discover Map—https://pennstate.maps.arcgis.com/apps/opsdashboard/index.html#/a80f41228a4c477293d4ff48850d91e9.

[10] https://unece.org/sites/default/files/2021-10/ECE_MP.WAT_66_new_web.pdf

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APPENDIX

TABLE A1 Sources used for collecting practical literature in this study.

			UN general	UN specialized agencies				UN funds and programmes			UN other					
Source	JRC	OECD	Digital library	FAO	WB	UNIDO	UNESCO	UNEP	UNDP	UNICEF	UNECE	GEF	ADB	GIZ	WEF.org	BMZ
Link 1	Link 1	Link 1	Link 1	Link 1	Link 1	Link 1	Link 1	Link 1	Link 1	Link 1	Link 1	Link 1	Link 1	Link 1	Link 1	Link 1
Link 2	NA	NA	NA	Link 2	Link 2	NA	NA	Link 2	Link 2[a]	Link 2	NA	NA	NA	NA	NA	NA
Included[b]	14	0	8	5	3	0	0	2	0	0	14	1	0	2	204	3

[a]A search bar was not available.

[b]Only publications that had a substantive reference to the WEF Nexus were included and excluded results that had a passing reference to the Nexus or results that were in the form of video or audio materials.