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DOI
10.1016/B978-0-323-91223-5.00007-1

Publication date
2022

Document Version
Final published version

Published in
Water - Energy - Food Nexus Narratives and Resource Securities

Citation (APA)
Sušnik, J., Masia, S., & Jewitt, G. (2022). Scales of application of the WEF nexus approach. In *Water - Energy - Food Nexus Narratives and Resource Securities: A Global South Perspective* (pp. 49-65). Elsevier. https://doi.org/10.1016/B978-0-323-91223-5.00007-1

Scales of application of the WEF nexus approach

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1. Introduction

Water, energy, and food (WEF) form a coherent system, commonly referred to as the WEF nexus (Hoff, 2011), which exists as a "hyperconnected" system akin to ecological systems governed by complexity and feedback (WEF, 2016). The WEF nexus, including its management, is operational from global to local scales, where local level impacts and measures (e.g., climate change mitigation and adaptation measures) can add up to have larger-scale consequences. Similarly, global-level system behavior modulates the local level response regarding nexus resources and management (Fig. 4.1). The nexus resource base, and its effective functioning, is essential for human well-being at all scales (e.g., human development demands abundant, high-quality, easily accessible resources). Despite this, about 1 billion people lack access to clean water, 2.5 billion people lack basic sanitation, 1.4 billion have no electricity, and over 850 million are chronically malnourished while global food waste is about 30% of production (Moe and Rheingans, 2006; IMechE, 2013; World Bank, 2013a,b; World Hunger, 2013). In addition, because of the connected nature of WEF resources, and their dependence on climate and socioeconomic pathways, the interconnected nature and scale of global risks resulting from climate change and socioeconomic development (Cramer et al., 2018; Byers et al., 2018) may feedback to impact the functioning of the WEF resource nexus.

Since about 2010 when research into the WEF nexus started in earnest, researchers on the WEF nexus have recognized the multiscalar facet of the WEF nexus. As such, studies have been conducted on the nexus, both qualitative and quantitative, at household, local, regional, national, and global scales. These studies demonstrate the potential of the nexus approach when adapted

Water - Energy - Food Nexus Narratives and Resource Securities. https://doi.org/10.1016/B978-0-323-91223-5.00007-1

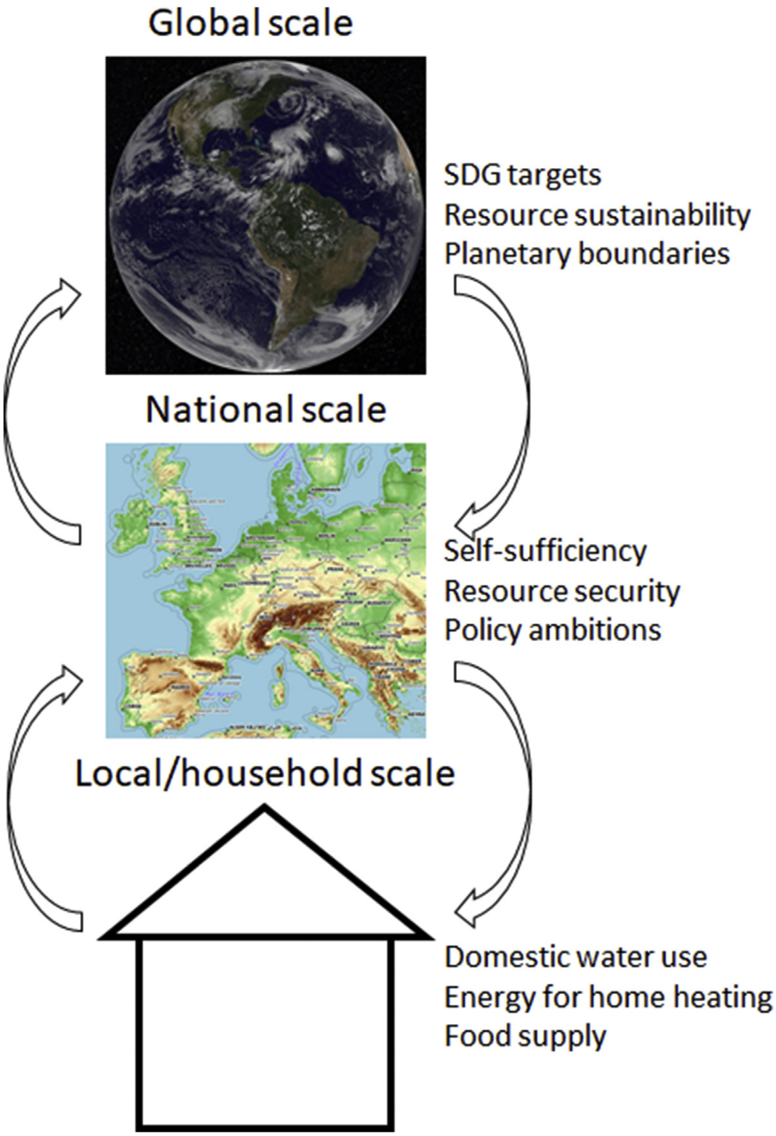

FIGURE 4.1

Schematic showing the mutual relationships between the WEF nexus at scales from global, to national, and down to household. At each scale, some key issues of consideration are highlighted. "Planetary boundaries" refers to theoretical boundaries on various global metrics proposed by Steffan et al. (2015). Resource security includes quantity, quality, and accessibility. *SDG*, Sustainable Development Goal; *WEF*, water—energy—food.

appropriately to studying WEF nexus issues at a range of scales, tailoring the methodology, focus, and research objectives to meet the scale under consideration.

In this chapter, case studies from the literature at spatial scales from household to global are presented so as to offer an overview of nexus issues being considered and studied, the range of applicability of the nexus approach, and to suggest potential options for improved policy and WEF resources decision-making relevance. These cases are mostly quantitative in nature, relying on models to assess the nexus at different scales. Yet almost all the studies presented use qualitative means at some point in the modeling process to "map" the systems under study, demonstrating that nexus modeling approaches cannot easily be split into qualitative or quantitative, but rather blending aspects from both (see Chapters 6 and 7). This chapter therefore aims to showcase the vast range in spatial scales and WEF nexus issues to which a nexus approach has been applied, demonstrating its flexibility to address a number of pertinent topics. At the same time, there remain several shortcomings, which will also be discussed. This chapter does not detail different WEF nexus methodologies, as these are covered elsewhere in this book.

2. The local scale: household to subnational

At the household level, Hussein et al. (2017) developed an integrated system dynamics model (SDM; Ford, 1999, and see Chapter 6) to capture the interactions between water, energy, and food resource at the household end-use level. The model and data were developed from a survey of over 400 local households in Duhok, Iraq. Hussein et al. (2017) tested the impacts on the WEF resource usage deriving from changes in user behavior, diets, income, family size, and climate variables. The model developed is one of the first dynamic models accounting for the interactions between water, energy, and food at the household level. Energy consumption was related to fuel type, the duration of usage of appliances and their wattage, and the desired water temperature. On the water side, the ownership of appliances, their flow rates, the duration of usage, and the frequency of usage were considered. For food, the model considered the consumption of different food commodities, the number of "cooking sessions" and their duration, the fuel or electricity usage of the cooker, the water consumption during cooking, and the amount of waste. As input to the model, family size, income, and seasonal variability could be altered, and the model outputs water, energy, and food demands, wastewater, and an amount of food waste. Water demand was shown to be most sensitive to changes in the duration of using water appliances in the garden and the number of garden watering sessions, while energy demand was most sensitive to the use of air conditioning units in the home. The study by Hussein et al. (2017) is perhaps the only one comprehensively modeling all three sectors' interactions, and assessing the impact of different scenarios, at the household level. This is important as the aggregated effects of household resource demand, and the implications of that demand on other nexus resources, may sum up over large spatial areas (e.g., a city), to have considerable regional resource implications, potentially linked to resource exploitation or carbon emissions, for example. Other studies modeling household scale resource demand either focus on single resources, or only consider interactions between two resources such as energy and water (e.g., Cheng, 2002; Kadian et al., 2007; Kenway et al., 2013; Cominola et al., 2016). This demonstrates that studies considering all three WEF nexus elements, their interactions, and their connection with wider resources availability and sustainability are rare. Such deficiencies should be addressed to improve understanding of how household-level resource use interacts both as a discrete system and as part of the wider (i.e., national or regional level) resources systems, and how policy may impact on both local-level resources use and higher-level resource sustainability.

Bahri (2020) developed "system archetypes" for the water, energy, food, and land sectors surrounding the Jatiluhur reservoir, West Java, Indonesia. Each archetype is represented as a causal loop diagram (CLD, cf. Chapter 6) describing the critical causal relationships between elements within each sector of the WEF system (e.g., water level in the reservoir, fish production, turbine flow for power generation, and the link to industrial and economic development). Each sectoral archetype was combined to form a complete nexus model of the region. While no modeling is conducted per se, the relational diagrams developed can aid nonexperts and policymakers "trace" causal relations through the whole nexus (Purwanto et al., 2019) in a qualitative way, leading to a better appreciation of potential whole-nexus response to (policy) interventions, and potentially contributing to more efficient nexus-wide policymaking.

At the city scale, Valek et al. (2017) assess the water—energy nexus in the Mexico City water system (supply and wastewater). While it can be argued that the water—energy nexus is "obvious," it is often overlooked as to just how closely connected these two resources are, especially in an urban context where water and energy may almost be seen as two sides of the same coin. This study helps to elucidate the urban water—energy link. This study is also interesting because while in most places it is the groundwater supply that consumes most energy resources (in a relative sense compared to surface water supplies), here it is the surface water supply that consumes most energy due to the topographical peculiarities of the city. At the time of the study, system water losses where c. 40%, and wastewater treatment was minimal. Specific features of the Mexico City water supply system were that surface water was pumped over large distances and a topographic barrier exceeding 1000 m elevation, and that local groundwater sources are overexploited, leading to city center subsidence. The supply from surface and groundwater sources was split about 50:50, each contributing about half to the water supply (Fig. 4.2A). On the energy side,

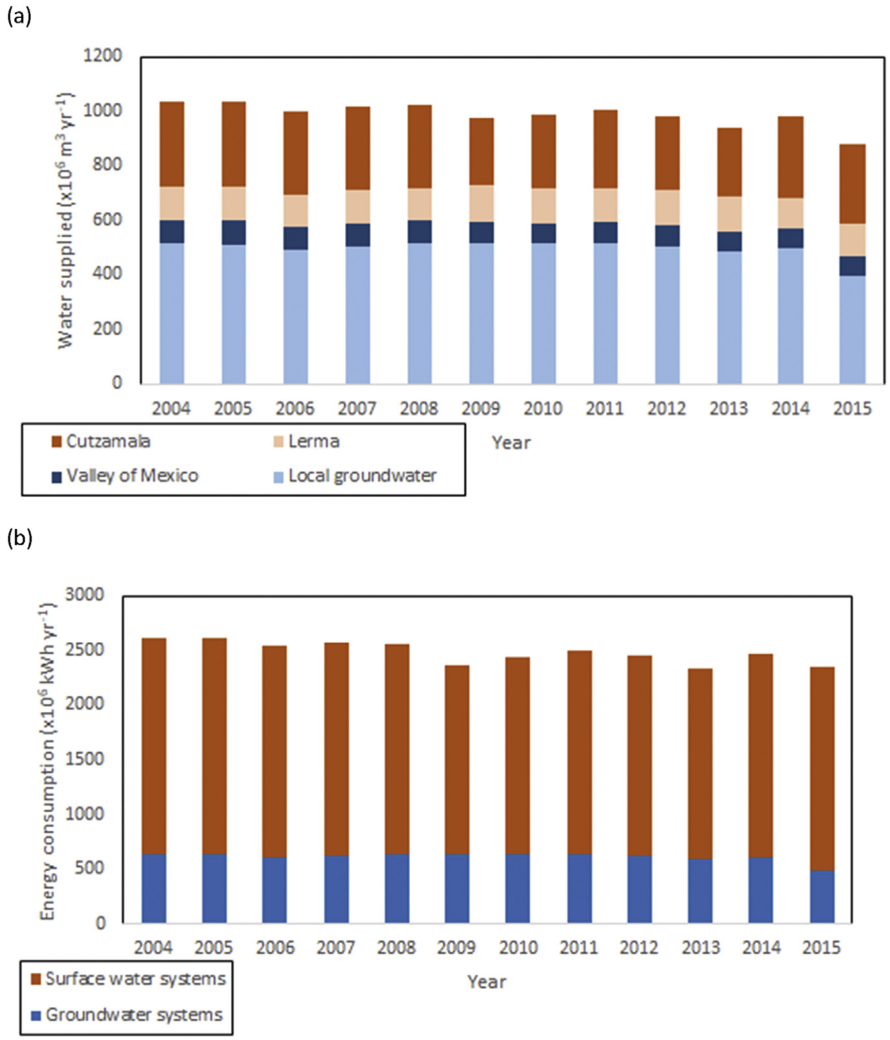

FIGURE 4.2

(A) The contribution to water supply in Mexico City from surface water (Cutzamala and Lerma) and groundwater (Valley of Mexico and Local groundwater) systems. The split is almost 50:50; (B) the energy attributed to the water supply of the water and groundwater sources in Mexico City. Surface water sources consume the vast majority of energy for water supply. *Figures adapted from Valek, A.M., Sušnik, J., Grafakos, S., 2017. Quantification of the urban water-energy nexus in México City, México, with an assessment of water-system related carbon emissions. Sci. Total Environ. 590–591, 258–268.*

the vast majority of water system energy consumption was related to surface water supply, and not to groundwater as is often the case (Fig. 4.2B), due to the vast topographic barrier that needs to be overcome, which requires considerable energy. Of the small amount of energy associated with wastewater treatment at the time of the study, most was attributed to treatment itself, and only a small fraction was due to pumping as the wastewater system was largely gravity-fed. Since the study, a large wastewater treatment facility has been built for the city, meaning that more wastewater is now treated and to a higher degree, but also that the water—energy nexus relationships and divisions in the city water system have changed and therefore need to be updated.

Using a multiregional input—output (MRIO; Chapter 6) analysis, Chen et al. (2018a) show how much water and energy resources of the hinterland of a city contribute to the consumption within that city by considering the resources "embedded" within the products consumed in the city. This is important as many cities globally rely significantly on their hinterlands and beyond to provide the resources required to allow for optimal functioning of city services. Likewise, the characteristics of a city's resources demands have a profound impact on resources exploitation and sustainability in locations that may be distant to the city itself. It is therefore important to better understand the resource demands of a city, and where these resources are sources from to better mitigate and adapt to potential constraints in the future. The study is focused on Hong Kong and its dependency on the Guangdong hinterland. It is shown that 79% of freshwater in Hong Kong was imported from Gaungdong, placing a large resources stress on that region. Note that this demand might place the Hong Kong water demand in conflict with water demands within the Gaungdong region itself. It is also shown that the energy "embedded" in this water supply from Guangdong was higher than the local Hong Kong water-related energy consumption, again leading to Hong Kong placing a high energy demand on a distant region. It is also shown that wastewater treatment consumes more energy than the water supply sector, mainly due to the high level of wastewater treatment standards in the city. While the local water consumption in the energy sectors is 10 times that of residential consumption in Hong Kong, this water is sourced from the sea, and much is returned after use (i.e., a low consumptive fraction). Expected growth in population in the city will likely lead to an 8%—9% increase in resource demands, both within the city and from the hinterland, potentially leading to resource-related constraints in the future.

Moving up to the regional scale, Purwanto et al. (2019, 2021) conducted a WEF resource security analysis (i.e., including aspects of resource quantity, quality, and accessibility) in Karawang Regency, Indonesia. In Indonesia, much resource-related decision-making is devolved to the Regency level but is guided by nationally determined plans and objectives. In Purwanto et al. (2019), a

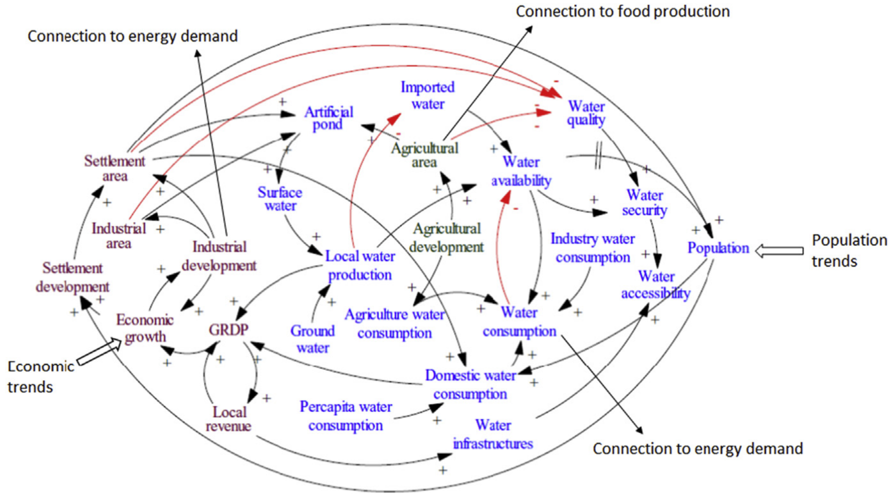

FIGURE 4.3

The CLD of the water sector in Karawang Regency, Indonesia, with links to food production, energy demand, population, and economic trends indicated. *CLD*, causal loop diagram. *Modified from Purwanto, A., Sušnik, J., Suryadi, F.X., de Fraiture, C., 2019. The use of a group model building approach to develop causal loop diagrams of the WEF security nexus in a local context: a case study in Karawang Regency, Indonesia. J. Clean. Prod. 240, 118170.*

detailed qualitative CLD of the WEF nexus (the so-called K-WEFS model; Fig. 4.3) was developed in a collaborative group model building exercise with local expert stakeholders from all the WEF sectors and from planning agencies. The model connects the water, energy, and food sectors with developments in local population and economic trends (Fig. 4.3). Without the development of a quantitative model, the significant added value of a qualitative approach including stakeholders is demonstrated. Local policymakers have a better appreciation of the complexity of this local WEF nexus and are better placed to assess the wider impacts of implementing sectoral-specific policy measures, and to develop policies that address many nexus issues simultaneously while identifying and attempting to minimize detrimental trade-offs and negative impacts across sectors.

In a follow-up study, Purwanto et al. (2021) develop and demonstrate a quantitative system dynamics model (SDM; Chapter 6) using the causal loop diagram (Fig. 4.3) as a guide. The SDM tries to accurately recreate the CLD within the constraints of data availability. Once the model was validated against historical observations, it was used to assess the impact of proposed interventions in the Regency. From these analyses, unanticipated synergies and trade-offs were identified and quantified. The CLD, together with the SDM, has resulted in a series of practical recommendations for local policymakers, therefore making this study a good example of moving from nexus thinking to policy-relevant nexus implementation, something that is urgently called for (Brouwer et al., 2018).

Bakhshianlamouki et al. (2020) conducted a WEF nexus analysis in the Urmia Lake Basin, Iran, in a basin-scale study. A conceptual mapping of the WEF nexus system is developed with input from local experts from which a quantitative SDM is developed. As Urmia Lake is undergoing declining lake levels due to water overuse, the Urmia Lake Restoration Programme (ULRP) has proposed a series of restoration measures in an attempt to halt and even reverse this decline. The study tested these measures for their efficacy and impact across the wider nexus in the basin. While some measures are broadly beneficial, some unanticipated negative impacts such as increasing fuel demand for water supply in agriculture were uncovered. Through such an analysis and reporting back to the ULRP, measures can be revised and adjusted to minimize such adverse impacts, leading to win-win situations in the efforts to restore Urmia Lake water level. This study better "grounds" nexus research in real issues and could serve as an example for other studies where real policy decisions are becoming critically important. It shows that modeling nexus issues can lead to suggestions as to potential ways forward and can act as a point of discussion in future policy talks.

3. The national scale

Moving up to national scale nexus analyses, Wang et al. (2018) used MRIO and ecological network analysis to assess the water–energy nexus in China. It was found that major cities consume significant "embedded" water and energy resources and that water resources are generally transferred from west to east and north to south across China. While this analysis is detailed, using considerable national-level trade data to demonstrate the flow of resources between cities and regions in China, little is suggested with regard to practical policy changes that could be implemented. Nor is the methodology capable of assessing dynamic interactions or system changes over time. However, as with the local-level study of Chen et al. (2018a), this study helps to place cities and their resource consumption within wider environmental and resource sustainability contexts, especially as, alluded to aforementioned in Valek et al. (2017), water and energy are especially interconnected in urban areas. As cities continue to grow, more emphasis will have to be given as to where cities get their resources from, and how resource interconnectedness may have implications for resource sustainability in the long run.

In South Africa, Nhamo et al. (2020) use an analytical hierarchical process (AHP) methodology and WEF nexus indicators suggested by the World Bank to assess the performance of the nexus in South Africa. Food selfsufficiency and water productivity targets are well achieved, but apparently at the cost of progress in other nexus goals such as energy accessibility and water availability. In addition, the high dependence of South Africa on coal for energy generation means that while energy productivity targets are all met, the climate impacts are scored poorly. Nhamo et al. (2020) go further, by demonstrating how South Africa has performed in achieving national-level SDGs related to the nexus, and how progress has been made between 2015 and 2018. While water and energy productivity have improved, efforts in cereal production and energy accessibility have got worse. This analysis appears to suggest national-level conflicts in South Africa in its ambitions to achieve multiple SDG targets simultaneously. Through such a nexus analysis, these trade-offs can be identified and addressed, potentially leading to more holistic policy being developed that attempts to harness synergies and avoid trade-offs.

Laspidou et al. (2020) conduct a highly detailed nexus analysis for Greece, using dedicated sectoral thematic models and data combined in an SDM modeling framework and disaggregated into 14 interacting regions in Greece. The study uses extensive data from several thematic models, EUROSTAT data (ec.europa.eu/eurostat/home), as well as data from national Greek statistics to develop a highly complex, interacting system dynamics model. The model is disaggregated to represent 14 regions in Greece, which interact and "trade" resources with each other (Fig. 4.4). It is shown that in Greece, about half of water resources come from surface water. Over 80% of water demand in Greece is consumed by agriculture and livestock for food production, demonstrating a strong and critical nexus connection between these sectors. The direct climate impact of the energy sector to climate emissions is also shown, with those regions having large fossil-based energy industries contributing significantly to national greenhouse gas (GHG) emissions totals. Most energy consumption in Greece is in the "built environment."

Through such a detailed analysis of resource demand and of resource requirements in different sectors and their impacts (e.g., the amount of energy used in the water sector, and the concomitant climate impact of that water-related energy demand) at the national and regional levels in Greece, policy- and decision-makers are better placed to consider policy design that results in lower overall resource consumption along with lower environmental impact. In addition, cross-sectoral synergies can be better identified, and suggestions can be made as to where best to apply a policy within the country, as national blanket policy implementation may not be most efficient. Although such suggestions are not made in the study, follow-up work could use these findings as a starting point for such policy-relevant advice.

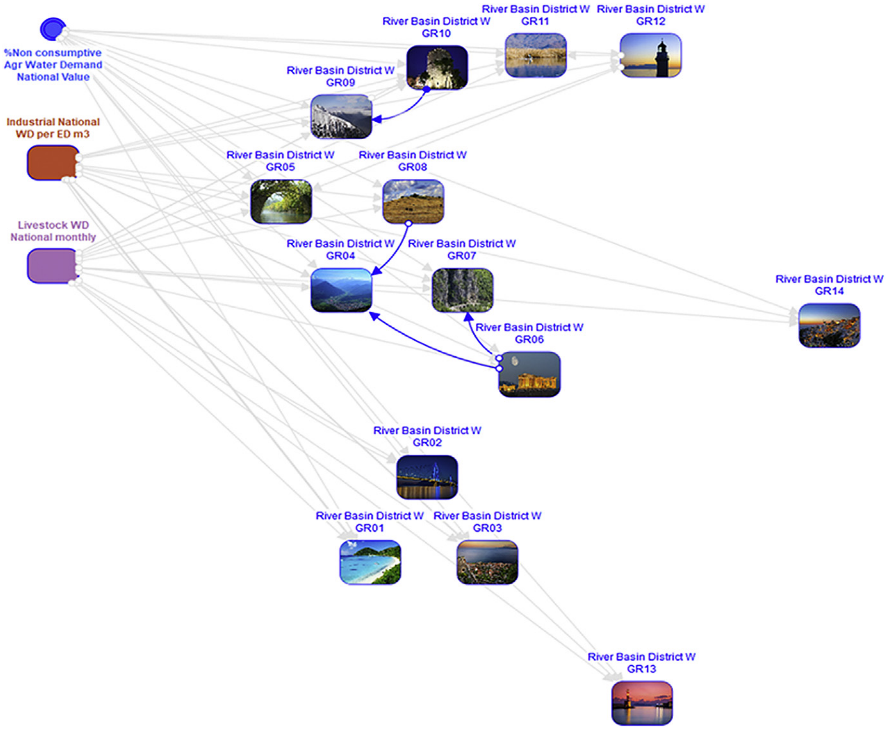

FIGURE 4.4

The Greek national-level SDM disaggregated into 14 interacting regions. Regional totals are summed to national values. *SDM*, system dynamics model.

As a final example of national-scale WEF nexus analysis, Janssen et al. (2020) investigate the nexus of water, energy, food, land, and climate in the Netherlands (Fig. 4.5) using the drivers–pressures–states–impact–response (DPSIR) methodology combined with systems thinking. The study also assesses the impacts of various resource-related innovations on the nexus.

A wide suite of innovations across the sectors is first identified, and then both the effort to implement the innovation and its expected impact (assessed on a relative scale from 1 to 10) are assessed for each. For example, the wider implementation of district heating scores relatively low on effort, but highly on impact. This is because the impact to the energy sector is high, and at the same time, district heating is already partly implemented in the Netherlands, making it easy to extend to new areas. From the work, concrete suggestions for policy are made, bringing traditionally theoretical nexus modeling to real-world application, a feature lacking in many nexus studies.

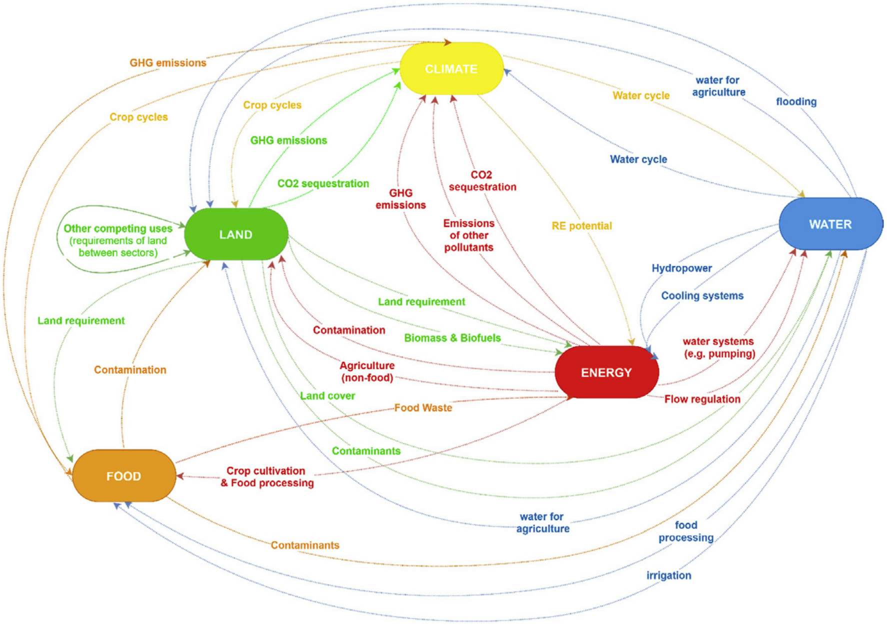

FIGURE 4.5

Interactions between the water, energy, food, land, and climate sectors in the Netherlands. *From Janssen, D.N.G., Ramos, E.P., Linderhof, V., Polman, N., Laspidou, C., Fokkinga, D., de Mesquita e Sousa, D., 2020. The climate, land, energy, water, and food nexus challenge in a land scarce country: innovations in The Netherlands. Sustainability 12, 10491.*

4. Higher-level nexus studies

At the highest spatial scales, studies tend to be conducted at the global level, deriving broad conclusions about the nature of the global WEF system. Sometimes, such studies are disaggregated into smaller global regions to analysis variability and particularities in results.

Perhaps one of, if not the first global-scale nexus study was conducted by Meadows et al. (1972) in the classic "Limits to Growth" study. The high-level global scale dynamics of the population—pollution—capital—resource nexus was simulated using an early application of the system dynamics paradigm. In this study, common global finite resources such as cropland, fossil fuel stocks, and metals contribute to development, population growth, and pollution of the environment. Simulations suggest that as resources are depleted and pollution crosses thresholds, the global system is unable to support further development, leading to collapses in food and industrial output, and ultimately in population. While criticized at the time for being too speculative, recent reanalysis has shown that the *trends* predicted in the 1972 study are reflected in observed data over the intervening 30 years (Turner, 2008), leading to concerns about the future of resources, production, and ecosystem and human health.

More recently, Chen et al. (2018b) carry out a global-scale MRIO analysis to examine agricultural land and freshwater use that is embodied in global supply chains. It is shown that globally, developed and major developing economies such as China are major drivers in land and freshwater use due to their large and increasing product demand. This is restated as a “transfer” of water and land resources from resource rich but less-developed economies to resource poor but economically highly developed nations. For example, Africa as a continent is shown to contribute significant water and land resources to the production of goods destined for Europe. It is expected that the intensification of globalization will only increase this disparity and drive land and water “displacement” from poor to rich nations. Through this analysis, suggestions can be made on how to optimize supply chains and improve efficiencies to reduce these inequities.

Focusing largely on global water system dynamics, Simonovic (2002) uses a system dynamics modeling approach to investigate the behavior of the global water system and its response to changes in arable land, industrial capital and production, and population, somewhat similar to the study of Meadows et al. (1972), albeit with a different focus. Indeed, the standard runs in the Simonovic model derived from Meadows et al. (1972). The intimate relationship between population growth and water abstractions is clearly demonstrated in the simulations. The importance of water quality is also highlighted as being critically important for continued development, an issue that appears to have been underappreciated until recently. It is also shown that water must be considered as one of the most important factors for continued human development globally, again a fact that is only recently starting to get more attention.

As final examples, Sušnik (2015, 2018) analyses the global-scale WEF nexus using a system dynamics approach in combination with data-based correlative and causal statistical analysis between the WEF sectors and gross domestic product (GDP) as a proxy for development. In the earlier work, Sušnik (2015) demonstrated temporally robust correlative relationships between WEF parameters and GDP. From this, using global GDP projections, global water withdrawals, food production, and energy (electricity) generation were projected to 2100. It was shown that the trajectory of growth in these three WEF sectors was strongly related to the GDP growth scenario. The stronger the GDP growth, the more resources were expected to be exploited. This is a crucial finding, as GDP is still the “benchmark” by which economic “performance” and “development” are measured. If resource use is indeed closely connected to GDP change, then constantly increasing global GDP implies an evergrowing demand for, and exploitation of, water, energy, and food (land) resources, something that is clearly not possible on a finite planet. A suggestion from this work is that GDP and resource use must be "decoupled" as soon as possible. This early work did not consider causal relations between the WEF sectors, nor did it consider dynamic feedbacks.

To address these gaps, a follow-up study (Sušnik, 2018) was carried out, where the WEF—GDP nexus was further explored (Fig. 4.6). In this study, apart from including feedback between the sectors (Fig. 4.6), the strength of causal relationships was quantitatively analyzed. This allowed the dominant causal direction between two variables to be assessed, and the relative strength of linking equations forming feedback loops was scaled to represent causal asymmetries. In addition, uncertainty in future projections was accounted for using a Monte Carlo modeling procedure. While water and food historical values were well captured by the model, energy was overestimated. For the future projections, as in the earlier study, the trend of resource use depends largely on the GDP projection. Stronger GDP growth implies more resource use. There is also considerable bandwidth in projections. The estimates in Sušnik (2018) agree well with independent projections from the literature for water and food resources, but overestimate energy production projections. While useful regarding global scale trends, these two studies do not capture national-level variability, highlighting a need for future research.

5. Spatial interactions in the nexus

The studies presented deal with specific cases at specific and fixed spatial scales (e.g., household, national). However, it must be acknowledged that actions within the nexus take place between these scales, and the different scales interact with each other (cf. Fig. 4.1), affecting the processes at the different

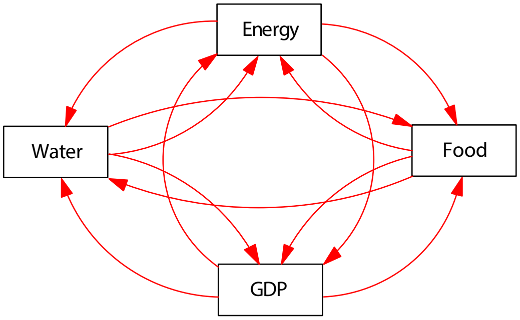

FIGURE 4.6
Schematic representation of the WEF—GDP nexus analyzed in Sušnik (2018). *GDP*, gross domestic product; *WEF*, water—energy—food.

scales. For example, national policies might be informed by higher-level policy goals. Within Europe, many water and agricultural policies at the national level are guided and shaped by the EU-level Water Framework Directive (WFD; ec.europa.eu/environment/water/water-framework/index_en.html) and Common Agricultural Policy (CAP; ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy/cap-glance_en) respectively. However, there is sufficient flexibility in the EU Directives to allow for "fine-tuning" or interpreting these policies according to national-level characteristics and priorities, giving rise to considerable heterogeneity in their implementation. Likewise, national-level policies may be reflected differently in local-level policymaking, having an influence on local nexus-related decisions and resource management. It is less clear how actions at the local level may feed up to influence policy decisions at higher levels. One recent example from the United Kingdom is that of household wood-burning stoves that have recently undergone a popular resurgence. Due to the level of uptake and the resultant particulate pollution levels being recorded, it is possible that changes in national level energy and clean air policy will be implemented in an attempt to mitigate this effect, though this is yet to be seen.

Considering the nexus in terms of resources, Bijl et al. (2018) show that the WEF resources vary greatly in terms of their locations of production and the extent to which they are traded. They also show that the spatial scales of trade are related to the physical characteristics of the resources and that global- and continental-scale trade characteristics are important when considering local and national solutions to nexus issues. Abulibdeh and Zaiden (2020) present a framework where different scales are nested within each other. For example, the national scale may be concerned with households and urban area dynamics. This is nested within the regional scale, concerned with wider water, energy, and food resources production. Nexus risks such as population growth, sectoral coupling, and energy prices are considered, as are the impact of policies, which are seen to influence all scales and can mitigate risks, and thus form the highest-level nest.

6. Conclusions

This chapter has shown that the WEF nexus is operational at scales from household to global, with numerous studies being applied at all these scales. The WEF nexus approach, comprising a number of methodological approaches dealt with in other chapters in this book, is shown to be highly flexible and has been adapted to many geographical and socioeconomic conditions, as well as to many nexus issues specific to each study or location. This flexibility is arguably the greatest asset of the nexus approach, making it suitable to study many pertinent issues at a range of spatial and temporal scales. At the same time, there are interactions between these spatial scales, which have not been addressed in nexus studies. Global-, regional-, and national-level policies and ambitions can have significant implications for local-level resource demand, use, and sustainability. Likewise, local-level resource exploitation can aggregate up to have national- and global-level implications, thus impacting on policy formulation and implementation. This interacting multiscale aspect of the WEF nexus has not yet been explored and represents a major challenge for future research efforts. What is much less studied is differences in the temporal scales of nexus sectors, impacts, and feedbacks, and how these temporal scales differ at different spatial scales. This is a research gap that represents a major challenge for future nexus research. It is likely that local-level change occurs relatively quickly when compared with national and international scales; however, this is yet to be robustly tested.

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