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Water-Energy-Food Nexus Tools in Theory and Practice: A Systematic Review

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Sector-based resource management approaches partly contribute to the insecurities in water, energy and food sectors and resources. These approaches fail to acknowledge and capture the interlinkages between these connected resources, a key strength in the water-energy-food (WEF) nexus approach. However, the multi-centric, multidimensional, and spatiotemporally dynamic WEF nexus is complex and uncertain, thus requiring dedicated tools that can unpack it. Various sources have blamed the slow uptake and practical implementation of the WEF nexus on the unavailability of appropriate tools and models. To confirm those claims with evidence, literature on WEF nexus tools was searched from Scopus and Web of Science and systematically reviewed using the PRISMA protocol. It was found that the WEF nexus tools are being developed increasingly, with a current cumulative number of at least 46 tools and models. However, their majority (61%) is unreachable to the intended users. Some available tools are in code format, which can undermine their applicability by users without programming skills. A good majority (70%) lack key capabilities such as geospatial features and transferability in spatial scale and geographic scope. Only 30% of the tools are applicable at local scales. In contrast, some tools are restricted in geographic scope and scale of application, for example, ANEMI 3 and WEF models for large and household scales, respectively. Most (61%) of the tools lack wide application in actual case studies; this was partly attributed to the tools not being readily available. Thus, efforts should be made to disseminate and ensure end-users' uptake and application of developed tools. Alternatively, the user-friendly tools should be developed on-demand as requested and inspired by potential clients. Developers should consider utility, transferability and scalability across uses and users when improving existing tools and developing new tools so that they are adaptable, only requiring new, specific location-adapted inputs and data. Where and when it is necessary to capture spatial dynamics of the WEF nexus, tools should be geographic information system (GIS)-enabled for automatic WEF nexus location selection, geospatial mapping, and visualization. Such GIS-enabled WEF nexus tools can provide a bird's eye view of hotspots and champions of WEF nexus practices.

Keywords: water-energy-food nexus, model, format, GIS, scale, case study, implementation, availability

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INTRODUCTION

Water, energy, food, and land drive economic and social development. These strategic resources are degrading and over-exploited by, among many factors, population growth, economic development, dietary shifts, urbanization, pollution, as well as changes in culture, technology, and climate (Mabhaudhi et al., 2016). Projections for the near and distant future expect increased demand for water, energy, and food (Hoff, 2011; IRENA, 2015; Martinez-Hernandez et al., 2017; Tashtoush et al., 2019; Schull et al., 2020). The insecurities of these key resources are further amplified by the disconnected policies and sector-focused approaches to resources management, which ignore the resource interlinkages, coexistence and transboundary nature (Leck et al., 2015). Integrated management of the resources that underpin the water, energy and food security avoid the unintended effects of sector-based approaches to unlock the potential for achieving the Sustainable Development Goals (SDGs) (de Andrade Guerra et al., 2021). This has led to the pursuit of the water-energy-food (WEF) nexus approach as a holistic, integrated approach to managing natural resources that was proposed in the Bonn 2011 Nexus Conference for WEF Security Nexus Solutions for the Green Economy (Leck et al., 2015; Schull et al., 2020). Water, energy and food are inextricably and intrinsically linked in ways that actions in one sector influence the others, synergistically or often adversely, at different levels and scales (Hoff, 2011; IRENA, 2015). The WEF nexus has gained undivided attention in the agenda of research, policy dialogue and development (Bazilian et al., 2011; Eftelioglu et al., 2017). This has seen WEF nexus being mainstreamed into thematic areas, strategies and policies by local, regional, and international institutions, governments, and organizations (SADC, 2016; GWP-SA, 2019a,b). The actual nature and significance of interconnections between the WEF resources are context-specific, hence the need to explore and understand the interdependence of water, energy and food security and the natural resources that underpin their security (Liu et al., 2017; Salam et al., 2017). Despite the hype of the WEF nexus agenda, several authors concur that the actual translation of the theory into practice is lagging hence the need to investigate the limited uptake of the promising approach (Byers, 2015; Daher and Mohtar, 2015; Liu et al., 2017; Galaitsi et al., 2018; McGrane et al., 2019; Nhamo et al., 2020a; Naidoo et al., 2021).

WEF nexus tools were previously reviewed on several characteristics, including feedback analysis, optimization and visualization (Wicaksono et al., 2017; Wicaksono and Kang, 2019), informing policy (Shannak et al., 2018) as well as entry requirements, exits and analytical capabilities (Rosales-Asensio et al., 2020). Mannan et al. (2018) reviewed analytical features of WEF nexus tools, while Dai et al. (2018) focused on model types, spatial scale, purpose and nexus challenge level. Dargin et al. (2019) delved on the complexity of WEF nexus tools, while Flammini et al. (2014), IRENA (2015), Kaddoura and El Khatib (2017), and Shinde (2017) reviewed their suitability, analytic modeling capabilities, inputs, and outputs. Reviews by Albrecht et al. (2018) and Zhang et al. (2018) included concepts and methodologies in the WEF nexus and tools.

These previous studies usually reviewed <10 different WEF nexus tools to provide useful information on the characteristics of different WEF nexus tools. They also overlooked other significant characteristics that may undermine the applicability of these tools. Such characteristics or criteria include availability, format, application scales, geospatial analytic capabilities and previous use, among others. Eftelioglu et al. (2017) and Hiloidhari et al. (2017) highlighted that geospatial analytic capabilities in WEF nexus tools solve spatial decision problems because WEF nexus tools and geographic information system (GIS) are complementary. GIS is a computer-based information system and spatial decision-making tool that supports the precise assessment of distributed WEF resources, thereby addressing economic and environmental goals (Johnson, 2009; Janipella et al., 2019). Thus, GIS-enabled WEF nexus tools assist in providing a bird's eye view for analysis, comparison and identification of WEF nexus hotspots and champions, with the possibility of exploring impacts of interventions and transfer of good practices and technology (Daher and Mohtar, 2015; Fernandes Torres et al., 2019; Lin et al., 2019). WEF nexus tools and GIS can be integrated through "hard-linking" and "soft-linking." The former effectively automates the exchange of input and output data between the WEF nexus and GIS for analysis, mapping, and visualization. "Soft-linked" coupling requires the user to manually prepare and transfer information, which is cumbersome and somehow prone to error (Eldrandaly, 2007; Ramos et al., 2019). The status of geospatial analytic capabilities in existing WEF nexus tools is unknown and needs to be addressed. While geospatial capabilities are not a panacea to analyses, they are useful for allowing analyses at different spatial scales and visualization of results in a way that is easier for users and decision-makers to understand and utilize. Also, the trend in models now-a-days has been to add the functionality so that users have an option to use it if they need to.

The WEF nexus field is rapidly evolving, and it is expected that many new tools were developed in addition to the previously reviewed and more will still be developed. Some critical issues on the characteristics of WEF nexus tools remain vague. For example, what is the general historic and current trend in developing WEF nexus tools? How accessible are the tools that have been developed and reported by other users (Byers, 2015)? Is there a lack of WEF nexus tools and, is it justified? What are they likely to find if a user (new or old) searches online for WEF nexus tools? What are the formats of existing WEF nexus tools? Can the existing WEF nexus tools handle spatial data to characterize the WEF nexus spatially? If yes, how are geospatial capabilities incorporated in existing WEF nexus tools? What are the least and most popular WEF nexus tools in case studies? Thus, there is a need for an updated review of WEF nexus tools to clarify WEF nexus tools' status and trends of development, their availability and accessibility, format, spatial scale of application, geospatial capabilities and their application in previous case studies. The global aim of this study was to provide a review of the state-of-the-art of WEF nexus tools and their suitability in supporting the implementation of the WEF nexus approach. To fulfill this aim, this study sought to systematically review the available literature and potentially address the following specific objectives to:

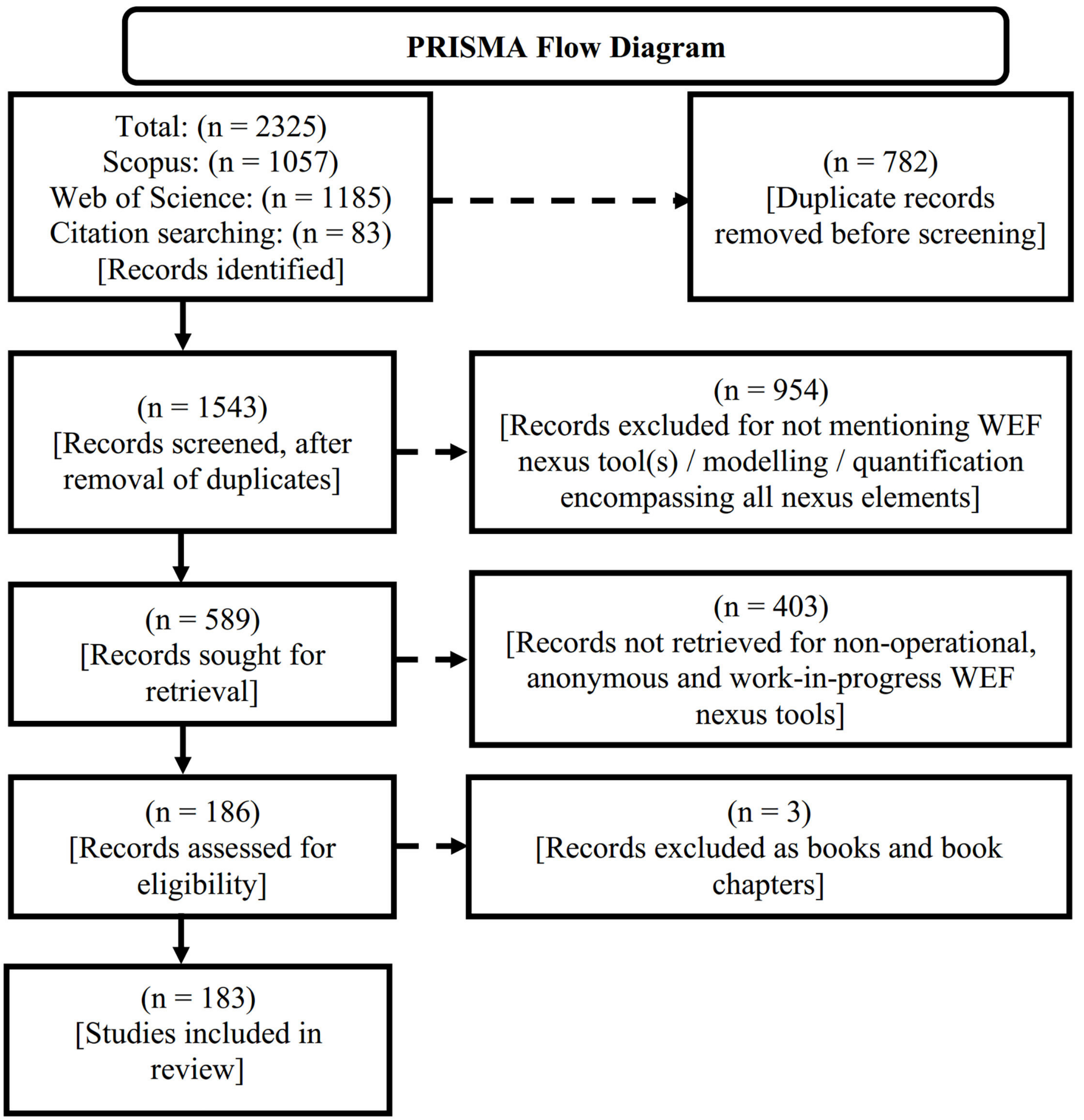

FIGURE 1 | The PRISMA 2020 framework and flow diagram for the systematic review, which includes searches of databases and other sources (adapted from Haddaway et al., 2021a,b and Page et al., 2021a,b).

i. assess the historic and current trends in the development of WEF nexus tools;
ii. provide an inventory/compendium of existing WEF nexus tools;
iii. review the availability, format, spatial scales of application, and geospatial analytic capabilities of existing WEF nexus tools; and
iv. assess the application of existing WEF nexus tools in previous case studies.

This review will serve as an update on new and old users' WEF nexus tools and a starting point for present and future developers who intend to improve existing or create new WEF nexus tools. Secondary to this and without necessarily comparing WEF nexus tools, this review is intended to be a knowledge synthesis to

TABLE 1 | The adapted PICOS strategy used for literature searching.

PICOS	Description
Population	WEF nexus
Indicator	WEF nexus tools, models, applications
Comparison	N/A
Outcome	Applicability characteristics of WEF nexus tools
Study designs	Qualitative, quantitative and mixed

TABLE 2 | Search topics for retrieving documents related to WEF nexus tools in Scopus and WoS.

Search topic (first row)	Search topic (second row)	Search topic (second row)
(water-energy-food) OR (water-food-energy) OR (energy-food-water) OR (energy-water-food) OR (food-energy-water) OR (food-water-energy) OR WEF OR WFE OR EFW OR EWF OR FEW OR FEW	AND nexus	AND (tool OR model* OR application OR "geographic information system" OR gis OR geospatial OR spatial OR map* OR web)

guide and inform interested users of WEF nexus tools on what tools to use under different contexts. This will enhance the quick, easy and effective selection of WEF nexus tools for different conditions and requirements in facilitating the implementation of the WEF nexus approach.

MATERIALS AND METHODS

This study conducted a WEF nexus tools systematic review by mapping broad literature to answer questions regarding development trends, availability, format, spatial scale, geospatial analytic capabilities, and case studies. These characteristics were excluded in previous reviews which focused on concepts, methodologies, complexity and analytical capabilities. Although geospatial tools are useful for certain problems but not for all, interested users need to be guided and informed on status of geospatial analytical capabilities in existing WEF nexus tools. The review was done step-wise, guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol (Moher et al., 2009), which assist in systematically searching, identifying, and selecting articles on search platforms and reviewing them through appraisal and synthesis of research evidence (Grant and Booth, 2009). Page et al. (2021a,b) went on to update, further explain and elaborate PRISMA, which was also applied by Fernandes Torres et al. (2019) in reviewing literature for proposing a systematic procedure of the nexus concept. The PRISMA flow diagram (**Figure 1**) was conveniently generated with the user-friendly open-access R package and ShinyApp for PRISMA Flow Diagram[1] by Haddaway et al.

[1]https://estech.shinyapps.io/prisma_flowdiagram/; https://doi.org/10.5281/zenodo.5082518

TABLE 3 | Definitions of characteristics of WEF nexus tools.

Tool characteristics	Description
WEF system tool (herein synonymous with model, application)	The mathematical relationships between food, energy, and water systems that that simplify and represent reality by capturing their spatial and/or temporal dynamics, as well as feedbacks between them. A WEF nexus tool is an intellectual construct that describes a system's structure and function to give insights into select attributes of physical, biological, economic, or social dimensions and dynamics of a WEF system (EPA, 2009; Saundry and Ruddell, 2020).
Availability	The quality or state of presence, ready reachability, and accessibility by public users[a]
Web availability	The quality or state of being available at a specific expected internet or online location[b]
Broken or dead links	A hyperlink on a web page that no longer works, maybe because the destination web page no longer exists or has been moved or error[c]
Format	The form or type of the tool includes web applications, desktop applications, codes, Excel worksheets, and serious games/simulators[d]
Web application (or web app)	An application program usually hosted on a remote server and accessible through web-browsers (Bourne, 2014; Sturm et al., 2017).
Desktop application (or desktop app)	An application that runs stand-alone and locally on a computer device such as a desktop or laptop[e]
Code	The symbolic arrangement of data or instructions in a computer program or the set of such instructions[f]
Excel worksheet	A collection of cells organized in rows and columns that keeps and manipulates data[g]
Serious game	A "learning by playing" decision-based platform, including role plays, that allows policymakers to play out scenarios and see what would bring the best outcome (Vamvakeridou-Lyroudia et al., 2017; Saundry and Ruddell, 2020).
Unknown	When the form of the tool is not stated by the developers, previous users or literature[h]
Spatial scale	The spatial extent or level of application for the tool measured by area, distance or length, including ecological, hydrological and administrative[i] (Saundry and Ruddell, 2020).
Geospatial capabilities	Spatial mapping, visualization and analysis through the use of either open-source GIS or commercial products and software (Johnson, 2009; Janipella et al., 2019).
Case study (practice)	A published use of the tool in assessing real-life circumstances or simulating and modeling hypothetical scenarios; the application of Nexus research to real-world problems (Saundry and Ruddell, 2020; Vinca et al., 2021).
Low case studies	Refers to previous use of the tool in between one to three areas
Moderate case studies	Refers to previous use of the tool in between four to 10 areas
Geospatial capabilities	Refers to previous use of the tool in more than 10 areas

[a]*https://blog.amplexor.com/website-availability-what-is-it*
[b]*https://blog.amplexor.com/website-availability-what-is-it*
[c]*https://www.techopedia.com/definition/23236/broken-link; https://www.computerhope.com/jargon/b/broken_link.htm*
[d]*https://dictionary.cambridge.org/dictionary/english/format; https://www.collinsdictionary.com/dictionary/english/format*
[e]*https://encyclopedia2.thefreedictionary.com/desktop$+$application*
[f]*https://www.thefreedictionary.com/computer$+$code*
[g]*https://www.excel-easy.com/basics/worksheets.html*
[h]*https://www.merriam-webster.com/dictionary/availability*
[i]*https://www.igi-global.com/dictionary/mapping-the-chromosome-through-a-novel-use-of-gis-and-spatial-analysis/43412*

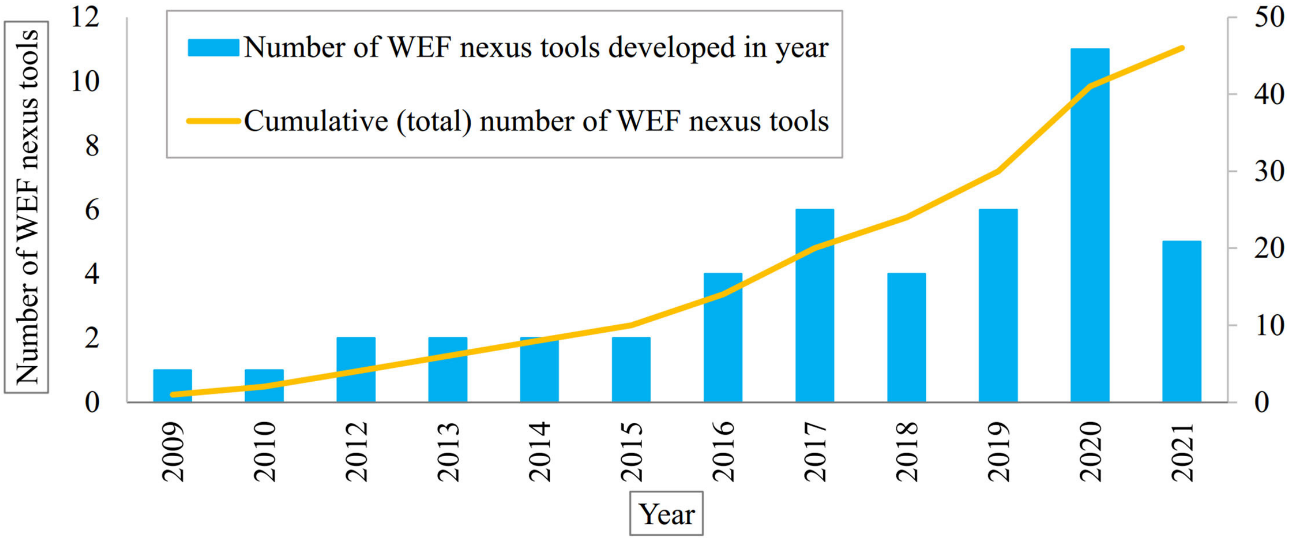

FIGURE 2 | Trend in the development of WEF nexus tools.

(2021b), as recommended by Page et al. (2021a). The PRISMA steps involved, among others, eligibility criteria, information sources, search strategy, screening, selection, data collection, defining data items, and analysis.

Eligibility Criteria

The study used the population, indicator, comparison, outcome and study design (PICOS) strategy, which limits the number of irrelevant articles (CRD, 2006; Methley et al., 2014) (**Table 1**). The PICOS strategy informed the search strategy and the subsequent inclusion-exclusion criteria. Given that the WEF nexus is a fairly novel area of research, broad eligibility criteria were adopted for publications mentioning the development and application of WEF nexus tools. In this regard, only studies with named and operational WEF nexus tools were included, excluding anonymous and non-operational tools.

Information Sources and Search Strategy

The potentially relevant studies in the literature were searched using the same search criteria within two online literature databases, Scopus[2] and Web of Science Core Collection (WoS)[3] (Accessed on 02 July 2021). These two multidisciplinary databases were selected for their comprehensive coverage and high-quality scientific publications that allow systematic review. Their journal coverage is also remarkably greater than other common databases, even in natural science and engineering disciplines. In addition, citation searches were conducted in reviews to identify WEF nexus tools and their corresponding publications that could be missed in Scopus and WoS databases, including those by international organizations such as Food and Agriculture Organization (FAO) and International Renewable Energy Agency (IRENA). The search criteria in the two databases (Scopus and WoS) involved searching topics using Boolean expressions. The search topics were formed from the keywords "nexus, tool, model, application, spatial, map, geographic information system, GIS," together with iterations of "water, energy, food" and WEF. The details of the search topics used are presented in **Table 2**.

Consideration was given to peer-reviewed papers (articles, reviews), scientific book chapters, papers from proceedings and materials from special issue editorial material, institutional documents including dissertations, theses, or technical papers, all written and published in English. The WEF nexus approach, tools and integration of geospatial features are still novel. Thus, the date of publication, geographic scope, journal disciplines and impact factors were kept open to capture all WEF nexus tools and versions, from earliest to latest. All records obtained from Scopus, WoS, and citation searches were combined to facilitate the removal of duplicates.

Screening and Selection of Studies (Inclusion and Exclusion Criteria)

In line with the objectives of this systematic review, the titles, abstracts, and keywords of the searched studies were reviewed and screened for selection. The screening was in favor of publications on (i) WEF nexus tools that have an operational version(s) instead of proposed or work in progress, and (ii) capturing at least all three components of the WEF nexus: water, energy, and food. Sometimes the "land" was considered a proxy for the food component since it is a key element directly linked to food production. Secondly, books and chapters were excluded because they replicated some published journal articles. Eventually, the eligible papers were retrieved for review. These eligible papers and sources may not include all the WEF nexus literature out there. However, they best represent the previous

[2]https://www.scopus.com/
[3]http://www.webofknowledge.com/

work relevant to addressing and fulfilling our research questions and objectives.

Collecting Data

A data extraction sheet was designed in simple, flexible, and functional MS Excel based on the study objectives. Key data on the selected papers were extracted from the eligible studies and organized in the data extraction sheet. These were organized in columns by the tool's characteristics, including acronym, authors/developers, year of initial development, availability, format/form, the spatial scale of application, geospatial capabilities, and the number of previous case studies. The sub-columns for availability contained general availability, web availability, and dead links. The sub-columns for the column for format were web applications, desktop applications, code, Excel, serious games and unknown. The sub-columns under spatial scale of application presented five classes namely (i) global, (ii) continental/economic region/basin/transboundary, (iii) country/national, (iv) province/sub-basin/catchment, and (v) local including sub-catchment/municipal/city/town/household/project. The sub-columns under the column for number of case studies included three classes according to frequency, namely low (one to three), moderate (four to 10), and high (more than 10).

Data Items and Analysis of Studies

The characteristics of the WEF nexus tools used in this study were criteria briefly defined and described (**Table 3**) from previous related reviews (Flammini et al., 2014; IRENA, 2015; Shinde, 2017; Dargin et al., 2019) as well as authors' discretional synthesis.

All the tool characteristics defined in **Table 3** are desirable attributes in the intended users' applicability of WEF nexus tools. For example, the availability and accessibility of a WEF nexus tool in the public domain is a key prerequisite to its applicability by the intended users. Thus, tools' links provided by developers and previous users, such as web addresses and digital object identifiers (DOIs), were tested. On encountering broken or dead links, a basic search for the tool was conducted on the tool's related website or Google Search Engine[4]. All evidence of the tools' characteristics was gathered from literature without contacting the authors/developers to avoid bias. The results were presented as tables and charts for analysis, visualization, and interpretation.

RESULTS AND DISCUSSION

The pursuit for the WEF nexus approach has seen the advent of several tools for analyzing, modeling, and simulating the WEF nexus in terms of resource supply, demand, nexus indicators and indices. This section presents the findings from reviewing the searched literature against the characteristics and criteria that was previously presented in **Table 3**.

Literature Search

The detailed results of the search and selection process are shown in the flow diagram in **Figure 1**. Initially, 1,057, 1,185, and 83 records were obtained from Scopus, WoS, and citation searches. Duplicates were removed in EndNote from these records to remain with 1,543 papers. The screening and selection of the 1,543 studies with the inclusion and exclusion criteria yielded 183 papers that were eventually retrieved for review, whose findings are presented in the succeeding sections.

Trends in Development of WEF Nexus Tools

Overall, reviewing the literature identified 46 WEF nexus tools. From a quantitative perspective, this is quite a large number which contrasts previous reports of lack in WEF nexus tools (Byers, 2015; Liu et al., 2017; Nhamo et al., 2020a; Naidoo et al., 2021). Even if no publication date range was imposed during the literature search, **Figure 2** shows how, among the papers selected and reviewed in this study, the advent of WEF nexus tools started around 2009–2012. Generally, the development of new WEF nexus tools has been gaining momentum with time since 2012, as evidenced by the increasing annual trends and cumulative total number with time (**Figure 2** and **Table 4**).

The trends of annual increases in developed WEF nexus tools with time testifies to the continuously increasing momentum of the WEF nexus agenda in research and maybe practice. Shinde (2017) also observed this increasing trend, implying that implementing the WEF nexus, which has been lagging, is attempting to catch up with WEF nexus agenda research and dialogues. The progressive trend in WEF tools development is motivated by the increased traction of the WEF nexus concept in international policy and research, including the iconic World Economic Forum Water Initiative (World Economic Forum, 2011) and Bonn 2011 Conference on The WEF Security Nexus Solutions for the Green Economy (Hoff, 2011). Interestingly, the rising trends coincide with the adoption of the related SDGs, with the literature showing emphasis on SDGs 2 (zero hunger), 6 (clean water and sanitation) and 7 (affordable and clean energy) a few years later in 2015.

From **Figure 2**, the existence of WEF nexus tools such as MuSIASEM (46) and ANEMI (45) pre-2011 shows that the WEF nexus concept predates 2009. The year 2011 was just a landmark when the concept gained momentum and recognition in wider research and policy agenda circles. The annual rate of development of WEF nexus tools stagnated during 2009–2010, increased in 2012 but stagnated until 2015, increased in 2016–2017 and then fell in 2018, followed by consecutive increases in 2019–2020. The year 2020 boasts of the largest number (11) of developed WEF nexus tools, including NEST (14), iWEF (15) and WEF Nexus Index (16); while an almost half year of 2021 (January to July) recorded five (5) developed WEF nexus tools. If the past and current trends are anything to go by, more WEF nexus tools are being and will continue to be developed in the future. This will provide researchers, practitioners, non-practitioners, decision- and policymakers with a wide array of tools that they can use to translate the WEF nexus approach from theory to practice. What remains to be theoretically and practically investigated are the key characteristics of these reported tools, especially their availability to interested users, their format, spatial and temporal scales of application, geospatial analytic capabilities, and popularity in practice. Addressing such

[4]https://www.google.com/

TABLE 4 | Brief summaries of existing WEF nexus tools.

WEF nexus tool	Short description
WEF Nexus Discovery Map (1)	WEF Nexus Discovery Map is a map-based pool/database of cataloged and classified WEF nexus information from otherwise geographically and topically diverse independent and academic communities worldwide. It shows WEF nexus projects' specific information, such as the institution that produced the work, local collaborators, relevant web page, and point of contact. The WEF Nexus Discovery Map dashboard incorporates the WEF Nexus Index Map (Arenas et al., 2021).
BP-DEMATEL-GTCW (2)	Back Propagation neural networks–DEcision Making Trial and Evaluation Laboratory–Game Theory Combination Weight (BP-DEMATEL-GTCW) Model is a two-step measurement model for the symbiotic and symbiotic level indices used to study the nexus in the form of the WEF ecosystem from the perspective of WEF symbiosis. Its applications include identifying key influencing factors that affect the symbiotic security of the WEF ecosystem (Chen and Chen, 2021).
ITEEM (3)	Integrated Technology-Environment-Economics Model (ITEEM) integrates various models for technology (grain processing, drinking water treatment, environment (watershed model for hydrology, water quality, crop production, nutrient cycling), and an economics model for assessing total benefit that includes non-market evaluation of environmental benefits (Li et al., 2021).
WEF-Sask (4)	Water-Energy-Food (WEF) - Sask (WEF-Sask) Model integrates production (supply) and demand sides of WEF systems into a single system-of-systems model using the system dynamics approach to gain insights into inevitable trade-offs and synergistic interactions between WEF systems under challenges brought by socioeconomic and climatic changes and limited water resources (Wu et al., 2021).
CALFEWS (5)	California Food-Energy-Water System (CALFEWS) links the operation of state-wide, inter-basin transfer projects with coordinated water management strategies abstracted to the scale of irrigation/water districts to describe the integrated, multi-sector dynamics that emerge from the coordinated management of surface and groundwater supplies (Zeff et al., 2021).
NeFEW (6)	Nexus of Food, Energy, and Water (NeFEW) Toolbox is a data analysis toolbox for synthesizing available global data to enable estimating country-specific estimates of water resources (blue, green, gray) required to produce different types of food and energy, the energy required per quantity of water or agricultural product supplied, and CO2-equivalent emissions associated with water and energy provision (Sadegh et al., 2020).
MAXUS Model (7)	MAXUS highlights, simulates, and optimizes inter-sectoral and international development strategies in the WEF sectors. The model consists of an objective function, balances, dimensions, constraints and decision variables (Burger and Abraham, 2020).
WEF Nexus SD (8)	The Water-Energy-Food Nexus System Dynamics (WEF Nexus SD) Model is based on system dynamics to study intricate connections between WEF and specific supply-and-demand mechanisms of water resources in each sub-system. The sub-systems include the external social, economic, and eco-environmental, all integrated by the model to determine the dynamic balance of water resources (Chen and Chen, 2020).
FPC (9)	Farm Performance Calculator (FPC) contains data and conversion coefficients derived from the (FArming Tools for external nutrient Inputs and water MAnagement) FATIMA project to calculate indicators and conduct energy, economic and environmental analysis for a simplified evaluation and analysis of the WEF nexus at the farm level. The main input for the calculator consists of agricultural and energy, while the main output consists of computations for the energy, water and food indicators (Fabiani et al., 2020).
WEF-P (10)	Water-Energy-Food Nexus Phosphate (WEF-P) Tool is an adaptation of the WEF Nexus Tool 2.0 (Daher and Mohtar, 2015). WEF-P assesses the impact of various scenarios and possible responses to resource management needs, by considering the supply the supply chain of the final product in terms of its resource consumption, including the set of processes that pass materials forward and various organizations/individuals directly involved in the flow of the products (Lee et al., 2020).
SD-WFE (11)	System Dynamics Water–Food–Energy (SD-WFE) Model is a spatiotemporal disaggregated WEF nexus model that assesses water and food supply security considering ecosystem provisioning services. The model contains modules for population, water, agriculture, and energy (Ravar et al., 2020).
WEST (12)	WEST (Water Economy Simulation Tool) is a simulation model that incorporates water, energy, food, and detailed economic data, usable for standalone analysis or incorporated, to show how jobs and economic growth interact with surface and groundwater use, food and energy (Reimer et al., 2020).
MIFCP-WEFN (13)	Multi-level Interval Fuzzy Credibility-constrained programming Water-Energy-Food Nexus (MIFCP-WEFN) Model helps plan the regional-scale WEF nexus system by identifying the optimal agricultural water resources management schemes through the leadership of water resources managers and the feedback of two diverse followers (i.e., managers for energy and agriculture) (Yu et al., 2020).
NEST (14)	NExus Solutions Tool (NEST) is an open modeling platform for integrated energy-water-land EWL systems analysis under global change by a hard-linked integration of multi-scale energy-water-land resource optimization framework with distributed hydrological modeling. It integrates a distributed hydrological model and a resource supply planning model (Vinca et al., 2020).
iWEF (15)	Integrative analytical model for the Water-Energy-Food nexus (iWEF) is an Analytic Hierarchy Process (AHP)-based model that establishes quantitative relationships among WEF nexus sectors, as well as an integrated nexus index that indicates resource utilization and performance over time, thereby providing evidence of WEF nexus to decision-makers and indicating priority areas for intervention (Nhamo et al., 2020a).
WEF Nexus Index (16)	The Water-Energy-Food (WEF) Nexus Index is a web-based WEF nexus global visualization map comprising an index that is a composite indicator derived from integrating WEF resource sectors' indicators. Within each resource are equally weighted "access" and "availability" sub-pillars, as well as relevant indicators from a total of 21 (Simpson et al., 2020).
AWEFSM (17)	Agricultural Water-Energy-Food Sustainable Management (AWEFSM) Model integrates multi-objective programming, non-linear programming, and intuitionistic fuzzy numbers into a general framework for the sustainable management of the limited water-energy-food resource in an agricultural system (Li et al., 2019).

(Continued)

TABLE 4 | Continued

WEF nexus tool	Short description
GREAT for FEW (18)	GIS-based Regional Environmental Assessment Tool for Food-Energy-Water nexus (GREAT for FEW) is based on the life cycle assessment (LCA) method for evaluating the FEW inter-linkages and informing decision-makers of the co-benefits and trade-offs from a wide variety of investments and policies for the present and the future. It combines a nexus assessment framework and a web-based GIS-enabled nexus platform that consists of a conceptual model, a database, and calculation methods (Lin et al., 2019).
EPAT (19)	Energy Portfolio Assessment Tool (EPAT) is a scenario-based holistic nexus tool and platform for energy stakeholders and policymakers to create and evaluate the sustainability of various WEF nexus scenarios (Mroue et al., 2019).
WHAT-IF (20)	Water, Hydropower, Agriculture Tool for Investment and Financing (WHAT-IF) is an open-source hydro-economic optimization model incorporating representations of the water, agriculture, and power systems in a holistic framework to explore joint development of nexus-related infrastructure and policies and evaluate their economic impact, as well as the risks linked to uncertainties in future climate and socio-economic development (Payet-Burin et al., 2019).
K-WEFS (21)	Karawang Water-Energy-Food (WEF) Security (K-WEFS) Model is a system dynamic model that assesses the WEF nexus based on four scenarios: changes in population growth, agricultural land conversion rate, per-capita resource consumption, and the development of artificial ponds and solar energy (Purwanto et al., 2019).
WEFSiM (22)	Water-Energy-Food (WEF) nexus Simulation Model (WEFSiM) is a system dynamics algorithm-based computer simulation and optimization model that calculates the supply and consumption, availability, and reliability of water, energy, and food resources nationwide considering the interconnections of resources (Wicaksono and Kang, 2019).
Daily (23)	Daily Model applies cost-benefit analysis to assess WEF nexus scenarios from integrating RiverWare, HEC-HMS, and CropWat that simulate hydrological processes, irrigation water requirements, and water allocation to hydro-energy generation and irrigation water supply (Basheer et al., 2018).
DAFNE (24)	The Decision-Analytic Framework to explore the water-energy-food NExus in complex and transboundary water resources systems of fast-growing developing countries (DAFNE) approach facilitates the quantitative assessment of the social, economic, and environmental impacts of expanding energy and food production in complex physical and political contexts, in interconnected natural and social processes, where the institutional setting involves multiple stakeholders and decision-makers. The approach consists of a Decision-Analytic Framework (DAF) for Participatory and Integrated Planning (PIP), an integrated WEF modeling framework and a web-based Negotiation Simulation Lab (NSL) (ETHZÜRICH, 2018).
SIM4NEXUS Models and Serious Game (25)	Sustainable Integrated Management FOR the NEXUS of water-land-food-energy-climate for a resource-efficient Europe (SIM4NEXUS) Models and Serious Game consist of a WEF system dynamic integrated model and serious games for investigating potential plausible cross-nexus implications and synergies under different climate change and socioeconomic pathway scenarios due to policy interventions for 12 multi-scale case studies ranging from regional to global (Sušnik et al., 2018).
UCEC (26)	Urban Circular Economy Calculator (UCEC) is an online open-access tool for cities to develop different circular economy scenarios associated with WEF management. Based on emergy accounting urban dynamic modeling, it uses WEF inputs from urban managers and policymakers to display the analysis of different urban circular economy scenarios considering technological roadmap alternatives performances from policy and technology solutions (Xue et al., 2018).
ABM-SWAT Model (27)	Agent-Based Model - Soil and Water Assessment Tool (ABM-SWAT) is an integration of ABM and SWAT that assesses the impact of climate and human/anthropogenic changes on the water, energy, food, and ecosystem sectors and characterizes the resulting trade-offs through a set of generic metrics related to the sustainability of water availability (Khan et al., 2017).
Nexus Game (28)	Water–Food–Energy Nexus Game is an integrated "hardware" simulation game addressing the interrelated challenges of WEF production to meet demand. It is set on two riparian countries sharing a transboundary river basin, representing inter-ministerial and international negotiations wherein players encounter and learn potential technological solutions and relational challenges to reduce their WEF footprints (CSS, IIASA, and SE4ALL, 2017).
WEF Model (29)	Water-Energy-Food (WEF) Model is a system dynamics-based model that captures the interactions between WEF at household scale and end-use level by estimating WEF demand and the generated organic waste and wastewater quantities and investigating the impact of change in user behavior, diet, income, family size and climate (Hussien et al., 2017).
Q-Nexus (30)	The Q-Nexus model is a quantitative WEF nexus assessment, simulation and optimization framework and platform to quantify, plan, simulate and optimize water, energy, and food as an interlinked system of resources that directly and indirectly affect one another. The model enables the analysis of WEF planning scenarios and policy options based on dynamic demand, technology and resource allocation (Karnib, 2017).
NexSym (31)	Nexus Simulation System (NexSym) is a modular tool based on a simulation and analytics framework for explicit systems dynamic modeling of local techno-ecological interactions relevant to WEF operations. It integrates models for ecosystems, technology, WEF production and consumption components, including waste treatment (Martinez-Hernandez et al., 2017).
WEFO Model (32)	Water, Energy and Food security nexus Optimization (WEFO) is an integrated multi-period socioeconomic model analysis framework and tool for predicting how to satisfy WEF demands based on model inputs representing production costs, socioeconomic demands, and environmental controls. WEFO's management objective is to minimize the total system cost, a sum of energy supply, water supply, electricity generation, food production, and CO_2 emission mitigation costs (Zhang and Vesselinov, 2017).
SEWEM (33)	System-wide Economic-Water-Energy Model (SEWEM) is an advanced hydro-economic optimization model analyzing basin-wide energy production alternatives and energy demand restrictions for agricultural and industrial production and water supply systems (Bekchanov and Lamers, 2016).

(Continued)

TABLE 4 | Continued

WEF nexus tool	Short description
BRAHEMO (34)	BRAhmaputra HydroEconomic MOdel (BRAHEMO) integrates physically-based spatially distributed hydrologic modeling, hydro-economic modeling, and ex-post scenario analysis to elicit the conditions of conflict and alignment of development trajectories (Yang et al., 2016b).
IBMR-MY (35)	Indus Basin Model Revised-Multi Year (IBMR-MY) is a hydro-agro-economic model extended with an agricultural energy use module. Its objective function maximizes the net economic benefit (from crop production and hydropower generation) of water uses in the basin (Yang et al., 2016a).
Pardee RAND WEF Security Index (36)	Pardee RAND Water-Energy-Food (WEF) Security Index is an online interactive WEF nexus security index with an unweighted geometric mean of three sub-indices, each for the three WEF sectors. Each sub-index comprises two or more indicators reflecting resource availability and accessibility (Willis et al., 2016).
WEF Nexus Tool 2.0 (37)	The Water-Energy-Food (WEF) Nexus Tool 2.0 is a scenario-based tool that consists of inputs that reflect national food, water, and energy strategic options and allows for creating and assessing different scenarios to achieve sustainable resource management strategies for national food production. The tool uses an input-output modeling framework and food as an entry point for calculating nexus resource flows and interactions and greenhouse gas (GHG) emissions for a given food self-sufficiency level (Daher and Mohtar, 2015).
PRIMA (38)	Platform for Regional Integrated Modeling and Analysis (PRIMA) is an innovative modeling system to simulate interactions among natural and human systems at scales relevant to regional decision-making. PRIMA aims to enhance scientific understanding and facilitate effective decision-making related to regional interactions among climate, energy, hydrology, land use, and socioeconomics. PRIMA's modeling framework integrates various models of regional climate, hydrology, agriculture and land use, socioeconomics, and energy systems using a flexible coupling approach. Due to its modular framework and structure, PRIMA is customizable, portable and flexible (Kraucunas et al., 2015).
EWF Nexus Tool (39)	Energy-Water-Food (EWF) Nexus Tool integrates energy, water, and food life cycle assessment in one robust holistic systems model of sub-systems at an appropriate resolution. The EWF Nexus Tool uses life cycle assessment principles to translate system outputs into environmental assessment scores, by operating through the four stages of life cycle assessment: the goal and scope definition, the life cycle inventory analysis; the impact assessment; and the interpretation of the results (Al-Ansari et al., 2014).
WEF Nexus Assessment 1.0 (40)	Water-Energy-Food (WEF) Nexus Rapid Appraisal (or Nexus Assessment 1.0) Tool rapidly informs nexus-related responses regarding strategies, policy measures, planning and institutional set-up, or interventions regarding bio-economic pressures. It provides users with 10 nexus context analysis indicators and 30 nexus intervention analysis indicators. The set of intervention scenarios includes power irrigation, bioenergy, hydropower and water desalination interventions from the perspective of water, energy, food, labor, and cost components (Flammini et al., 2014).
Nexus Webs (41)	Nexus Webs is a conceptual–analytical model of the components and linkages in a river basin representing how water use changes impact livelihoods and wellbeing. The four linked components include water use, assets, ecosystem services and wellbeing (Overton et al., 2013).
CLEWs (42)	Climate-, Land-, Energy- and Water-systems (CLEWs) tool applies a module-based approach to quantitatively and simultaneously assess/explore land, energy and water resource systems as closely linked resources (and climate) within a modeling framework that integrates detailed models from different tools. The tool iteratively passes data between sectoral models (Howells et al., 2013).
WEAP – LEAP (43)	Water Evaluation and Planning System – Long-range Energy Alternatives Planning System (WEAP - LEAP) were integrated to become WEAP-LEAP for integrated research planning, analyses and decision-making of the closely interlinked energy and water systems. They are connected seamlessly by a common "wizard" that allows exchanging parameters and outputs, such as hydropower generated or cooling water requirements, water supply characteristics for projecting energy demand, hydropower modeling and consistent weekly time-step calculations (SEI, 2012).
Foreseer (44)	The Foreseer Tool is a modular model for tracing and visualizing, using Sankey diagrams, the influence of future demand scenarios on requirements for energy, water, and land resources. The tool is based on a set of linked physical models for energy, water and land, or any other customized analyses such as climate change, technological change, or other effects (Allwood et al., 2016).
ANEMI (45)	ANEMI is an integrated assessment model of global change that emphasizes the role of water resources. The model uses feedback processes among its sub-systems and system dynamics simulation principles to analyze changes in the Earth system. ANEMI3 assesses and describes the state of and interactions between the Earth system's model sub-systems (or sectors), mainly climate system, carbon, nutrient and hydrologic cycles, population dynamics, land use, food production, sea-level rise, energy production, energy, economy, persistent pollution, water demand and water supply development (Davies and Simonovic, 2010).
MuSIASEM (46)	Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) is an integrated diagnostic and simulation tool that characterizes the metabolic pattern/flows of energy, food and water and their interlinkages about socio-economic (e.g., population dynamics) and ecological variables (e.g., land-use changes, greenhouse gas emissions) simultaneously. The MAGIC Nexus Game is a serious game based on MuSIASEM, to expose players to the main trade-offs and co-benefits in the nexus using a quantitative framework of relations between the nexus elements based on environmental footprint indicators (Giampietro et al., 2009).

TABLE 5 | Characteristics of existing 46 WEF nexus tools.

Tool	Availability					Format/form of tool					Spatial scale of application				Geo spa tial cap abili ties	Number of case studies		
	Av	*W*	*DL*	*WA*	*DA*	*Cod*	*Ex*	*Ge*	*Un*	*G*	*Con, ER, B, Tr*	*Cou, N*	*P, SB, Ca*	*L (Sc, M, H, Ci, To, Proj)*		*L (1–3)*	*M (4–10)*	*H (>10)*
WEF Nexus Discovery Map (1)	✓	✓		✓						✓	✓	✓	✓	✓	✓			✓
BP-DEMATEL-GTCW (2)									✓		✓		✓	✓				✓
ITEEM (3)						✓					✓				✓	✓		
WEF-Sask (4)									✓		✓					✓		
CALFEWS (5)	✓	✓				✓						✓				✓		
NeFEW (6)	✓	✓			✓							✓				✓		✓
MAXUS (7)					✓							✓	✓	✓	✓			✓
WEF Nexus SD (8)									✓				✓			✓		
FPC (9)							✓							✓		✓		
WEF-P (10)									✓		✓					✓		
SD-WFE Model (11)									✓				✓					✓
WEST Tool (12)	✓	✓				✓						✓	✓			✓		
MIFCP-WEFN Model (13)									✓				✓			✓		
NEST Tool (14)	✓	✓				✓					✓				✓	✓		
iWEF Tool (15)							✓				✓	✓	✓	✓		✓		
WEF Nexus Index (16)	✓	✓		✓								✓			✓			✓
AWEFSM Model (17)									✓		✓		✓	✓		✓		
GREAT for FEW Tool (18)	✓	✓		✓								✓			✓	✓		
EPAT (19)									✓			✓	✓			✓		
WHAT-IF (20)	✓	✓				✓					✓		✓			✓		
K-WEFS (21)									✓					✓		✓		
WEFSiM (22)									✓			✓				✓		
Daily (23)									✓		✓		✓		✓	✓		
DAFNE (24)			✓						✓		✓				✓	✓		
SIM4NEXUS Model and Serious Game (25)	✓	✓							✓				✓		✓			✓
UCEC (26)	✓	✓		✓										✓		✓		
ABM-SWAT (27)									✓		✓					✓		
Nexus Game (28)	✓							✓			✓							✓
WEF (29)					✓									✓		✓		
Q-Nexus (30)	✓	✓		✓								✓					✓	
NexSym (31)					✓									✓		✓		
WEFO (32)									✓		✓					✓		
SEWEM (33)									✓		✓		✓			✓		
BRAHEMO (34)									✓		✓					✓		
IBMR-MY (35)									✓		✓					✓		
Pardee RAND WEF Security Index (36)	✓	✓		✓								✓						✓
WEF Nexus Tool 2.0 (37)	✓	✓		✓								✓					✓	
PRIMA (38)		✓	✓		✓								✓		✓		✓	
EWF Nexus Tool (39)									✓			✓					✓	
WEF Nexus Assessment 1.0 (40)		✓	✓						✓			✓	✓	✓			✓	
Nexus Webs (41)									✓	✓	✓	✓	✓	✓		✓		
CLEWs (42)	✓	✓		✓						✓	✓	✓	✓	✓	✓			✓
WEAP – LEAP (43)	✓	✓			✓					✓	✓	✓	✓	✓	✓			✓
Foreseer (44)		✓	✓		✓					✓	✓	✓			✓			✓
ANEMI (45)	✓	✓				✓				✓	✓	✓						✓
MuSIASEM (46)	✓	✓							✓			✓			✓			✓

Av, availability; W, web availability; DL, dead (broken) link; WA, web application; DA, desktop applications; Cod, code; Ex, Excel worksheet; Ge, game; Un, unknown; G, global; Con, ER, B, Tr, Continental, Economic Region, Basin, Transboundary; Cou, N, Country, National; P, SB, Ca, Province, Sub-basin, Catchment; L (Sc, M, H, Ci, To, Proj), Local (Sub-catchment, Municipal, City, Town, Household, Project); Ge, Geospatial capabilities / features; L (1-3), Low case studies; M (4-10), Medium case studies; H (>10), High case studies.

questions and issues is critical in guiding users to selecting the WEF nexus tools that better suit their cases studies and peculiar requirements. The succeeding sections present results of the theoretical assessment of these key characteristics as criteria in reviewing the available literature on WEF nexus tools.

Existing WEF Nexus Tools

The 46 WEF nexus tools found in the literature are summarized in **Table 4**, including their names, developers, year of publication and brief description.

The characteristics of the existing 46 WEF nexus tools are presented in **Table 5**, which include availability, format, spatial scale, geospatial capabilities, and the number of previous case studies.

Availability and Format WEF Nexus Tools

Although availability and accessibility do not necessarily translate to usefulness, it is a necessary prerequisite that allows wide use of WEF nexus tools for improved nexus-friendly decision-making (IRENA, 2015). Logically, interested users can only choose from and use tools readily available at their disposal.

Less than half (39%) of the existing 46 tools are available to public users, despite the abundance of WEF nexus tools that have been developed (**Table 5**). The rest (61%) cannot be found in the public domain (**Figure 3**). This concurs with Vinca et al. (2020), who observed that existing WEF nexus tools and data are neither always openly availed nor integrative across the three sectors. Public availability and documentation of tools are imperative for capacity building, knowledge transfer and transparency (Antle and Valdivia, 2021).

Of all the 46 tools, only 43% are supposedly hosted on the public web domain (**Figure 4**), but reality shows that about a fifth of this category is dead links (**Figure 5**). They cannot be located where developers and previous users claim them to be or by searching online. These include DAFNE (24), PRIMA (38), WEF Nexus Assessment 1.0 (40), Foreseer (44) and MuSIASEM (46). For example, DAFNE (24) and its interactive portal is only accessible to specific practitioners and non-practitioners from the Zambezi and Omo-Turkana river basins.

The format for the largest portion (≈48%) of all existing tools is not stated and unknown (**Figure 6**). These include AWEFSM (17), WEFSiM (22), WEFO (32), EWF Nexus Tool (39), and Nexus Webs (41). They are automatically not readily available for application in case studies by interested users.

For those tools whose format was stated or observed, their descending order of prevalence includes web applications, desktop applications, codes, spreadsheets, and serious games.

The major format is web applications (≈18%). These include DAFNE's (24) Negotiation Simulation Laboratory (NSL), whose access is categorically restricted to DAFNE project partners and stakeholders (Melenhorst et al., 2018). Others include Q-Nexus (30), WEF Nexus Tool 2.0 (37), and Pardee RAND WEF Security Index (36). This complicates its use in other case studies outside DAFNE project participants, Zambezi and Omo-Turkana river basins. Despite their importance as visual portals and platforms providing essential information on the WEF nexus, some web-based tools, including WEF Nexus Index (16) and WEF Discovery Map (1), are just portals that lack essential WEF nexus quantitative analytic capabilities. Interested users can neither input nor analyze their own case study data in these tools; they can only retrieve prepared information on the preloaded case studies.

Desktop applications take the second largest proportion (≈15%) of WEF nexus tools. These include CALFEWS (5), NeFEW (6), WEF (29), and NexSym (31). Some desktop application tools such as NeFEW (6) require additional infrastructure such as MATLAB to run, implying the need for programming competence in MATLAB for interested users. The major limitation of these compiled desktop applications types of tools is the lack of flexibility in cases where a user may desire to link them with other models or adapt the code for specific study purposes such as interdisciplinary policy analysis (Foster et al., 2017).

Approximately 13% of the tools are codes archived in GitHub and Zenodo online libraries. These include NEST (14), WHAT-IF (20) and ANEMI (45). GitHub[5] is a code hosting platform for project collaboration and version control, while Zenodo[6] is an open dissemination research data repository. Although the codes are available, which promotes transparency and flexibility for integration and customization, especially for users knowledgeable with programming, they pose difficulty in applying them by the non-professional user because of programming competence requirements and lack of graphical user interface (GUI).

Approximately 4% of WEF nexus tools are Excel worksheets and in the custodian of their developers. These include FPC (9) and iWEF (15), and interested parties must request these worksheets from the authors and developers. This is a potential barrier to their wide application by interested users, depending on the willingness and time taken to share the tool.

Serious games constitute the minority (2%). These simulation games include Nexus Game (28), Serious Game for SIM4NEXUS (25), MAGIC Nexus Game (46) (Schyns et al., 2020). These and DAFNE's (24) NSL are "edutainment" tools that offer a safe virtual online environment for negotiating and "learning by planning" on implications of participants' choices, decisions, and actions in the WEF nexus. They expose players to the interconnections between the WEF resources and sectors, acting as test beds for policies and thus capacity building in the WEF nexus.

Despite their web availability and analytical capabilities, some tools' applicability is confined to the case study areas developed and tested for. For example, GREAT for FEW (18) is applicable only in Taiwan because it lacks flexibility and key information for other areas from the user's perspective (Lin et al., 2019). The same applies to WEF Nexus Tool 2.0 (37), whose geographical scope was originally developed for Qatar (Daher and Mohtar, 2015). SIM4NEXUS (25) models were specifically developed for the context of European countries (Sušnik et al., 2018). This can pose a limit to its applicability in other areas and conditions.

[5]https://www.w3schools.com/whatis/whatis_github.asp
[6]https://help.zenodo.org/

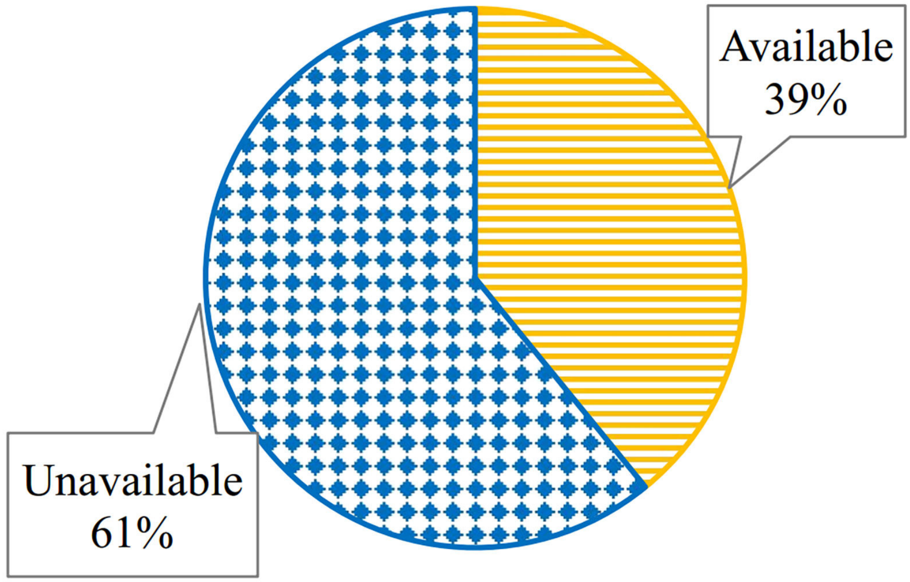

FIGURE 3 | General claimed availability of WEF nexus tools.

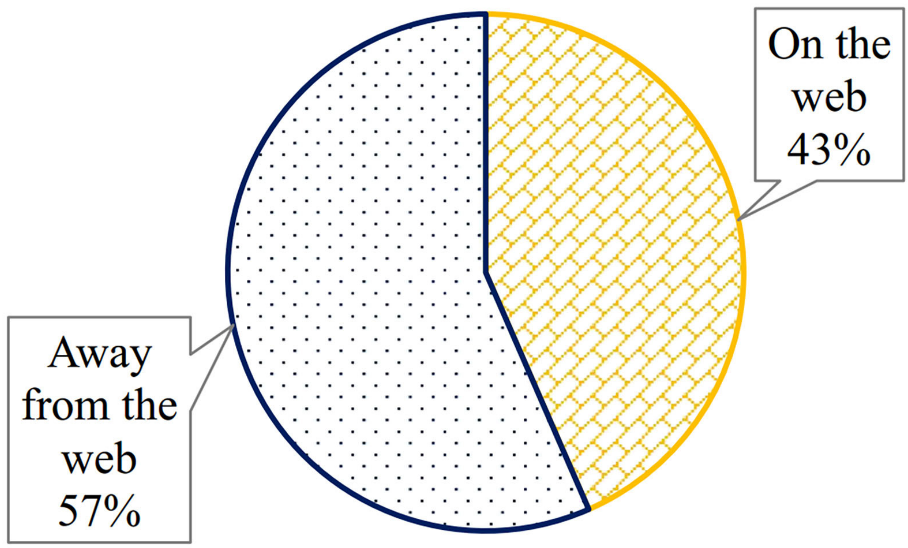

FIGURE 4 | Claimed availability of WEF nexus tools in the public domain.

Spatial Scales of Application and Case Studies of WEF Nexus Tools

Tools for large spatial scales such as continental, regional, transboundary basin, and national applications dominate, followed by medium and local scales (**Figure 7** and **Table 5**).

The latter include ANEMI (45), WEF Nexus Index (16) and Pardee RAND WEF Security Index (36). Thus, these large-scale tools are appropriate for aggregate level studies and inform WEF policies and decisions. However, these large-scale tools are inappropriate for local-scale studies. Policy- and decision-makers require WEF nexus insights at different levels of administration, which can be policy- and community-relevant scales, be it national, regional or local scales (IRENA, 2015; Albrecht et al., 2018). This highlights a gap for local-scale tools that can model, simulate and analyze local WEF nexus for assessing challenges, impacts, interventions and adaptation to change that can promote sustainable development at the grassroots level (Terrapon-Pfaff et al., 2018). However, some tools tend to be use-, user-, and scale-selective. For example, ANEMI3 (45), WEF Nexus Tool 2.0 (37) and the WEF model (29) are most appropriate for large, national, and household scales, respectively (Davies and Simonovic, 2010; Daher and Mohtar, 2015; Hussien

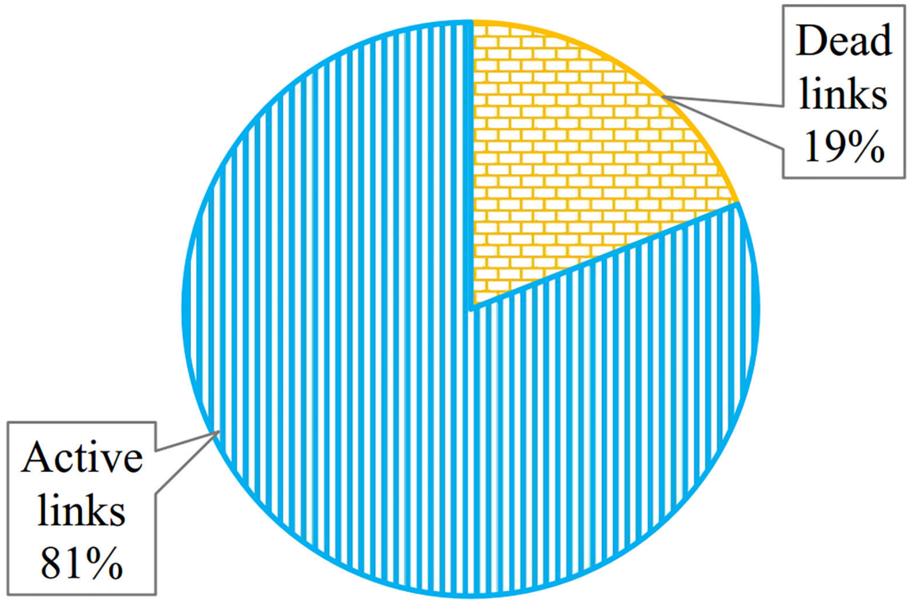

FIGURE 5 | Real web availability of WEF nexus tools.

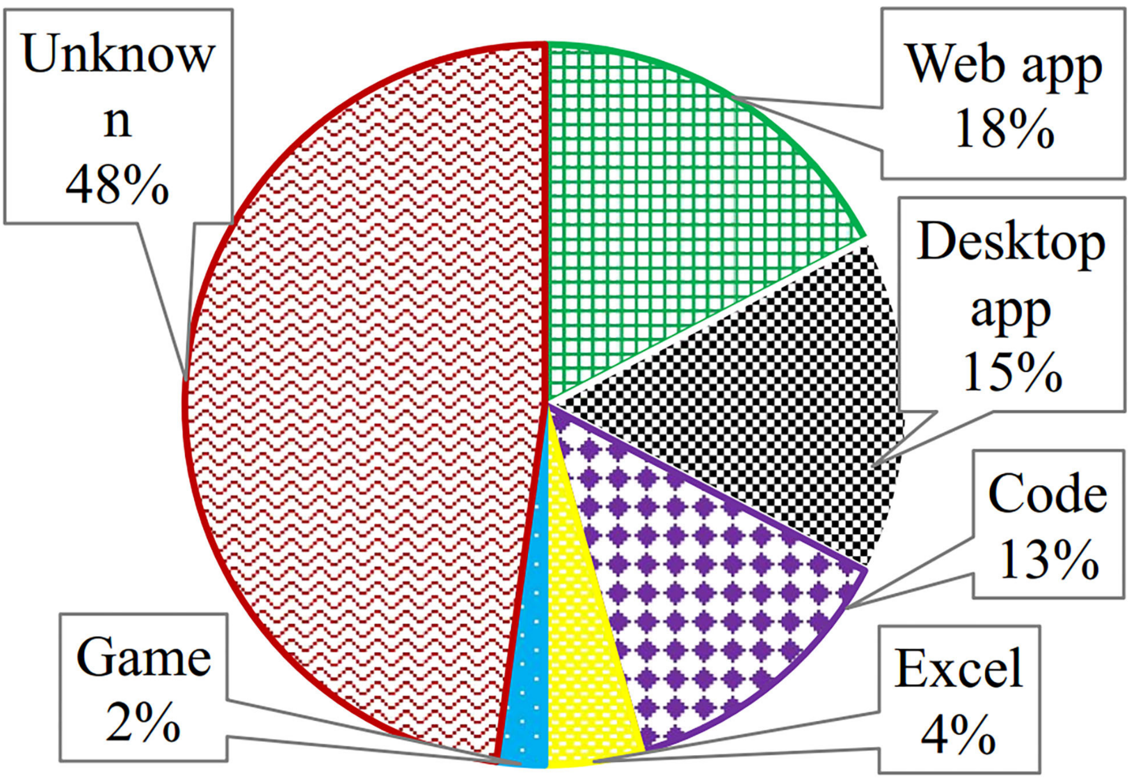

FIGURE 6 | Format of WEF nexus tools.

et al., 2017). EPAT (19) and WEF Nexus Tool 2.0 (37) use energy and food as entry points, respectively, with a potential bias toward those individual sectors and their policies and players in the WEF nexus. Similarly, Byers (2015) reported the existence of a variety of WEF nexus tools that operate at different scales or were developed for specific case studies. This tendency of

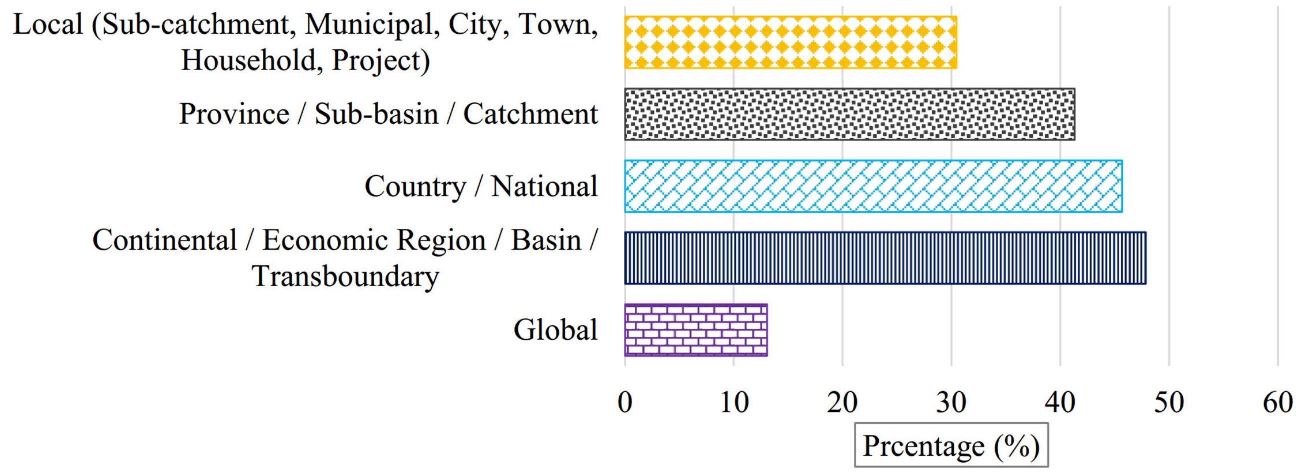

FIGURE 7 | Spatial scales of application of documented WEF nexus tools.

tools to be specific in application scales, uses and users may limit their applicability in case studies of different scales and contexts. Preferably, WEF nexus tools should be robust, multi-scalar, flexible and adaptable across users, uses, spatial scale and scope, only requiring new, specific location-adapted inputs and data (IRENA, 2015). This flexibility is critical for WEF nexus tools to be adapted to different contexts and geographies. They can be mandated for utility in and by a wide range of uses and users, respectively (Albrecht et al., 2018). For example, the iWEF (15) tool is applicable at regional scale (southern Africa) (Mabhaudhi et al., 2019), national scale (South Africa) (Nhamo et al., 2020a) and local scale (Sakhisizwe Local Municipality) (Nhamo et al., 2020b), respectively. However, developing multi-scalar tools is elusive due to different input data requirements at different scales bound by ecological, hydrological, and administrative boundaries. To be widely used in implementing the WEF nexus approach, WEF nexus tools should be accessible, especially to developing country analysts, and applicable to finer geographical coverage (Bazilian et al., 2011). Sustainable implementation of the WEF nexus requires open access to relevant tools to readily avail them for use in many contexts across the world by knowledgeable practitioners and non-practitioners (Byers, 2015).

Geospatial Analytic Capabilities in WEF Nexus Tools

Sometimes it is necessary to spatially characterize the WEF nexus in cases where and when the phenomena vary in space and location (Eftelioglu et al., 2017; Hiloidhari et al., 2017). Out of the 46 tools that were reviewed, only less than one-third (≈30%) possess geospatial capabilities (**Figure 8** and **Table 5**). The rest (≈70%) can only aggregate and generalize the WEF nexus in their analyses or display without performing geospatial mapping and visualizing the WEF nexus. This majority is useful in situations that do not require the spatial disaggregation of the WEF nexus, for example, in the context of similar distribution of trade-offs and synergies between WEF resources and sectors. Thus, this majority cannot characterize the spatial dynamics of the WEF nexus, which poses a big limitation to the tools because WEF resources are spatially distributed in nature. This concurs with Shannak et al. (2018) and Ravar et al. (2020), who reported that even though WEF resources are exposed to intense variations in time and space, most presented models are not spatially or temporally disaggregated, which gives rise to deviation from the spatial reality.

WEF resources vary in space and time, thus requiring spatial and temporal disaggregation with appropriate tools for comprehensive analysis that can inform improved planning for sustainable management. As much as it is necessary to determine aggregate and average values in WEF nexus analysis, it is equally important to characterize its dynamics in space and time because different areas have different WEF nexus conditions such as resource supply, demands and utilization. This spatial-temporal characterization can be achieved by running several point measurements and analyzing the WEF nexus, which is time-consuming and tedious. Fortunately, this can be done simultaneously, efficiently, and effectively using geospatial features in WEF nexus tools, either as built-in or loosely coupled for pre-processors of input datasets and/or post-processors of outputs. Though less common, the former method hard-links geospatial features and the WEF nexus tool such that it is relatively convenient and easier for the user since the GIS-enabled WEF nexus tool automatically exchanges information and analyses WEF nexus in space, without need for manual preparation and transferring of information between the two systems. The latter mode of soft-linking or loose-coupling requires the user to manually prepare, manipulate, and transfer information between the geospatial tool and the WEF nexus tool, which is inconvenient, tedious, and prone to error by the user. GIS enhances finer spatial detailing of the WEF nexus profile in study areas (Eldrandaly, 2007; Ramos et al., 2019).

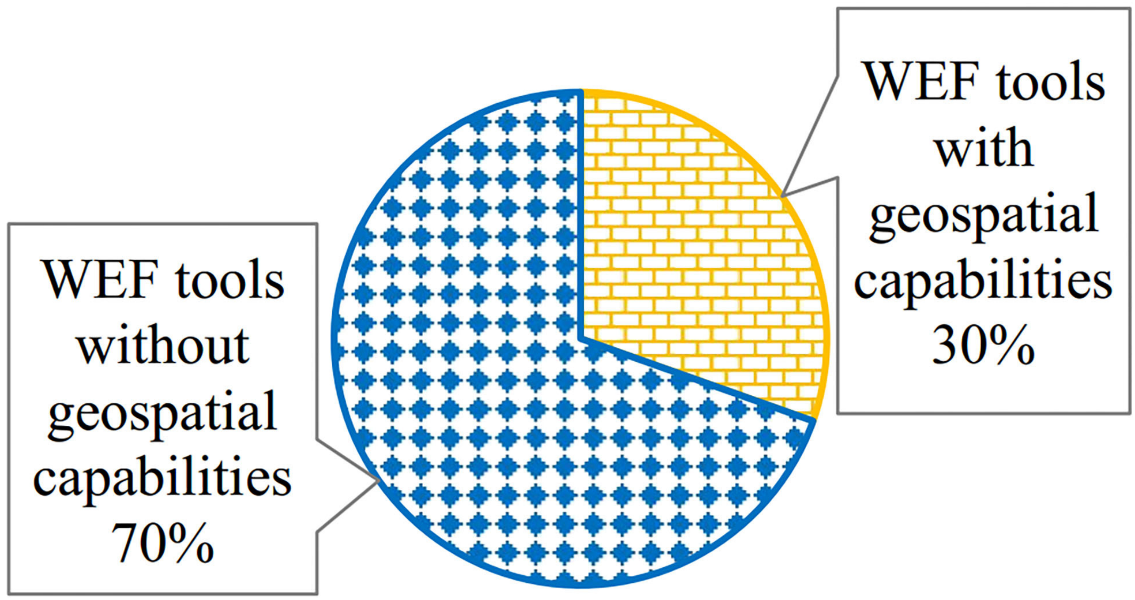

FIGURE 8 | WEF nexus tools and their geospatial capabilities.

The minority of existing WEF nexus tools that have spatial capabilities, either by "hard-linking" or "soft-linking," are presented in **Table 6**.

Integration of GIS and WEF nexus tool should collectively accomplish pre-processing, spatial analysis, mapping/visualization, regardless of the integration arrangements of the two systems or sub-systems.

Evidence from existing WEF nexus tools with geospatial capabilities shows that "soft-linked" WEF nexus tools and geospatial features make use of pre-processing, spatial input datasets, thematic layers, and post-processing. In modular "soft-linked" integration of the WEF nexus tool and GIS capabilities, the user performs geospatial tasks manually, as shown in **Figure 9**.

In this modular integration arrangement, the geospatial data may include land use, administrative boundaries, basins, sub-basins, climate change, socioeconomics variables, and WEF nexus variables (Vinca et al., 2020). Other spatial data that may need pre-processing include existing infrastructure, terrain, environmental policy, availability of natural resources, technology-specific siting suitability criteria, land use, land cover, and economic analyses of grid interconnection costs and locational marginal prices (SEI, 2012; Kraucunas et al., 2015).

On the other hand, "hard-linked" integration with GIS is common in web and desktop applications. "Hard-linked" WEF nexus tool and GIS operate with automation on behalf of the user, as shown in **Figure 10**.

"Hard-linked" GIS-enabled WEF nexus tools depict that common techniques for this integration arrangement include the use of WebGIS, base maps, geodatabases, and geoportals. The "hard-linked" integration allows for flexible web hosting of the tool, locating case study areas, real-time interaction, mapping, and visualizing spatial distributions of WEF nexus (Lin et al., 2019; Simpson et al., 2020; Arenas et al., 2021). Other benefits include storing, integrating, and sharing project GIS datasets (Melenhorst et al., 2018). Thus, geospatial capabilities in WEF nexus tools make it possible to effectively locate suitable sites, quantify spatial WEF requirements, supply, budgets, and footprints.

Therefore, there is great potential for comprehensive WEF nexus analysis and characterization if more of the reviewed existing WEF nexus tools could be equipped with geospatial capabilities, especially the user-friendly "hard-linked" integration. This tight coupling allows for automated exchange of information within the integrated system of the GIS-enabled WEF nexus tool, thus more convenient and easily applicable. This integration method removes the need for extra commitment in GIS training, data preparation and processing that comes with "soft-linked" integration of WEF nexus tools and GIS capabilities.

WEF Tools in Practice

The frequency of case studies for WEF nexus studies can be essential evidence of the practical applicability of the applied tools, especially if various authors applied the tools in different locations and conditions.

A majority (≈61%) of the existing 46 WEF nexus tools have been used in a few case studies between one to three applications (**Figure 11** and **Table 5**). Despite showing great potential, most of these tools, including GREAT for FEW (18) and DAFNE (24), were only applied by their developers in the original case studies for which they were developed. Interestingly, some tools that scored medium to high in the frequency of case studies were used in multiple areas by their developers only, with few case studies or none by other authors outside the development team.

Such tools include BP-DEMATEL-GTCW (2) and SD-WFE (11) applied in various locations in China (Chen and Chen, 2021) and Iran (Ravar et al., 2020), respectively. The lack of popularity in use can be linked to the fact that they are unavailable. Interested users cannot easily access most tools (**Table 7**), wherein a significant number (10) of the widely used tools are readily available for users. The majority (21) of the tools used in a lower number of case studies are out of ready reach by the interested public users.

Thus, the widespread use of WEF nexus tools must be promoted by availing them in the public domain, where they can be accessed without hassles. This regular use by different authors in different locations (i.e., different countries) and conditions can provide the feedback necessary for independent validation, further enhancing and improving tools.

TABLE 6 | WEF nexus with geospatial capabilities.

Tool	Geospatial features	Mode of GIS integration
WEF Nexus Discovery Map (1)	Base map and hosting through ArcGIS	Hard-linked
ITEEM (3)	Spatial input datasets	Soft-linked
MAXUS (7)	Pre-processing of input datasets	Soft-linked
NEST (14)	Spatial input datasets	Soft-linked
WEF Nexus Index (16)	Global base map	Hard-linked
GREAT for FEW (18)	Base map and input datasets as spatial maps	Hard-linked
Daily Model (23)	Spatial input datasets and satellite-based climatic products	Soft-linked
DAFNE (24)	Spatial input datasets, Geoportal with a dynamic, customizable interactive web map by Web GIS plus customized additional "marker" layer	Hard-linked
SIM4NEXUS (25)	GIS layers for dams' location; GIS layers for digital elevation model	Hard-linked
Q-Nexus (30)	Base map	Hard-linked
PRIMA (38)	Spatial input datasets	Soft-linked
CLEWs (42)	Spatial input datasets	Soft-linked
WEAP-LEAP (43)	Thematic maps (land use), maps of basin	Hard-linked
Foreseer (44)	Spatial input datasets	Soft-linked
MuSIASEM (46)	Spatial input datasets	Soft-linked

LIMITATIONS OF REVIEW

The study adapted a systematic review which sought to systematically search for, appraise and synthesize research evidence, based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. We acknowledge that a weakness of systematic reviews is that by restricting search and inclusion criteria, often some literature may be excluded. However, despite that weakness, systematic reviews are still highly regarded because the transparency in the reporting of its methods, which allow for repeatability of the process.

This assessment ignored the option of contacting the authors or developers of tools, who could have provided more details to answer the study questions. However, this was intentional to get the true picture of WEF nexus tools in the public literature and the web domain. This was to ascertain what is known and unknown as represented by the available information, whether in its sufficiency or insufficiency. The focus on named tools may have left out some anonymous and general tools. However, their inclusion in this study would be difficult without unique identities. Similarly, tools whose development was proposed or still in progress, such as the Sustainable Development (SD) Calculator (Mosalam and El-Barad, 2020), were left out due to their incompleteness in development and application. The WEF nexus can be broadened to include several other dimensions such as economy, health, environment, nutrition, politics, climate, and land. This is consistent with the water-energy-food-everything (WEF-e) system mentioned by Saundry and Ruddell (2020), with potential for complexity and dimensionality as the number of dimensions and variables increase. Thus, our study focused on tools and models that capture the interlinkages of at least the three basic dimensions of the WEF nexus, that is water, energy and food. However, the investigation of the actual nature and number of dimensions characterized by the individual WEF nexus tools was outside our scope and is a subject for further study.

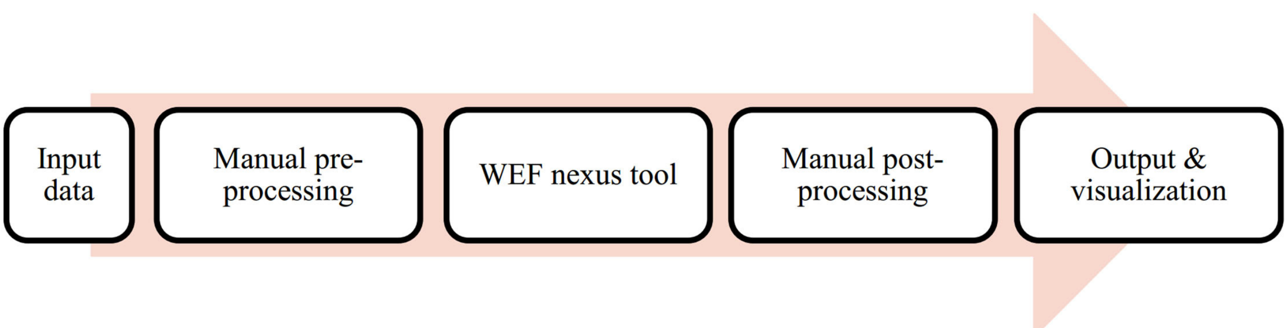

FIGURE 9 | Manual operation of "soft-linked" WEF nexus tool and geospatial capabilities from user's perspective (adapted from Burger, 2018 and Burger and Abraham, 2020).

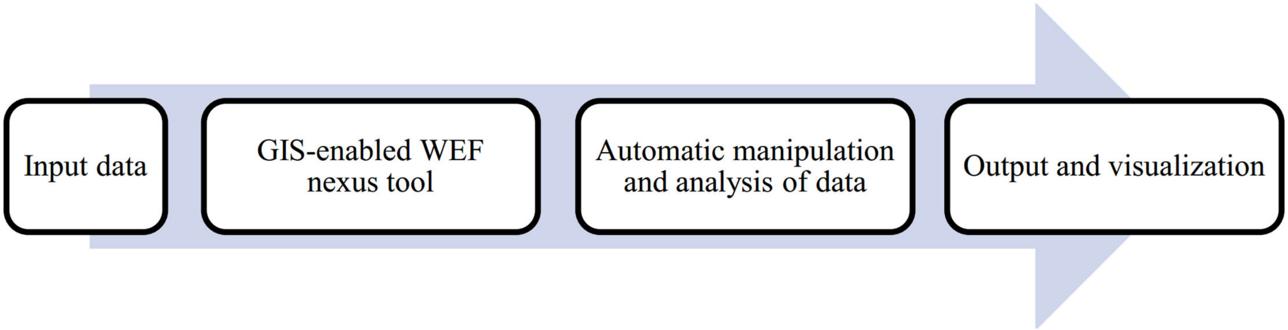

FIGURE 10 | Mode of operation for "hard-linked" GIS-enabled WEF nexus tool (adapted from Burger, 2018 and Burger and Abraham, 2020).

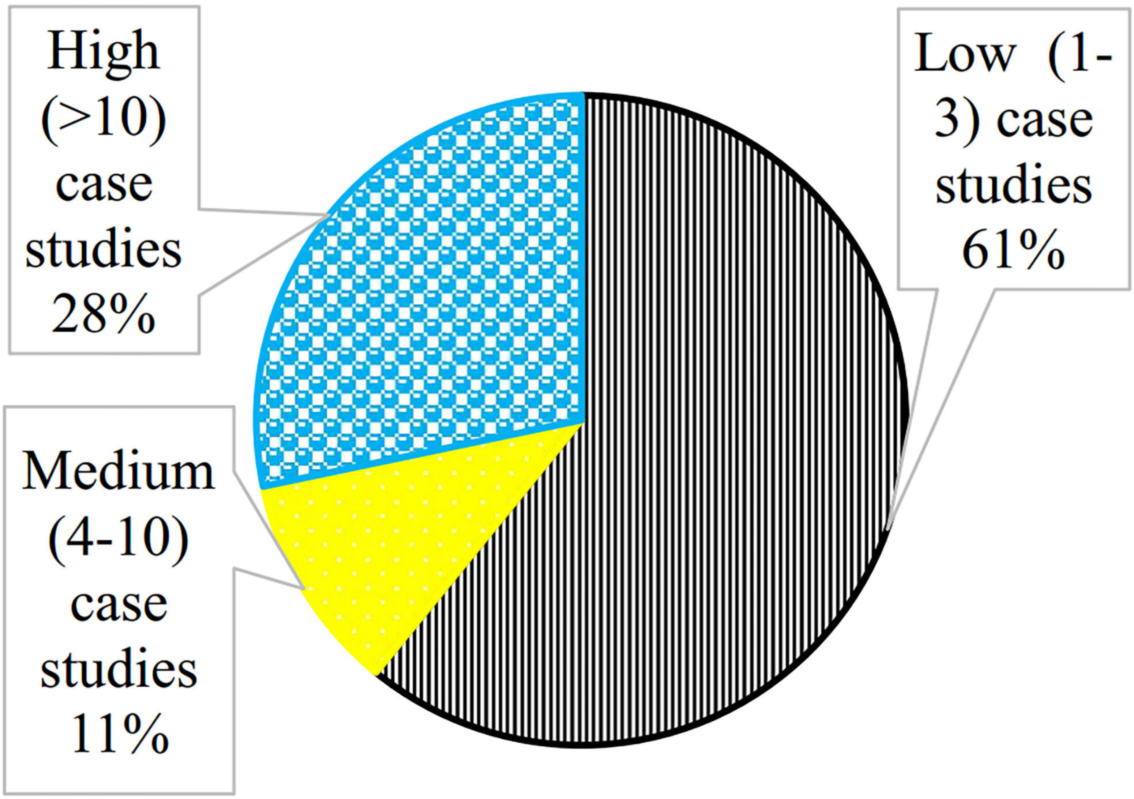

FIGURE 11 | WEF tools in case studies.

CONCLUSION AND RECOMMENDATIONS

This study sought to assess evidence of WEF nexus tools in theory practice, particularly trends in development, availability, formats, spatial scales of application and application in case studies. WEF nexus tools are being increasingly developed. Currently, we have a cumulative abundance of at least 46 uniquely identified tools dedicated to the WEF nexus. Despite their relative abundance, most developed WEF nexus tools are elusive and unreachable to the public. Thus, developers are encouraged to promote the availability and accessibility of their tools through dissemination. A good starting point is their open deployment on the public web domain, so that the tools can be freely available, applied and rigorously tested. This public deployment will provide users with a wide range of choice of tools for translating WEF nexus theory into practice to fulfill its revered potential, with an opportunity for feedback that can further improve their applicability through practical testing and application. Time, costs, and human resources could also be saved by using or customizing available tools instead of developing from scratch every time a study

TABLE 7 | WEF nexus tools, ready availability and their case studies.

Low (1-3) case studies		Medium (4-10) case studies		High (>10) case studies	
Available	**Unavailable**	**Available**	**Unavailable**	**Available**	**Unavailable**
6	21	2	3	10	4
ITEEM (3); WEF-Sask (4); **CALFEWS (5)**; WEF Nexus SD (8); FPC (9); WEF-P (10); **WEST (12)**; MIFCP-WEFN (13); **NEST (14)**; iWEF (15); AWEFSM (17); **GREAT for FEW (18)**; EPAT (19); **WHAT-IF (20)**; K-WEFS (21); WEFSiM (22); Daily (23); DAFNE (24); **UCEC (26)**; ABM-SWAT (27); WEF (29); NexSym (31); WEFO (32); SEWEM (33); BRAHEMO (34); IBMR-MY (35); Nexus Webs (41)		**Q-Nexus (30)**; **WEF Nexus Tool 2.0 (37)**; PRIMA (38); EWF Nexus (39); WEF Nexus Assessment 1.0 (40)		**WEF Nexus Discovery Map (1)**; BP-DEMATEL-GTCW (2); **NeFEW (6)**; MAXUS (7); SD-WFE (11); **WEF Nexus Index (16)**; **SIM4NEXUS (25)**; **Nexus Game (28)**; **Pardee RAND WEF Security Index (36)**; **CLEWs (42)**; **WEAP-LEAP (43)**; Foreseer (44); **ANEMI (45)**; **MuSIASEM (46)**	

Bold, readily available.

is carried out. Building on existing tools would ultimately enhance collaboration and avoid duplication of efforts. The ready availability and ease of accessibility for some WEF nexus tools for potential end-users allows these tools to be applied more easily in nexus-friendly policy- and decision-making processes. Accordingly, some dead and expired links of web-based WEF nexus tools need to be updated, for example, Foreseer (44) and PRIMA (38).

Regarding format, developers should strive to deliver WEF nexus tools in convenient, compatible, and friendly forms with a wide range of users, from starters to seasoned. Considerations include minimizing code types of tools requiring users to have programming skills and maximizing web and desktop application tools with user-friendly GUIs. Serious games play a critical role in educating and building capacity on WEF nexus principles and practices. In multi-player mode, these "edutainment" games can enhance the safe interaction of individuals with each other and the WEF nexus dynamics and scenarios.

Although no one size tool fits all, developers should consider transferability and scalability for wide utility when improving existing tools and developing new tools. This would ensure that the WEF nexus tools can be applied under various geographic scopes, scales, and conditions without fundamentally changing their structure. Preferably, multi-scalar and local scale tools are needed. Such tools should be flexible and adaptable, only requiring new, specific location-adapted inputs and data. Preferably, WEF nexus tools and models should be developed on-demand as requested by potential clients. Developers need to engage and collaborate with the users in the process, drawing inspiration from the users' needs, expectations, and requirements. This user-inspired design and development is critical to enhance user experience and ensure applicability of the developed tools.

There is a critical mismatch between the requirements of geospatial capabilities in most WEF nexus tools and the dynamic nature of WEF resources whose nexus they are supposed to quantify, analyze, and visually map. Most existing WEF nexus tools are spatially disaggregated and lack the essential geospatial capabilities, such as GIS integration, which leads to an unrealistic characterization of WEF nexus dynamics. Only a minority of the tools are integrated to geospatial capabilities, either built-in or loosely coupled for pre-processing input datasets and/or post-processing outputs.

Most of the existing WEF nexus tools lack popularity in wide applications. They have been used in a few case studies, mostly applied by their developers in the original case studies for which they were developed. This is caused by unavailability because interested users cannot easily reach and access them. Only by their ready availability can these tools be used and assessed for actual applicability in different locations and conditions. The free availability of WEF nexus tools ensures broader chances of engagement, especially for users without adequate resources to procure costly modeling software in developing countries.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

CT, AS, ZK, TM, and MM conceptualized the study. CT led reviewing and analyzing literature, preparing figures, tables, and the writing of the manuscript. AS and TM provided supervision. TM provided funding. All the authors provided feedback and reviewed the manuscript. All authors contributed to the article and approved the submitted version.

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