Science of the Total Environment 931 (2024) 172839

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Developing meaningful water-energy-food-environment (WEFE) nexus indicators with stakeholders: An Upper White Nile case study

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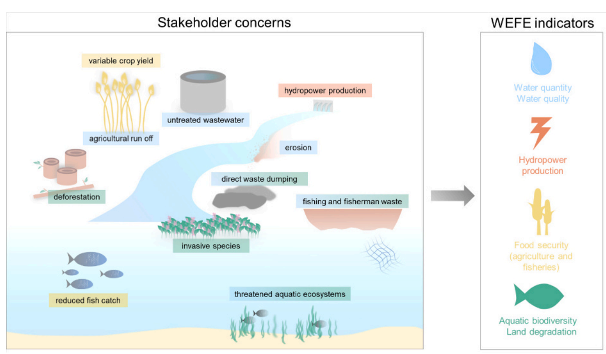
HIGHLIGHTS

- East Africa is faced with many water-energy-food-environment (WEFE) nexus challenges.
- Stakeholders' interviews identified water quality and aquatic ecosystem challenges.
- Existing WEF nexus tool is insufficient in addressing these challenges.
- Novel WEFE indicators developed ensures that future research is fit-for-purpose.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Jacopo Bacenetti

Keywords:
Water-energy-food nexus
Water quality
Aquatic biodiversity
Lake Victoria
East Africa

ABSTRACT

The Upper White Nile (UWN) basin plays a critical role in supporting essential ecosystem services and the livelihoods of millions of people in East Africa. The basin has been exposed to tremendous environmental pressures following high population growth, urbanisation, and land use change, all of which are compounded by the threats posed by climate change and insufficient financial and human resources. The water-energy-food-environment (WEFE) nexus provides a framework to assess solution options towards sustainable development by minimising the trade-offs between water, energy, and food resources. However, the majority of existing WEFE nexus indicators and tools tend to be developed without consideration of practitioners at the local level, thus constraining the practical application within real-world contexts. To try to address this gap and operationalise the WEFE nexus, we examined how local stakeholders frame the most pressing WEFE nexus challenges within the UWN basin, how these can be represented as indicators, and how existing WEFE nexus modelling tools could address this. The findings highlight the importance of declining water quality and aquatic ecosystem health as a

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https://doi.org/10.1016/j.scitotenv.2024.172839
Received 29 September 2023; Received in revised form 23 December 2023; Accepted 26 April 2024
Available online 28 April 2024

result of deforestation and increasing agricultural intensity, with stakeholders expressing concerns for the uncertain impacts from climate change. Furthermore, a review of current WEFE nexus modelling tools reveals how they tend to be insufficient in addressing the most pressing environmental challenges within the basin, with a significant gap regarding the inclusion of water quality and aquatic ecosystem indicators. Subsequently, these findings are combined in order to guide the development of WEFE nexus indicators that have the potential to spatially model the trade-offs within the WEFE nexus in the UWN basin under climate change scenarios. This work provides an example of how incorporating local stakeholder's values and concerns can contribute to the development of meaningful indicators, that are fit-for-purpose and respond to the actual local needs.

1. Introduction

Water, energy, and food security are fundamental for human health and sustainable development. The world's population and demand for natural resources are growing, and since the 1970s, the world's population has doubled and the extraction of living materials from nature has tripled (WWF, 2020), with the carrying capacity of multiple Earth's ecosystems being reached or surpassed (Gerten et al., 2013). The pressure on natural resources will only continue to worsen under projected trends of increased human population and per capita consumption (KC and Lutz, 2017), the impacts of which are exacerbated by the climate and nature crisis (IPCC, 2022). In order to support the potential 9 billion inhabitants by 2050, the global demand for water and food is estimated to increase by 30 % and 50 % respectively, and the demand for energy will double (Boretti and Rosa, 2019; Flammini et al., 2014).

Natural resources are deeply interconnected and understanding the potential trade-offs and synergies for their utilisation is crucial. For example, food production requires water and energy, water management requires energy, and hydropower production requires water. Thus, a change in one will impact the other two (Nhamo et al., 2018). The potential cascades throughout these natural resources are illustrated by the agricultural sector, which accounts for 70 % of global freshwater withdrawals and 30 % of energy consumed (FAO, 2017; WWF, 2020). The vulnerabilities in natural resources may be further amplified by sector-based resource management and disconnected policies which do not account for the transboundary and interconnected nature of these natural resources (Taguta et al., 2022). The water-energy-food-environment (WEFE) nexus considers these interdependencies, enabling integrated assessment and implementation of solution options towards sustainable development that break down the historical siloed approach to resource management (De Laurentiis et al., 2016; Hoff, 2011). The socio-ecological perspective of the WEFE nexus encourages a system wide approach that is critical to understanding water, energy, and food security at this time of increasing environmental pressures on intertwined natural systems, which are faced with the dual threats of the climate and nature crisis (IPCC, 2022; Johnson et al., 2019). The framework also supports the achievement of existing inter-sectoral policies and targets, such as the United Nations Sustainable Development Goals (SDGs) which are reliant on multi-sectoral strategies considering water, energy, food, and ecosystems (Adamovic et al., 2019; Carmona-Moreno et al., 2021).

The WEFE nexus provides an important cross-sectoral perspective on resource management, however, existing work remains largely theoretical. The current WEFE nexus literature emphasises the potential application and the importance of this framework within policy, but provides limited guidance on the operationalisation of the nexus, with few examples of technical contributions existing (Botai et al., 2021; Byers et al., 2018; Daher and Mohtar, 2015; Liu et al., 2017; Nhamo et al., 2020). Translating the WEFE nexus from theory into practice is challenged by factors such as: the lack of sufficient funding, equipment, and skilled personnel; insufficient considerations for stakeholder needs; the unavailability of appropriate tools and models; insufficient relevant input data; challenges in the political economy of resource allocation; and lack of awareness and commitment from affected member countries (Botai et al., 2021; Liu et al., 2017; Markantonis et al., 2019; Nhamo et al., 2018; Taguta et al., 2022). In addition, policy developments tend to be crafted at higher levels of government without consideration for local values and concerns, lacking meaning to local scales, communities, and practitioners (Blake, 1999; White and Bourne, 2007). Furthermore, local stakeholders are often overlooked within nexus research, meaning more work needs to be done to ensure that nexus assessment responds to their actual needs (de Strasser et al., 2016). Engaging local stakeholders throughout the WEFE nexus research process may reduce the disconnect between the production and the use of scientific findings, allowing policymakers and researchers to harmonise policies to specific regions and local stakeholder priorities (Broek, 2019). Ultimately, incorporating the values and concerns of local stakeholders increases the sustainability, applicability, quality, and efficiency of WEFE nexus research. The importance of engaging stakeholders in WEFE nexus research is gaining traction (Bielicki et al., 2019; Hoolohan et al., 2018; Howarth and Monasterolo, 2016, 2017), yet examples are largely focused on engaging with stakeholders only as end-users of the technical information provided by models, rather than including them throughout the design process of developing indicators and tools. To address this gap, principles to strengthen the application of WEFE nexus research have been proposed, covering the use of diverse stakeholder engagement methods (e.g. workshops, bilateral meetings, structured surveys, and semi-structured interviews), employing appropriate data analysis methodologies (e.g. pairwise matrix and cognitive mapping), expanding institutional design (e.g. inclusion of vertical and horizontal governance levels and policies), including transdisciplinary research, and integrating into climate services (Tudose et al., 2023). The successful application of these principles in European case studies underscores the necessity for further regional studies across the globe to adopt these methods to enhance the societal value and usability of research results (Mauser et al., 2013; Tudose et al., 2023).

This paper seeks to identify key WEFE nexus challenges and concerns for the Upper White Nile (UWN) in East Africa, which is a WEFE nexus challenged area that is faced with tremendous pressures from land use change (e.g., wetland encroachment and deforestation (Waiswa et al., 2015)), invasive species (e.g. the Nile perch fish and water hyacinth), and a growing population (annual growth rate roughly 2.7 %), the impacts of which are augmented by the climatic and ecological crisis (Rasul and Sharma, 2016; Van Ittersum et al., 2016). This is done through semi-structured interviews with local stakeholders related to water, energy, food, and environmental resources across Uganda, Kenya, and Tanzania. Indicators are then developed based on a gap analysis of the environmental issues against a literature review of existing nexus modelling tools and indicators (Janssen et al., 2009). Although there are multiple reviews on WEFE nexus methods (Byers, 2016; Dai et al., 2018; Dargin et al., 2019; Kaddoura and El Khatib, 2017; Rosales-Asensio et al., 2020; Schull et al., 2020; Shinde, 2017; Taguta et al., 2022), no existing reviews analyse the WEFE model output indicators, which is a novel focus of the present study. Furthermore, none of these review papers explore whether the development of models and tools included stakeholder consultation and engagement, which is an additional novelty of the current paper. In addition, this paper analyses how the existing output indicators correspond to the environmental impacts in the UWN basin, and whether they are sufficient in addressing stakeholder concerns. These findings are valuable in informing future WEFE nexus research for the UWN basin, and ensuring outputs are informed by the regional environmental context and stakeholder priorities. These results can contribute to policy developments and implementation at the local levels in the region.

2. Methodology

This paper applies qualitative methods (semi-structured interviews) to investigate the critical WEFE nexus challenges in the UWN basin, explore the applicability of existing WEFE nexus models, and develop indicators that address the established gaps and priorities within natural resource changes in the basin. After a process of stakeholder-mapping which included natural resource users (e.g. fishermen) to natural resource regulators (e.g. environmental government ministries), semi-structured interviews were undertaken to gain a more detailed understanding of local pressures and their associated impacts. Following this, a review of existing WEFE nexus tools was undertaken to evaluate their relevance in tackling the WEFE nexus challenges specific to the UWN basin. Finally, a set of WEFE nexus indicators were developed following a gap analysis of the results from the stakeholder interviews and the review of WEFE nexus tools.

2.1. The Upper White Nile Basin case study and its nexus challenges

This study focuses on the Upper White Nile (UWN) basin (Fig. 1) in East Africa, which includes the Lake Victoria basin and Victoria Nile basin (NBI, 2022). Its catchment extends into Uganda, Kenya, Tanzania, Rwanda, and Burundi and the basin drains an area of 351,500 km^2. The UWN basin is home to Lake Kyoga and Lake Victoria. The latter is the second largest freshwater lake in the world (approximately 69,295 km^2) (Awange et al., 2019). Uganda has the largest area of the basin, followed by Tanzania, Kenya, Rwanda, and Burundi. In contrast to this, Lake Victoria itself is shared by only Tanzania (51 % by area), Uganda (43 %), and Kenya (6 %). The basin experiences a hot and humid climate with bi-modal rainfall pattern which has a short rainy season throughout October to December and a long rainy season from March to May (Global Environment Facility et al., 2016). The basin is home to about 70 million people, of which 4 million people depend on the income from fisheries on Lake Victoria (Njiru et al., 2008; Olokotum et al., 2020). The areas surrounding Lake Victoria are considered one of the most densely populated rural regions in the world (Olokotum et al., 2020), with an average population density of 500 people/km^2 (and up to 1200 people/km^2 in areas of Kenya) and an estimated population growth rate ranging from 2.2 % per year in Kenya to 3.0 % per year in Uganda, which is higher than most other African countries and the world average of 0.9 % (Olokotum et al., 2020; World Bank, 2022).

The population within the basin depends heavily on natural resources, of which agriculture and fisheries are the two most important livelihoods. However, these are hindered by a multitude of environmental challenges including land degradation, overfishing, soil and water pollution, biodiversity loss, eutrophication, invasive species, and changes in climate (Agutu et al., 2019; Awange et al., 2019; Getirana et al., 2020; Onyango and Opiyo, 2022; Soesbergen et al., 2019; Verschuren et al., 2002). The environmental degradation of Lake Victoria has resulted in an 80 % reduction of the lake's endemic fish species and a 70 % loss of forest cover in the catchment in the last four decades (Global Environment Facility et al., 2016; Soesbergen et al., 2019; Verschuren et al., 2002). The basin is dominated by rainfed agriculture (Sun et al., 2015), thus potentially rendering the area vulnerable to the impacts of climate change. Additionally, the White Nile river (which begins at the Lake Victoria outlet in Jinja, Uganda) provides approximately 90 % of Uganda's hydropower and a significant fraction of Kenya and Rwanda's power supply (which relies on hydropower for 39 % and 48 % of their energy production, respectively (Geoffrey et al., 2018; World Bank, 2015)), meaning that any changes in river flow will have widespread impacts (Getirana et al., 2020). Furthermore, the significant historical degradation to the aquatic ecosystems of the basin (Soesbergen et al., 2019; Verschuren et al., 2002) may continue to worsen as Africa's freshwater ecosystems are predicted to be damaged by land-use changes, over extraction of water, increasing pollution, and overfishing (IPCC, 2022), with climate change potentially playing a role in the changes of the temperature and lake levels of Lake Victoria, the former of which may have a larger impact on freshwater fish than changes in streamflow (Barbarossa et al., 2021). Adapting cross-sectoral policies that consider the WEFE nexus may be a key solution in addressing natural resource stressors and socioeconomic vulnerabilities within the UWN basin.

2.2. Local data acquisition

In order to investigate the environmental challenges within the UWN basin, a series of semi-structured interviews were undertaken. Stakeholders were identified through a stakeholder mapping procedure, based on the following criteria; (a) they represented a range of actors from NGOs and government institutions who are affected by, but also impact, the developments in and around Lake Victoria; (b) they represented a range of potential competing interests and type of entities, e.g. NGOs, civil society organisation (CSOs), and government institutions; and (c) they represented one or more of the areas of the WEFE nexus, including water, energy, food, and environment (Bielicki et al., 2019). A

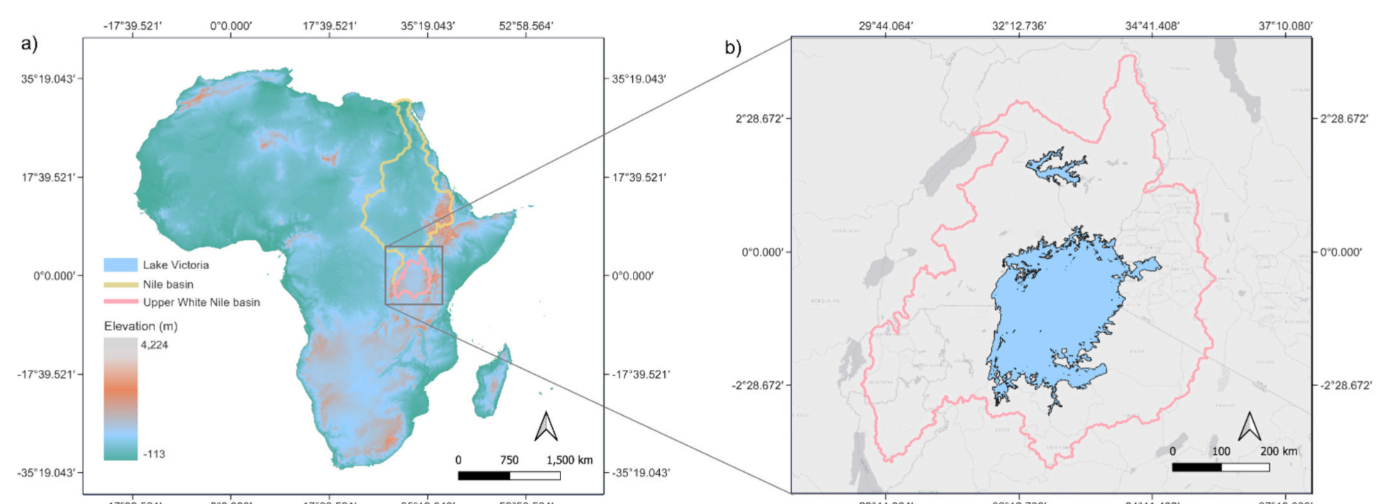

Fig. 1. a) Nile basin and Upper White Nile basin within Africa; and b) the Upper White Nile basin.

'snowball' sampling technique, a nonprobability sampling method, was applied in order to identify key stakeholders through existing contacts who further identified stakeholders and established contacts (Naderifar et al., 2017). Across 30 meetings with 18 different stakeholders in Uganda, Kenya, and Tanzania, key issues related to the WEFE nexus in the UWN basin were identified (Fig. 2). The 18 stakeholders were categorised into 8 stakeholder groups, corresponding to their involvement in different dimensions of the WEFE nexus (Fig. 2). In addition, although the various concerns that were discussed by stakeholders were classified according to which areas of the WEFE nexus they are most related to, due to the interconnected nature of the WEFE nexus, the concerns can often be classified into multiple categories.

Between July 2022 and July 2023, 24 in-person semi-structured interviews involving representatives from 18 local organisations were conducted. The first round of interviews was conducted in July 2022, during which representatives from 8 local organisations were conducted. An initial set of indicators were developed from these interviews (see *Section 2.4*). These were then presented at a second round of interviews in July 2023, with the same stakeholders in addition to 10 new organisations, see *Supplementary Materials* for further information.

2.3. Nexus modelling tools and indicator review

A review of existing WEFE nexus modelling tools was undertaken using freely available documentation. This was done to understand the current capabilities of WEFE nexus tools and potential applications to the UWN basin. This paper's analysis begins with the recent review by Taguta et al. (2022), as this offers a current and exhaustive overview of established WEFE nexus modelling tools. It is noteworthy, however, that their review primarily centres on the water-energy-food (WEF) nexus and does not explicitly integrate environmental aspects. Given the current paper's emphasis on WEFE nexus modelling tools with regional applicability and policy significance, we specifically incorporated tools with regional applicability and policy significance identified in Taguta et al.'s (2022) review. The inclusion criteria for geospatial capabilities encompasses tools with features such as spatial mapping, visualisation, and analysis, using either open-source GIS or commercial products and software. This provides information on the spatial heterogeneity of WEFE nexus resources which is key for informing policies that seek to minimise trade-offs within the nexus.

The review by Taguta et al. (2022) employed a systematic step-wise approach guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol (Moher et al., 2009); additional details can be found in Taguta et al. (2022). Consequently, the tools highlighted in the previous review by Taguta et al. (2022) form the subset of tools under consideration in the present review. Relevant papers and documentation were identified through searches on Google Scholar, Scopus and Google Search Engine. The search topics encompassed the tool names in both acronym and full form, for example ("CLEWS" OR "The Climate, Land (Food), Energy and Water systems").

The inclusion criteria for this paper took into account various sources, including peer-reviewed papers, institutional documents (such as dissertations, theses, or technical papers), and official documentation available corresponding tool websites (e.g. https://wefnexusindex.org/ for the WEF Nexus Index). All sources considered were required to provide a technical description or application of the named tool, and to

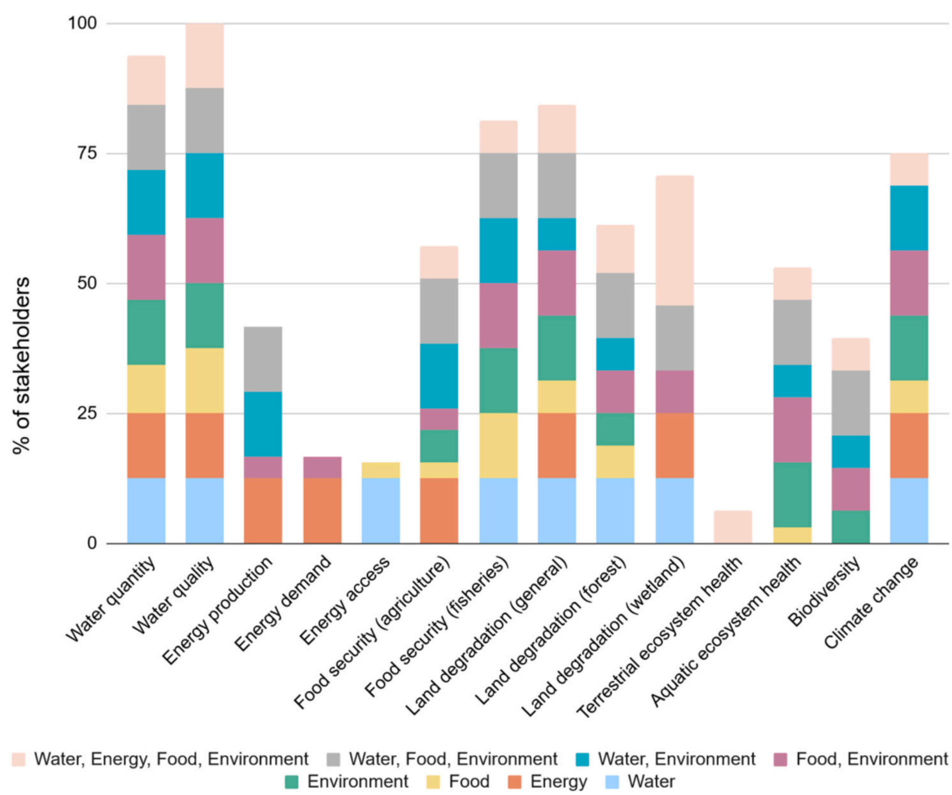

Fig. 2. Summary of stakeholder comments on the environmental challenge (*x axis*) within the UWN basin. Stakeholders grouped by WEFE nexus area includes: **Water** = National Water & Sewerage Corporation, Uganda (NWSC); **Energy** = Uganda Electricity Generation Company Limited (UEGCL); **Food** = Uganda Police Marine (UPM); Farmers, Uganda; Fishers Union Organisation, Tanzania (FUO); Fishermen, Uganda; **Environment** = Lake Victoria Centre for Research and Development (OSIENALA); Mabamba Wetland Eco-tourism Association, Uganda (MWETA); **Food and Environment** = Association of Fishers and Lake Users of Uganda (AFALU); Academia, Uganda (Environmental sciences); Ministry of Agriculture, Animal Industry and Fisheries, Uganda (MAAIF); **Water and Environment** = Ministry of Water and Environment, Uganda (MWE); Institute of Resource Assessment, Tanzania (IRA), University of Dar es Salaam; **Water, Food, Environment** = Austrian Development Agency (ADA); **Water, Energy, Food, and Environment** = Nile Basin Initiative (NBI); United Nations Educational, Scientific and Cultural Organization (UNESCO); Lake Victoria Basin Commission (LVBC); Lake Basin Development Authority (LBDA).

be written and published in English. Relevant information from the selected documentation was organised into columns on a data extraction sheet created in MS Excel (Table 1). The analysis of WEFE nexus tool indicators and whether stakeholders were engaged in the process of tool development are novel. The authors or developers of the tool were not contacted during this process to avoid bias.

2.4. WEF nexus indicator development

The approach to develop a set of WEFE nexus indicators that effectively illustrate the most pressing challenges within the UWN integrated the insights gained from the stakeholder interviews and the WEFE nexus modelling tool review. The initial two steps occurred concurrently. Firstly, a series of stakeholder interviews were conducted to understand the most critical environmental challenges within the UWN basin (see *Section 2.2*). Stakeholder-identified environmental stressors were condensed, and relevant scientific literature was explored using Google Scholar and Scopus. Various search terms, combining the relevant environmental stressor and the basin, were used (e.g. "nitrogen" OR "nutrient pollution" OR "nitrogen pollution" AND "Lake Victoria" OR "Victoria basin" OR "Victoria catchment" OR " Victoria watershed" OR "Victoria Nile" OR "Upper White Nile" OR "White Nile" OR "Uganda" OR "Kenya" OR "Tanzania" OR "Rwanda" OR "Burundi"). Key papers and associated literature were examined to understand the scope and prevalence of the environmental issues. Only environmental pressures discussed by a significant proportion of stakeholders (minimum 25 %) and confirmed in scientific literature were included. This approached aimed to balance comprehensiveness and specificity, ensuring that well-discussed issues were included without setting the threshold too high, thus avoiding the potential omission of key information and ensuring representation of voices from underrepresented stakeholder groups.

In parallel, a review of existing WEFE nexus tools was initiated (see *Section 2.3*). The indicators (i.e. model outputs measuring variables related to the WEFE nexus) from these tools were summarised. Following this, a gap analysis was conducted, identifying overlaps and gaps between stakeholder perspectives and the capabilities of WEFE nexus modelling tools. The results were visualised in a Venn diagram, illustrating missing WEFE nexus indicators in existing tools, according to stakeholder concerns. This process generated an initial set of indicators, which were then refined iteratively through collaborative consultations with stakeholder. The first-round indicators were presented a year later during a second round of stakeholder interviews, gathering feedback on current indicators and identifying missing ones. This iterative and inclusive approach enhanced the scientific quality and usability of the developed WEFE nexus indicators for the UWN basin.

Table 1
Information extracted from documentation concerning WEFE nexus tools.

Tool characteristics	Description
Tool	A tool designed to model the mathematical relationships within food, energy, and water systems that simplify real-world complicities by accounting for their spatial and/or temporal dynamics.
Stakeholder consultation (SH cons.)	Indicates whether the development of the WEFE tool involved or sought input from stakeholders – response options include "Yes" or "No".
Water indicators	Outputs produced by the tool that measure variables related to water, encompassing both quantity (e.g. river flow) and water quality (e.g. nutrient load)
Energy indicators	Outputs produced by the tool that measure variables related to energy, encompassing both production (e.g. energy from hydropower) and consumption (e.g. energy consumed by water treatment facilities)
Food indicators	Outputs produced by the tool that measure variables related to food, encompassing both production (e.g. crop yield) and consumption (e.g. food demand)
Environmental indicators (Env. indicators)	Outputs produced by the tool that measure variables related to the surrounding land and ecosystems (e.g. land quality or biodiversity)
Climate change scenarios (CC scen.)	Indicates whether the tool has the capability to incorporate climate change scenarios within its modelling framework - response options include "Yes" or "No".
Socioeconomic scenarios (SE scen.)	Indicates whether the tool has the capability to incorporate socioeconomic development scenarios within its modelling framework - response options include "Yes" or "No".
Geographic resolution (Geog. res.)	Describes the geographical extent that can be encompasses within the modelling framework, such as global, national, regional/basin, or urban/city/household.
Spatial resolution (Spatial res.)	Describes the spatial resolution of the model outputs, such as if results are presented at a grid scale with a particular resolution (e.g. 50 km).
Temporal resolution (Temp. res.)	Describes the temporal resolution of the model outputs, such as whether results are presented at a daily, monthly, annual, or decade resolution.

3. Results and discussion

This study applied qualitative methods to understand the most pressing water-energy-food-environment (WEFE) nexus challenges within the Upper White Nile (UWN) basin, how these can be reflected in indicators, and how existing WEFE nexus modelling tools could address these.

3.1. Semi-structure stakeholder interviews

The semi-structured interviews revealed how stakeholders are largely concerned with land degradation, water quality, and aquatic ecosystem related issues (see Fig. 2). Despite the inclusion of stakeholder mapping which aimed to capture the diversity of the stakeholder landscape, it is important to stress that these interviews were resource limited and are not sufficient to provide a complete overview of the environmental concerns of stakeholders in the UWN basin, but rather gives a starting point to understanding what the highest priority is perceived locally when assessing the WEFE interactions in the UWN basin. As indicated by Fig. 2, the WEFE related concerns discussed were varied and far reaching.

3.1.1. Water related concerns

Based on the identification by the stakeholders, water quality was the most pressing water related concern for the UWN basin (discussed by 100 % of stakeholders). Stakeholders described how the growing population, land degradation and deforestation, unsustainable waste disposal, poor sanitation practices by local communities, untreated discharge from factories and industry, fertiliser and pesticide runoff, sand mining, and invasive species contributed to the reduced water quality, which is in agreement with other studies within the basin (Juma et al., 2014; Magunda and Majaliwa, 1999; Mugidde et al., 2005; Riedmiller, 1994; Roegner et al., 2020; Verschuren et al., 2002). Of these, the impacts of pollution from industry discharge and agricultural runoff were most frequently discussed. Pollution from industrial sources (such as sugar refineries, oil and soap mills, and dairies) and agriculture (such as fertiliser from coffee, tea, cotton, maize, and cotton farms) has increased tremendously, with total nitrogen and phosphorus application increasing on average by 85 % across the basin in the last 50 years (FAO, 2023). This has accelerated eutrophication within the basin's waters (Magunda and Majaliwa, 1999; Ntiba et al., 2001), which was a main concern for 38 % of the stakeholders. In addition, many stakeholders expressed concerns regarding the impacts of reduced water quality and eutrophication on the aquatic ecosystems, which have been historically threatened by anoxia and invasive species in addition to the reduced water quality (Mugidde et al., 2005; Njiru et al., 2008; Ntiba et al., 2001; Raburu et al., 2009). In accordance with this, Mugidde et al. (2005) found the average chlorophyll-*a* concentrations in 2000 within Lake Victoria to be 45.7 mg L^{-1} (ranging from 3.0 to 656.0 mg L^{-1}), which was five times higher than what was found in the 1960s and in tandem has reduced water transparency by a factor of four. Alongside concerns for the impacts of reduced water quality on aquatic ecosystem health, many stakeholders discussed the implications for human health, such as an increase in waterborne diseases. In addition, the economic effects of reduced water quality were raised, such as the increase in water treatment costs.

Within Uganda, a large contributing factor to water pollution is poor waste management, for example, only 40 % solid waste is collected and managed, and there remains a low efficiency of sewage treatment plants (Juma et al., 2014; Komakech et al., 2014; Matagi, 2002; Mwanuzi et al., 2005; Olokotum et al., 2020). In relation to these issues, the stakeholders also discussed how limited monitoring and lack of enforcement of the existing regulations contributed to the exacerbation of water quality issues. In order to address this, suggestions included promoting ownership, increasing awareness of the issues, finding alternative sources of livelihood to reduce environmental pressures, building more sanitation and water treatment facilities, and having more funding to support improved monitoring and enforcement. Furthermore, water quantity issues were also discussed by all stakeholders. As the recharge of Lake Victoria heavily depends on rainwater, changes in precipitation can have a drastic effect on the lake and downstream communities. The recent flooding of Lake Victoria in 2019–2020 and the resulting destructive impacts on infrastructure, water quality, and surrounding land were discussed by multiple stakeholders.

3.1.2. Energy related concerns

Energy related concerns were the least frequently discussed WEFE nexus topic, but this may be due to the nature of the stakeholders interviewed. Approximately half of stakeholders touched upon energy related concerns, and those that did, discussed the importance of hydropower production and the impacts of water quantity on energy production. The region has been exposed to a high variability in river flow and lake levels, and Uganda has experienced energy crises both in the early 2000s due to a drought limiting hydropower production, and in 2020 following floods that impacted dam infrastructure (Beaubien, 2006; Pombo-van Zyl, 2020). Furthermore, there was a brief mention of the impact of hydropower dams on local ecology, including the effect on the dispersal of fish populations. An additional comment relating to energy needs within the basin touched upon the energy requirements for the planned irrigation expansion within Uganda and the limited accessibility (both due to infrastructure and cost) to electricity in rural regions. However, this was not explored in depth. In reality, the region has limited energy access, which can be seen in Uganda where over half (58 %) of the population (18 million people) do not have access to electricity (World Resources Institute, 2023), with only 5 % of the country having access to the grid (Tumwesigye et al., 2011).

3.1.3. Food related concerns

The majority of the discussions related to food concerns focused on fisheries and the impacts of overfishing, invasive species, poor water quality, and flooding on the fish populations. The fisheries within Lake Victoria are highly important for providing a source of income and food for a large proportion of the population within the basin (Matsuishi et al., 2006; Mkumbo and Marshall, 2015). Stakeholders explained that the sensitivity of the Nile perch made it vulnerable to environmental changes. Thus land degradation, decreased water quality, changing water levels and temperature, eutrophication, and anoxia has led to a decrease in the fish population, threatening livelihoods, regional economy, and food security. The impacts of soil erosion, soil fertility loss, pollution, and variable weather were also discussed by stakeholders, with the majority raising crop productivity related concerns (75 %). In the context of crop related concerns, stakeholders discussed the spatially diverse patterns of crop productivity across the basin. For instance, whilst southern Uganda maintains relative stable food security, the northern regions of the basin have experienced significant food security challenges. In addition, stakeholders recognised the importance and potential risks associated with changing climatic conditions for crop production, given the prevalence of traditional farming methods and rainfed agriculture throughout the basin.

3.1.4. Environment related concerns

Environmental concerns related to land degradation were identified as one of the most significant challenges within the basin, with all stakeholders expressing concerns in the far reaching impacts of this issue. Particularly pressing examples of land degradation include deforestation, encroachment into wetlands, and degradation of inshore and riparian vegetation. Of these, deforestation and degradation of wetlands were emphasised to be the most significant challenges in the basin (Fig. 2), particularly due to the impacts this has on ecosystems, water quality, and food security (both agriculture and fisheries). This corresponds to the environmental challenges identified in the scientific literature, many of which cite land use change as one of the greatest pressures within the basin, which is underpinned by a whole suite of drivers such as population growth, agricultural expansion, forest exploitation, and infrastructural development (Chapman et al., 2008; Muyodi et al., 2010; Ntiba et al., 2001; Odada et al., 2009; Waiswa et al., 2015). In accordance with this, a study by Mugo et al. (2020) found that within the Lake Victoria basin, large scale farmlands and urban areas have increased by 55 % and 890 % respectively between 1985 and 2014, whilst wetlands and closed woodland have decreased by 33 % and 75 % respectively. The inverse correlations between area under urban centres and areas under indigenous forests, wetlands, and open grasslands suggest that urban growth is contributing to the loss of forests, wetlands, and grasslands. Furthermore, studies have found the deforestation rates to be highest in Uganda, which saw an annual deforestation rate of 3.3 % between 2000 and 2015 (compared to 0.2 % for Burundi, 0.3 % for Kenya, 1.7 % for Rwanda, and 0.8 % for Tanzania) (FAO, 2020). Tropical forest deforestation can have widespread impacts, including soil erosion, loss of soil fertility and productivity, water quality degradation, decrease in agricultural productivity, threatened biodiversity, decline in carbon sequestration, changes in rainfall patterns, and increased poverty of local communities (Muhati et al., 2008; Tangley, 1986; Waiswa et al., 2015), many of which stakeholders touched upon during the interviews. For example, the majority of stakeholders (88 %) expressed concern about increasing soil erosion which has been observed within the UWN basin, particularly along the shores of Lake Victoria where soil erosion rates have reached 17–87 ton ha^{-1} yr^{-1} in Uganda and Tanzania (Isabirye et al., 2010), and globally, East Africa is among the regions with the highest erosion rates, which are further predicted to increase under climate change following increases in rainfall and climate extremes (Borrelli et al., 2017).

3.1.5. Additional concerns

Lastly, most stakeholders discussed issues regarding the governance and/or the enforcement of existing policies. Socio-political and socio-economic issues were described as the foundation for many of the resulting environmental pressures within the UWN basin, which in addition often provides a barrier in the operationalisation of the WEFE nexus. However, it is important to understand the limitations of scientific research and the importance of engaging with those impacted by the issues addressed. Participants argued that the institutional and social issues could be combated with a variety of measures, such as: better financing for environmental research and policies; enforcement of existing policies; increased awareness and education of the environmental stressors, their impacts, and sustainable practices; providing livelihood alternatives that help alleviate existing environmental pressures; and to empower the water and land rights of communities to increase ownership and inspire enhanced stewardship of their surrounding ecosystems.

Furthermore, although climate change was raised in the majority of the stakeholder interviews, it was not discussed as one of the primary concerns within the basin. However, despite the high uncertainty in climate projections in Africa, current work suggests that climate change may pose a considerable challenge within the UWN basin, particularly through the impacts of enhanced spatio-temporal precipitation variability and lake-water level and quality fluctuations on aquatic biodiversity, crop yield, and crop and waterborne diseases (Ogega et al., 2020, 2023; Scheffers et al., 2016; Wainwright et al., 2021). Although the impacts are poorly studied, there are suggestions that the eutrophication of Lake Victoria may have been accelerated by climate change, largely underpinned by increased water temperatures and reduced vertical mixing (Lehman, 1998). Furthermore, future impacts of climate change within the basin may include an increase in extreme precipitation, with Lake Victoria becoming a hotspot for thunderstorms which may further impact eutrophication, water quality, water quantity, and aquatic ecosystems (Ogega et al., 2020; Tariku and Gan, 2018; Thiery et al., 2016). In tandem with this, the basin has also been exposed to prolonged droughts following periods of low rainfall and high temperatures, resulting in low crop productivity due to the reliance on rainfed agriculture (Ampaire et al., 2017; Awange et al., 2007; Kogo et al., 2021).

3.2. Nexus modelling tools and indicator review

The present WEFE nexus tool review was based on the recent review by Taguta et al. (2022), which was guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol (Taguta et al., 2022). The review by Taguta et al. (2022) identified 46 water-energy-food (WEF) nexus tools, of which 15 (32 %) were classified as having geospatial capabilities. Considering that WEFE nexus resources are spatially and temporally distributed in nature, it is key that future modelling frameworks capture these spatial-temporal dynamics, especially with the aim of improving their application to regional policy. The current paper focused on these 14 tools (Table 2), with WEF Nexus Discovery Map excluded as it functions as a map-based database for existing nexus studies, and thus, does not function as an analysis tool. Further research was undertaken using scientific and grey literature to explore the 14 tools in more depth, including: models used; data requirements; WEFE nexus output indicators; whether stakeholders were consulted in the development of the tool; spatial and temporal resolution; future scenario capabilities; and data visualisation.

3.2.1. Use and scope of tools

Although the tools in Table 2 were classified as having 'geospatial capabilities' in the original review by Taguta et al. (2022), less than half (43 %) of the tools displayed outputs spatially. Furthermore, the usability and application of these tools are varied. A number of these tools are hard to access through the public domain, such as DAFNE, PRIMA, Foreseer, and MuSIASEM, some of which have restricted access to partners and stakeholders (Table 2, tools with limited availability are shaded in grey). Additionally, some tools function as visual portals and platforms for presenting information on the WEFE nexus, such as the WEF Nexus Index, but do not allow users to tailor the functions to their

Table 2
Results from WEFE nexus model review, summarising nexus indicators used and geospatial capabilities. Tools shaded in grey indicate that these are inaccessible to public use. Key: SH cons. = stakeholder consultation in model development; CC scen. = climate change scenarios; SE scen. = socioeconomic scenarios; Geog. res. = Geographic resolution; Spatial res. = spatial resolution (modelling tools with no spatial resolution have outputs by study location without providing spatial map); temp. res. = temporal resolution. See *Supplementary material* for further information on the subsets of nexus indicators used.

Tool	SH cons.	Water indicators	Energy indicators	Food indicators	Env. indicators	CC scen.	SE scen.	Geog. res.	Spatial res.	Temp. res.	Reference
CLEWs	No	Water quantity; water demand	Energy production; energy demand; energy cost	Food production (crop yield)	None	Yes	Yes	Global, national, regional, and urban	Varied (sub-regional, catchment)	Annual or decade	Howells et al., 2013
DAFNE	Yes	Water quantity; water quality; water demand; hydrological alteration index	Energy production; energy demand	Food production (crop yield, fish catch and livestock)	None	Yes	Yes	Basin	Varied (Biophysical Land Units)	Monthly or annual	DAFNE, 2016
Daily Model	No	Water quantity; water demand	Energy production	Food production (crop yield)	None	No	Yes	Basin	None	Annual	Basheer et al., 2018
Foreseer	No	Water quantity; water demand	None	Food production (crop yield)	None	Yes	Yes	National and regional	None	Annual	Curmi et al., 2013
GREAT for FEW	No	Water demand	Energy production; energy demand	Food production (crop yield)	Ecosystem quality	No	Yes	National or regional	Varied (sub-region)	Decade	Lin et al., 2019
ITEEM	No	Water quantity; water quality; cost of wastewater and drinking water treatment	Energy demand	Food production (crop yield)	None	No	Yes	National or regional	None	Daily, monthly, or annual	Li et al., 2021
MAXUS	No	Water quantity; water demand	Energy production; energy demand	Food demand; food transport	None	Yes	Yes	National or regional	Sub-region (administrative region)	Season or annual	Burger, 2018
MuSIASEM	No	Water quantity; water demand	Energy demand	Total food throughput	None	No	Yes	National, regional, and urban	None	Annual	Pérez-Sánchez et al., 2019
NEST	Yes	Water quantity; water demand	Energy production	Land use (by crop)	None	Yes	Yes	National and transboundary	None	Decade	Vinca et al., 2020
PRIMA	Yes	Water quantity	Energy production; energy cost; energy reliability	Food production (crop yields); food cost	None	Yes	Yes	Regional	Varied (0.05° - 2°)	Daily, monthly, or annual	Kraucunas et al., 2015
Q-Nexus	No	Water quantity; water demand	Energy production	Food production (crop yield)	None	No	Yes	National or regional	None	Annual	Karnib, 2018
SIM4NEXUS	Yes	Water quantity; water quality; water demand; water cos	Energy production; energy demand; energy cost	Food production (crop yield, livestock); food demand	Land quality	Yes	Yes	Global, national, and regional	None	Monthly or annual	Sušnik et al., 2018
WEAP-LEAP	No	Water quantity; water demand	Energy production; energy demand	Crop yield; water demand for agriculture	None	Yes	Yes	National, regional, and urban	None	Monthly or annual	G Liu et al., 2021
WEF Nexus Index	Yes	Water quantity; water demand; water access	Energy production; energy demand; energy access	Food production (crop yield); food access	None	No	Yes	Global	Country	Annual	Simpson et al., 2022

own case studies and data. Lastly, some of these tools are geographically limited, such as GREAT for FEW and SIM4NEXUS which have been developed for Taiwan and Europe respectively and therefore lack application to other regions of the world.

3.2.2. Stakeholder consultation in model development

Although many of the reviewed WEFE nexus modelling tools were developed with the intention to be used by policymakers and government agencies, only one-third of tools in this review (36 %) documented having consulted stakeholders during the development of nexus indicators and model integration. The tools that documented the involvement of stakeholders during the tool development process, on the other hand, undertook extensive workshops or nexus games, such as the DAFNE and PRIMA tools, which shaped the development of the WEFE nexus tools with the needs of the stakeholders. Additional tools which included stakeholder participation includes the NEST tool (part of IIASA's ISWEL project; https://www.iswel.org/), for which stakeholders at various scales (basin, country, and sub-national) actively participated in order to identify the most pressing nexus challenges (in this case, nutrient loading was identified as a key challenge) and co-designed and potential solutions under different development priorities. This shaped the scenario narratives for future development scenarios, model integration, and outputs for nexus indicators.

Although the indicators used by the different tools may be useful in a variety of regions, the inclusion of stakeholder consultations ensures that outputs are tuned to the regional and/or local needs, potentially increasing the regional practical application of the WEFE tools and uptake of assessment outcomes. In accordance with this, this paper ensured that relevant stakeholders were consulted and had the opportunity to share their thoughts on the WEFE challenges within the UWN basin. The findings from the semi-structured stakeholder interviews indicated that the basin has faced tremendous pressures from environmental degradation, particularly deforestation and encroachment into wetlands, which has contributed to further complex environmental challenges, such as declining water quality and reduced fish populations. Indeed, this can be seen in the amount of wetland area within Uganda, which has decreased from 15.5 % in 1994 to 13 % in 2017 (with 4.1 % of the remaining wetland being degraded) (NEMA, 2019). Some of the largest changes were seen in the Nakivubo wetlands which lost 62 % of wetland vegetation between 2002 and 2014, largely driven by crop cultivation (Isunju and Kemp, 2016; NEMA, 2019; Nyakaana et al., 2007).

3.2.3. Water indicators

Water related concerns have driven many WEFE nexus studies, and thus this review found that water indicators are well represented in the nexus modelling tools. The majority (93 %) of tools provided outputs on water quantity, mostly focusing on surface water (such as measures of river flow). Multiple tools consider water demand by a variety of sectors including: food, energy, and utilities. Additionally, a few tools included access to water resources, as well as availability. However, water quality indicators were severely lacking, with only three (21 %) tools providing measures of water quality. Of these, ITEEM used the hydrological model SWAT (Soil and Water Assessment Tool) to simulate nitrate and total phosphorus concentrations alongside measuring sediment load, as well as water quantity (streamflow) and crop yield (of corn, soybean, corn silage, and perennial grass). The second nexus modelling tool that provided water quality indicators, DAFNE, used a 1D General Lake Model to measure a different subset of water quality variables, including sediment transport, dissolved oxygen, and temperature. Although not direct measures of water quality, temperature and oxygen have acute impacts on aquatic ecosystems and nutrients, and can thus function as proxies for water quality and the relevant biological impact.

3.2.4. Energy indicators

The majority (86 %) of the WEFE nexus modelling tools provided measures of energy production, with a great variety of energy sources being considered, including but not limited to: hydropower, thermal, wind, solar, geothermal, nuclear, charcoal, oil, natural gas, petroleum, and biofuels. The most commonly represented energy source was hydropower, with at least 10 tools (71 %) considering energy generated from hydropower production. The energy demand from a myriad of sectors was also included in many WEFE modelling tools, some of which directly considered the interdependencies of the WEFE nexus, such as the energy demand for wastewater and drinking water treatment (ITEEM, CLEWs). Additionally, some models, such as Q-Nexus, SWIM4NEXUS, and CLEWs, considered the water use in the production of energy through processes such as power plant cooling. Lastly, a few tools incorporated measures of access to energy, which must be considered alongside energy availability for a complete measure of energy security.

3.2.5. Food indicators

Food indicators were well represented across WEFE nexus modelling tools, of which 71 % modelled food production. However, most of these considered only crop yield. A few tools, such as the WEF Nexus Index and DAFNE, extended their scope by incorporating protein and dietary energy supplied by crops or livestock on top of cereal yield. A small number of tools (14 %) provided measures of yield from animal products. However, only one model (DAFNE) included fish yield, which was calculated from statistical data that grouped all fish species together. In order to capture impact indicators of food insecurity, models such as the WEF Nexus Index included food access sub-pillars such as: prevalence of undernourishment; % of children under 5 affected by wasting; % of children under 5 who are stunted; and prevalence of obesity in adults. Lastly, a few tools considered linkages between food and other WEFE nexus areas, for example, providing indicators on: water required for crops (rainfed and irrigated); water productivity of crops; biomass for biofuel production, and energy use in agricultural sector and fertiliser production (see *Supplementary Materials*).

3.2.6. Environment and ecosystem service indicators

Despite the intrinsic importance of environmental variables (such as biodiversity and ecosystem health) in securing water, energy, and food resources, only 3 (21 %) of the modelling tools incorporated environmental indicators in their WEFE modelling frameworks. For example, DAFNE developed a Hydrological Alteration index, which measures the alteration of the hydrological regime with respect to a given reference, providing an indication of ecosystem functioning and delivery of ecosystem services. In addition, GREAT for FEW provides a measure of ecosystem quality, which considers the effect of water availability on terrestrial vegetation health, whilst SIM4NEXUS provided measures of land quality in one of the case studies, which is also intertwined with natural capital and the provision of ecosystem services. However, no tools considered direct measures of ecosystem services provisioning by nature and demand by people.

3.3. WEFE nexus indicators

Many of the environmental challenges discussed with stakeholders were represented within the 14 reviewed WEFE nexus modelling tools (Fig. 3). Nonetheless, there remain multiple gaps and underrepresented WEFE nexus indicators in the existing tools. For example, water quality issues were discussed by all of the stakeholders (Fig. 2), but is only represented in three WEFE nexus tools (Fig. 3). In addition, although ecosystem dynamics underpin natural resource security, they are scarcely included in WEFE nexus tools with only a small number providing measures of ecosystem health, such as the hydrological alteration index from DAFNE. However, all of the environmental indices included in models are proxies of biodiversity and ecosystem health with no direct quantifications (ETH, 2019) or spatial disaggregation (Lin et al., 2019). The simplification of complex environmental variables is likely related to modelling and data limitations, and can be seen in the

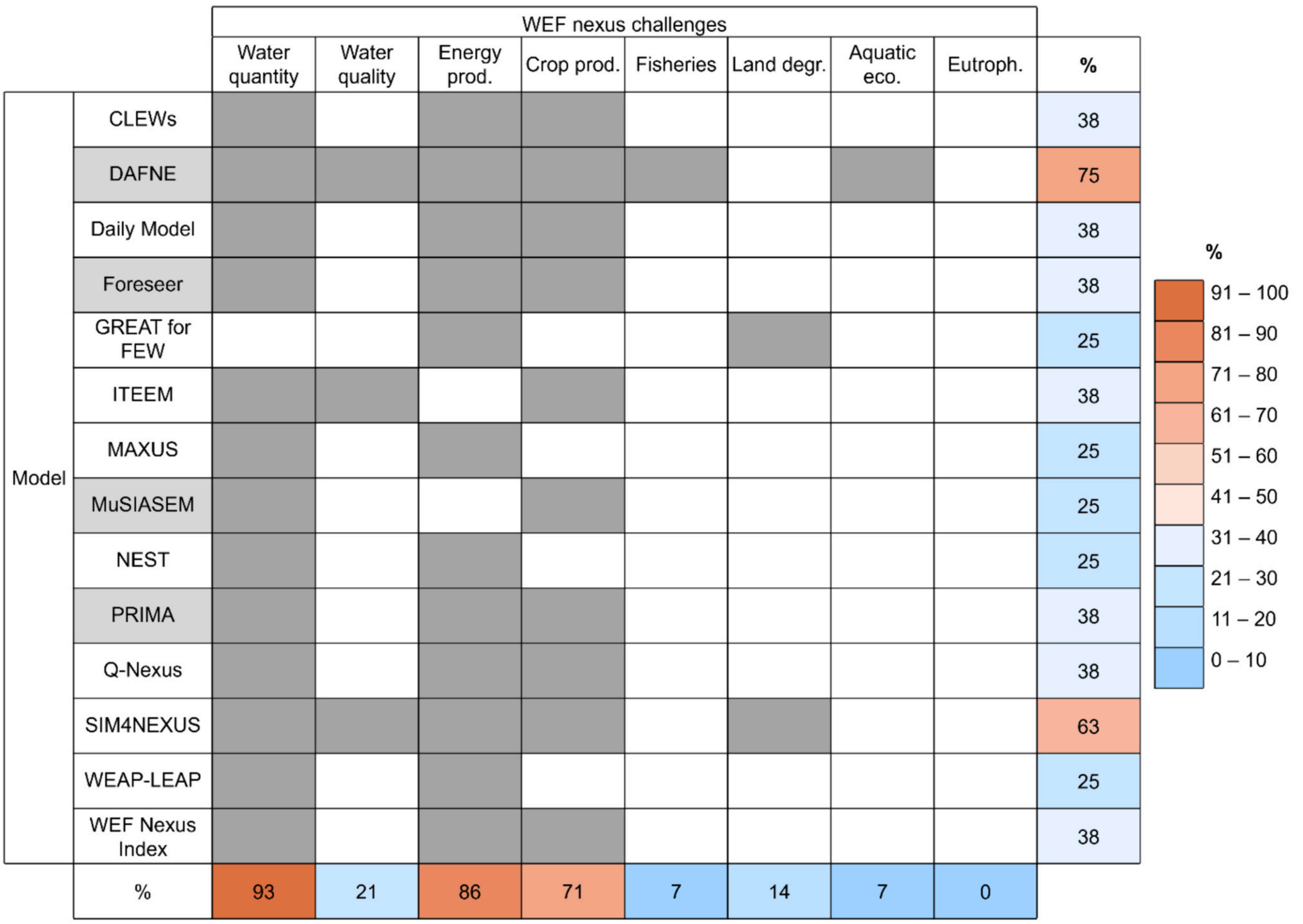

Fig. 3. Heatmap of model outputs against the WEFE nexus challenges in the UWN basin, based on the stakeholder interviews. Grey indicates that the tool included indicators relevant to the WEFE nexus challenge, whereas white indicates that it was not included in the tool. Energy prod = energy production; crop prod. = crop production; land degr. = land degradation; aquatic eco. = aquatic ecosystems; eutroph. = eutrophication. Tools which are inaccessible to the public are shaded in grey.

fish catch indicator from the DAFNE model, which has grouped all fish species together and does not provide measures for future scenarios (KU Leuven, 2018). Furthermore, Fig. 3 illustrates the disparity between stakeholder concerns within the UWN basin and the tools that succeed in addressing these, which suggests that no current tools can sufficiently capture the major environmental concerns expressed by stakeholders. For example, Fig. 2 highlights the overarching stakeholder concerns regarding water quantity, water quality, fisheries, aquatic biodiversity, fisheries yield, and land degradation, and yet the majority of WEFE nexus tools only represent water quantity, energy production, and crop production. Although most existing tools fall short in addressing the WEFE nexus priorities in the basin, DAFNE could be capable of capturing most of the challenges (75 %). However, it is worth noting although the indicators provided by DAFNE are more holistic than most models they remain insufficient, for example, by providing proxies or not giving measures for future scenarios.

The existing WEFE nexus modelling tools are insufficient in addressing the most pressing environmental challenges within the UWN basin (Fig. 3), and accordingly, future research should address these gaps to further the inclusion environmental (specifically ecosystem services) indicators. As illustrated by the stakeholder interviews, water quality and ecosystem health are among the most pressing issues within the basin that are intertwined with the other natural resources of the WEFE nexus. However, considerations for these were left behind in the existing WEFE nexus modelling tools. Through an iterative and collaborative process involving multiple consultations with stakeholders, a set of WEFE nexus indicators were refined and defined (Fig. 4). This evolutionary process provided a holistic and contextually relevant approach to develop WEFE nexus indicators for the UWN basin, ensuring that they serve as a valuable tool for decision-makers and stakeholders, enabling a more informed and integrated approach to sustainable development and resource management in the UWN basin.

Whilst the primary aim of the WEFE nexus is to connect biophysical systems in order to achieve sustainable development, the nexus has historically failed to sufficiently account for the environmental foundation that secures these natural resources (Albrecht et al., 2018; Botai et al., 2021; Hülsmann et al., 2019). Societal and environmental development hinges upon the safeguarding of biodiversity and ecosystem services, which are the benefits that humans derive from nature, and these are crucial components of the WEFE nexus (IPBES, 2019; Subedi et al., 2020; Vörösmarty et al., 2010). Healthy and stable ecosystems are able to provide clean and sufficient water to grow crops, provide energy from hydropower dams, and support fisheries and aquatic ecosystems (Subedi et al., 2020). In accordance with this, an extensive review by Smith et al. (2017) found different measures of biodiversity, including species richness and functional diversity, alongside habitat attributes such as vegetation cover, to be crucial in ecosystem service provision. In addition, these services flow from stocks of natural capital, and thus having forests, rivers, and grasslands intact is critical for environmental and human well-being (Costanza, 2020; Smith et al., 2017).

Loss of biodiversity can therefore have cascading impacts on the

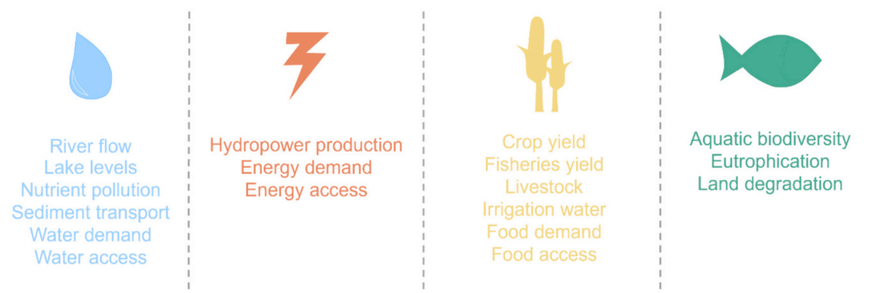

Fig. 4. Proposed WEFE nexus indicators for studies in the Upper White Nile.

security of ecosystem services, such as freshwater resources and soil health, and it is thus key that quantifications and valuations of biodiversity and ecosystem services are considered within WEFE nexus studies (Howells et al., 2013). For example, species diversity of algae and plants have been shown to improve water quality through increasing the uptake of nutrient pollutants from soil and water, for which Cardinale (2011) found that cultures with increased algal species diversity could remove nitrate up to 4.5-fold faster than species grown alone (Karabulut et al., 2016). If biodiversity disappears, so do food and water resources. Biodiversity is generally not accounted for within such studies, and the instances in which it is, proxies for biodiversity (such as 'average area that is protected in terrestrial sites important to biodiversity') are used, rather than actual measures of terrestrial or aquatic biodiversity (Hirwa et al., 2021; Yang et al., 2018). This is especially relevant within the UWN basin which has seen its biodiversity, particularly aquatic biodiversity, historically decimated by a variety of pressures, such as invasive species and eutrophication which contributed to the extinction of approximately 65 % of endemic cichlid fish species (Mkumbo and Marshall, 2015; Njiru et al., 2008; Ntiba et al., 2001; Verschuren et al., 2002), which has further accelerated reductions in water quality (Outa et al., 2020). Such biodiversity losses are predicted to continue under current trends in population growth, urbanisation, and agricultural intensification (Soesbergen et al., 2019). The importance of aquatic ecosystem health and fishery yield within the UWN basin is further emphasised by the findings from the stakeholders interviews (Fig. 2), and thus we propose the inclusion of indicators of fish catch and aquatic biodiversity (Fig. 4), both of which were discussed by the majority (88 %, Fig. 5) of stakeholders, and yet are included in the very few WEFE nexus modelling tools (7 % in both instances, Fig. 3).

In addition to including novel aquatic biodiversity and fish catch indicators, we propose the inclusion of explicit water quality metrics (Fig. 4), considering the overarching importance of this WEFE nexus challenge within the UWN basin and the limited representation of these within previous WEFE nexus studies. For example, the importance of nutrient pollution and sediment transport was raised by many stakeholders (100 % and 88 % respectively) and has been cited as major stressors within the basin (Getabu et al., 2003; Mugidde et al., 2005; Njiru et al., 2008; Ntiba et al., 2001), and yet these are almost entirely lacking from the existing WEFE nexus modelling tools. In addition, pollution from industrial effluent, landscape disturbances, and agriculture is cited as some of the greatest contributors to reduced water quality in the basin (Mugidde et al., 2005; Njiru et al., 2008; Ntiba et al., 2001) and within the turn of the century the nutrient loads within Lake Victoria have increased by two or threefold compared with the 1960s (Njagi et al., 2022; Talling and Lemoalle, 1998), emphasising the importance of including indicators that can capture such changes. This has resulted in eutrophication and threatened ecological functions, stressing the importance of considering eutrophication alongside nuanced water quality variables in future WEFE nexus studies (Olokotum et al., 2020; Opande et al., 2004; Verschuren et al., 2002; Wanda et al., 2015).

The novel proposed WEFE nexus indicators for the UWN basin are successful in capturing the greatest environmental challenges within the basin, as addressed by stakeholders and supported by scientific literature. The results from Fig. 5 depict how every proposed indicator was touched upon during the stakeholder interviews, with a higher priority for certain indicators such as: water quantity (river flows and lake levels), water quality (nutrient pollution and sediment transport), food production (fisheries yield), aquatic biodiversity, and land degradation. The inclusion of water quality, fisheries, and aquatic biodiversity metrics is novel and urgent at this time of increasing environmental pressures, and is required to strengthen the progress of holistic WEFE nexus research that promises real world application. The historical absence of these indicators in existing WEFE nexus tools (Fig. 3) may be driven by difficulty in finding appropriate models or required data, however, there are multiple case studies that use individual models to explore water quality and aquatic ecosystem variables within the UWN basin (J. Kimwaga, 2012a, 2012b; Natugonza et al., 2019; Simonit and Perrings, 2005, 2011), and thus future research may assess which existing models are most appropriate and potentially integrate them, rather than reinventing the wheel and designing models from scratch.

Furthermore, the proposed indicators capture a myriad of variables related to the health of ecosystems, which provides critical socio-ecological resilience required to support ecosystem services, livelihoods, and adaptations to climate change. Future studies that incorporate the proposed indicator framework thus have the potential to investigate the WEFE nexus synergies and trade-offs that would arise under different climate change adaptation strategies, for example, Nature-based Solution (NbS) such as ecosystem restoration and climate-smart agriculture (Agol et al., 2021). Numerous studies have explored the linkages between climate change and the WEFE nexus, stressing the importance of adopting integrated approaches to resource management at the regional level amid changing climatic conditions (Liu, 2016). All sectors of the WEFE nexus are vulnerable to the impacts of climate change, as observed in several countries in the UWN basin, where disrupted rainfall patterns have led to decreased crop yields and hydropower production (Kogo et al., 2021; Pombo-van Zyl, 2020; Wainwright et al., 2021). The far-reaching impact of climate change on the interconnected components of the WEFE nexus highlights the necessity for developing WEFE nexus indicators that can be assessed through climate impact models. These indicators that have been tailored to the environmental challenges in the UWN basin will enable future research to undertake a comprehensive exploration into the effects of climate change, ensuring the efficacy and coordination of adaptation strategies across WEFE sectors. The recognition of the importance of modelling the trade-offs within the WEFE nexus under climate change is gaining prominence. Indeed, 57 % of the nexus modelling tools reviewed in this paper allow for the inclusion of climate change scenarios (Table 2). This illustrates the potential applicability of the developed WEFE nexus indicators for the UWN basin in modelling tools, a crucial consideration given the potential significant changes in the basin amid climate change (Global Environment Facility et al., 2016; Johnson, 2010; Williams et al., 2015).

Following the proposed WEFE nexus indicators developed in this paper, future nexus modelling tools should now succeed in addressing

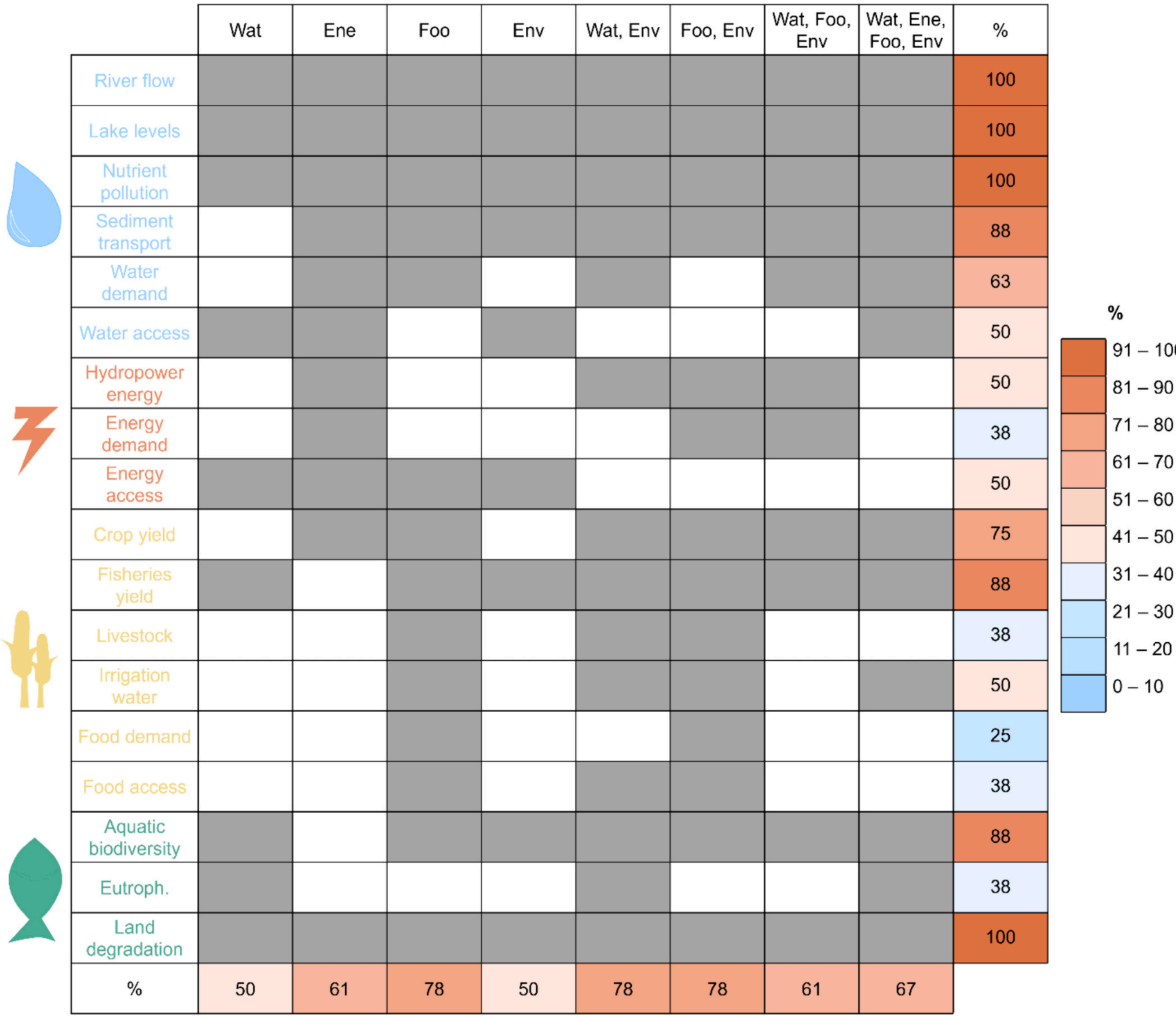

Fig. 5. Heatmap of proposed WEFE nexus indicators and environmental concerns expressed by UWN basin stakeholders. Stakeholders grouped by WEFE nexus area includes: **Water** (Wat) = National Water & Sewerage Corporation, Uganda (NWSC); **Energy** (Ene) = Uganda Electricity Generation Company Limited (UEGCL); **Food** (Foo) = Uganda Police Marine (UPM); Farmers, Uganda; Fishers Union Organisation, Tanzania (FUO); Fishermen, Uganda; **Environment** (Env) = Lake Victoria Centre for Research and Development (OSIENALA); Mabamba Wetland Eco-tourism Association, Uganda (MWETA); **Water and Environment** (Wat, Env) = Ministry of Water and Environment, Uganda (MWE); Institute of Resource Assessment, Tanzania (IRA); **Food and Environment** (Foo, Env) = Association of Fishers and Lake Users of Uganda (AFALU); Academia, Uganda (Environmental sciences); Ministry of Agriculture, Animal Industry and Fisheries, Uganda (MAAIF); **Water, Food, Environment** (Wat, Foo, Env) = Austrian Development Agency (ADA); **Water, Energy, Food, and Environment** (Wat, Ene, Foo, Env) = Nile Basin Initiative (NBI); United Nations Educational, Scientific and Cultural Organization (UNESCO); Lake Victoria Basin Commission (LVBC); Lake Basin Development Authority (LBDA). Grey shading indicates that the concern relevant to the proposed WEFE nexus indicator was raised by the stakeholders, and white indicates that it was not. The final column shows the % of stakeholders which discussed a certain WEFE nexus indicator, whereas the final row shows the % of WEFE nexus indicators discussed by a particular group of stakeholders.

the most pressing WEFE nexus challenges within the UWN basin, thus ensuring that the resulting research is fit-for-purpose and addresses the actual needs of stakeholders. However, it is important to acknowledge that previous and proposed work cannot address the underlying socio-economic drivers of environmental change, including alienation of local people from natural resources and a lack of ownership (Njiru et al., 2008; Waiswa et al., 2015), and more socio-economic work must be done so implementation can be successful. Furthermore, due to resource constraints, the utilisation of the co-creation process in this study is restricted. To realise a comprehensive co-creation process that cultivates a shared vision among stakeholders, future work should extend beyond individual stakeholder interviews. Instead, multistakeholder groups should be engaged, employing the principle of maximal variation to bring a wide range of stakeholder interests to the discussion table, all whilst acknowledging the impact of regional power dynamics (Tudose et al., 2023). It would be important to include a larger diversity of stakeholders, including practitioners and citizens, particularly as certain institutions may not be able to capture the concerns that are most pressing to the local population who are most directly impacted. Furthermore, to gain a more thorough understanding of the WEFE challenges in the UWN basin, future research should undertake structured interviews with a greater number of stakeholders, and with multiple individuals from each institution.

4. Conclusion

This paper explored the pressing water-energy-food-environment (WEFE) nexus challenges within the Upper White Nile (UWN) basin involving local stakeholders in the research process, finding that declining water quality, ecosystem health, and fish populations as a result of increasing pressures from agriculture, deforestation, and human population were among the greatest environmental challenges in the basin. In addition, this paper found that present nexus modelling tools are extensive in the geographic ranges and environmental issues represented, however, these tools are lacking in their ability to holistically represent WEFE nexus challenges and trade-offs within the UWN basin. These findings were coupled in order to develop holistic WEFE nexus indicators that address the challenges within the UWN basin and the gaps within present WEFE nexus tools, ensuring that indicators are effective and align with the needs of the WEFE nexus at the local scales. The case study analysis of the UWN basin reveals the importance of including biodiversity and water quality indicators when addressing the WEFE nexus, which requires the need for further WEFE tool developments.

Funding

This work was supported by the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement 956623.

CRediT authorship contribution statement

Annika Schlemm: Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Mark Mulligan:** Methodology, Supervision, Writing – review & editing. **Ting Tang:** Methodology, Supervision, Writing – review & editing. **Afnan Agramont:** Writing – review & editing. **Jean Namugize:** Writing – review & editing. **Enos Malambala:** Writing – review & editing. **Ann van Griensven:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors would like to thank all the stakeholders who contributed their time, insights, and expertise, who were all essential to make this research possible. These include individuals from: National Water & Sewerage Corporation, Uganda (NWSC); Uganda Electricity Generation Company Limited (UEGCL); Uganda Police Marine (UPM); Farmers in the Buikwe district in Uganda; Fishers Union Organisation, Tanzania (FUO); Fishermen in Entebbe in Uganda; Lake Victoria Centre for Research and Development (OSIENALA); Mabamba Wetland Ecotourism Association, Uganda (MWETA); Association of Fishers and Lake Users of Uganda (AFALU); Academia, Uganda (Environmental sciences); Ministry of Agriculture, Animal Industry and Fisheries, Uganda (MAAIF); Ministry of Water and Environment, Uganda (MWE); Institute of Resource Assessment, Tanzania (IRA); Austrian Development Agency (ADA); Nile Basin Initiative (NBI); United Nations Educational, Scientific and Cultural Organization (UNESCO); Lake Victoria Basin Commission (LVBC); Lake Basin Development Authority (LBDA). The authors would also like to thank those who supported establishing the stakeholder contacts and network, including individuals from Jaramogi Oginga Odinga University of Science and Technology (JOOUST) in Kenya, in particular Naphtaly Osika, Dennis Ochuodho, and Sam Ohanga. Further individuals who were key in furthering the stakeholder network include Albert Nkwasa, Hellen Aluku, Mary Kishe, and Milly Mbuliro. A particular thanks goes to Hellen Aluku who also attended one of the stakeholder meetings and provided support.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.172839.

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