A Systematic Review and Meta-Analysis of Water–Energy–Food Nexus Resilience: Global Insights and Implications for India

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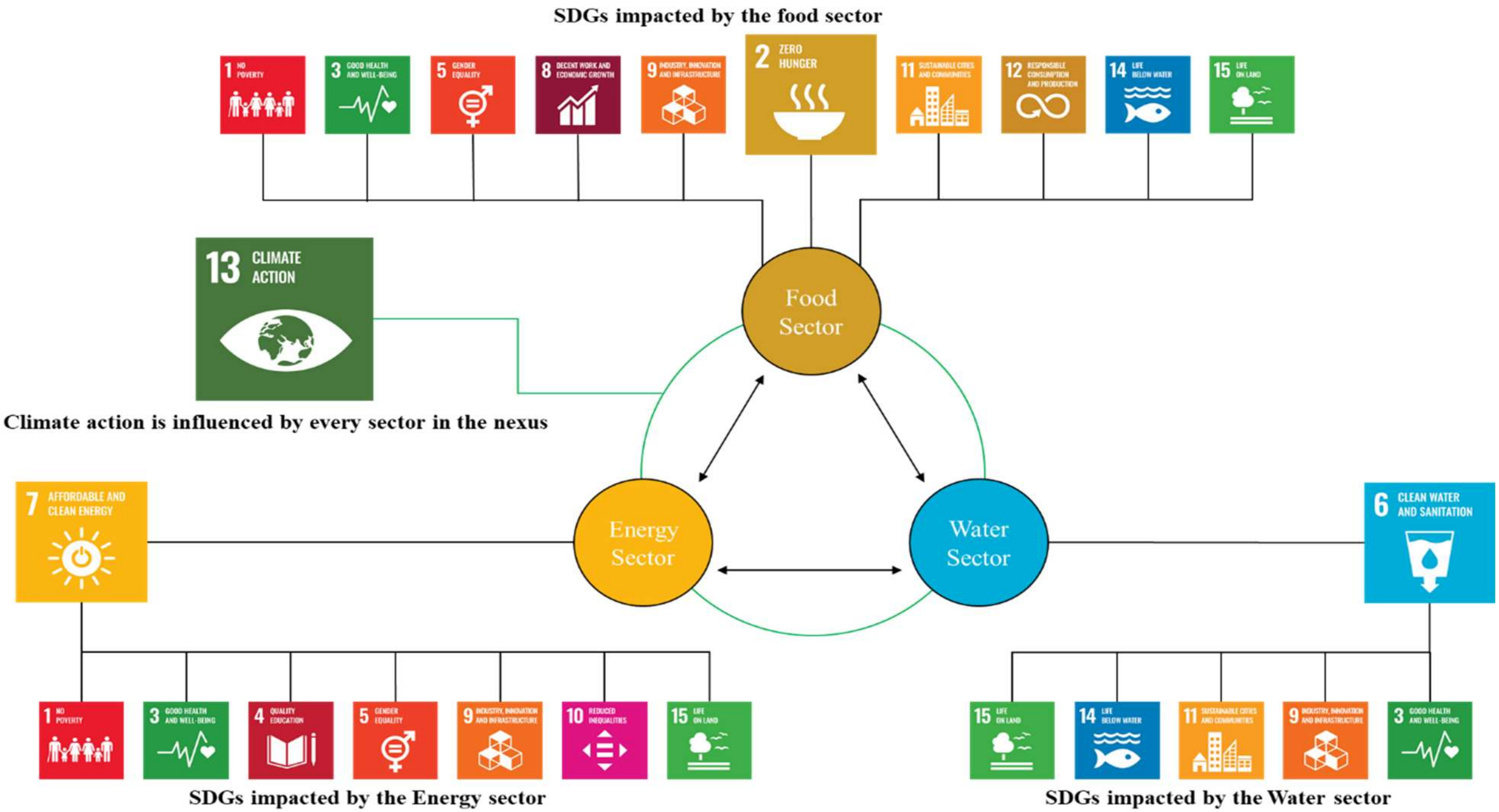
Context

- The Water-Energy-Food (WEF) nexus is central to sustainable development but is threatened by climate change, resource depletion, and fragmented governance.
  - Our rapidly growing population and uneven development are exacerbating pressure on natural resources.
  - The WEF nexus is a conceptual and practical tool to manage interdependencies among sectors.
  - Integrating resilience and systems approaches is essential for navigating trade-offs in climate-vulnerable regions.

Relevance for SDGs



Source: Lalawmpuii & Rai, 2023

Objective of the review

1. To map the evolution of WEF nexus literature globally and identify key frameworks and methods used.
2. To assess how resilience is integrated into WEF nexus modelling, especially via systems thinking and System Dynamics Modelling (SDM).
3. To identify specific research gaps, with an emphasis on policy relevance and application in India.

Methodology – Meta-Analysis Approach

- Search strategy: Forward snowballing via Connected Papers and Google Scholar; cross-referenced with Scopus AI.
- The starting set included three papers that were found to be most closely aligned with the proposed study objectives
    - Hogeboom et al., 2021 mapped the research landscape through a WEF nexus and climate resilience lens.
    - Ioannou & Laspidou, 2022, presents a resilience analysis framework for the WEF nexus under climate change, using a SDM to assess how policies can enhance system resilience. It applies parametric sensitivity analysis and resilience metrics in a national case study of Greece to determine which policy improves the system's ability to absorb disturbances and recover.
    - Ioannou & Laspidou, 2023, presents a framework and a replicable methodology to help policymakers prioritize investments by analyzing the interconnections between the WEF nexus and the 17 SDGs. Using a Fuzzy Cognitive Map analysis, it quantifies the impact of WEF – SDG interactions, identifying SDGs most influenced by the WEF nexus at a European-level, revealing key synergies and trade-offs.
- 200 papers identified

Screening and inclusion criteria

- Basic criteria for selection of papers:
  - Examination of title,
  - Language,
  - Publication year and
  - Type of publication (journal articles, report, book chapters)
  - Review of abstracts
- Review lenses:
  - WEF sectoral coverage
  - Integration of resilience
  - Systems thinking & SDM usage
  - Scale (global vs. regional vs. local)
  - Policy relevance
- 60 papers were finally selected, deeply reviewed and analysed

Coding and data extraction

- **Region and sectoral focus**
  - **Geography**: We noted whether the study focused on global contexts, multi-country regions (e.g., Sub-Saharan Africa), specific countries (e.g., India, China), or subnational case studies (e.g., river basins, districts).
  - **WEF Components**: We recorded whether the study focused on Water, Energy, or Food individually, two of them (e.g., Water-Energy), or all three (true WEF nexus).
- **Indicators extracted**
  - **Interlinkages**: Did the study analyze or model causal relationships (e.g., how irrigation affects energy demand)?
  - **Resilience**: Was resilience explicitly defined or measured? Did it refer to adaptive capacity, system robustness, redundancy, or transformability?
  - Other performance indicators: crop yields, GHG emissions, water use efficiency, access to energy, food security, etc.
- **Framework used**
  - **Descriptive/conceptual models**: Only narrative explanation or static diagrams.
  - **Quantitative models**: Optimization, scenario analysis, life-cycle assessment, etc.
  - **System Dynamics Models (SDMs)**: We noted rare cases using feedback loops, time-based modelling, or CLDs (e.g., SIM4NEXUS).
  - **Integration with policy frameworks**: Some studies aligned with SDGs, national policies, or decision support tools.
- **Temporal and spatial scales**
  - **Temporal**: Current conditions only, historical comparisons, or future projections/scenarios (e.g., to 2050).
  - **Spatial**: Did the study operate at the global level, national level (e.g., India-wide), state or regional level (e.g., Odisha), or sub-national/local (e.g., watershed, village)?

Typology & Thematic Clustering

- Transformation of raw coded data into meaningful research categories for comparative analysis.
- Each study was assessed and ranked across six thematic dimensions.

1. **WEF Coverage**
   - **Low**: Focused on one sector (e.g., just water).
   - **Medium**: Addressed two sectors (e.g., water-energy) but with limited integration.
   - **High**: Integrated all three sectors in analysis or modelling.
2. **Systems Thinking**
   - **Absent**: No mention or framing of system interdependencies.
   - **Basic**: Referenced system complexity or interactions but not operationalized.
   - **Strong**: Used causal thinking, feedback loops, or participatory system mapping.
3. **Systems Modelling**
   - **None**: Descriptive or conceptual only.
   - **Basic Quantitative**: Used optimization, statistical, or scenario models without feedback.
   - **Advanced**: Used system dynamics models (SDMs) or similar to capture interactions over time.
4. **Resilience Framing**
   - **Implicit**: Mentioned resilience without defining or measuring it.
   - **Conceptual**: Defined resilience but didn't quantify it.
   - **Operational**: Measured resilience indicators (e.g., adaptive capacity, robustness).
5. **Scale**
   - **Global/regional**: Multinational or continental scope.
   - **National**: Country-level studies.
   - **Subnational/local**: State, basin, or community-level modelling or analysis.
6. **Cross-Sector Integration**
   - **Weak**: Sectors discussed separately.
   - **Moderate**: Discussed connections but not analyzed them.
   - **Strong**: Explicitly modelled or quantified trade-offs and synergies between sectors.

- Ranking approach: Each study received a qualitative score (0–5) for each dimension. This enabled the creation of a heatmap-style ranking matrix to compare international and Indian studies.

Evolution of the WEF nexus

- Originally rooted in physical sciences, expanding toward socio-ecological systems
- Integrations with biodiversity, land, and climate added complexity (e.g., WEF-Biodiversity, WEF-Land)
- An observable trend in the development of the field, shifting from conceptual frameworks to development of policies, security risks, optimization and governance frameworks – moving from understanding to implementation
- A multitude of decision-support tools encompassing metrics, modeling and data analytics have been developed globally for studying the nexus - emphasizing interdisciplinary and cross-sectoral analyses
- However, most of the methods and tools lack integration of indigenous and traditional perspectives and local ecological knowledge.

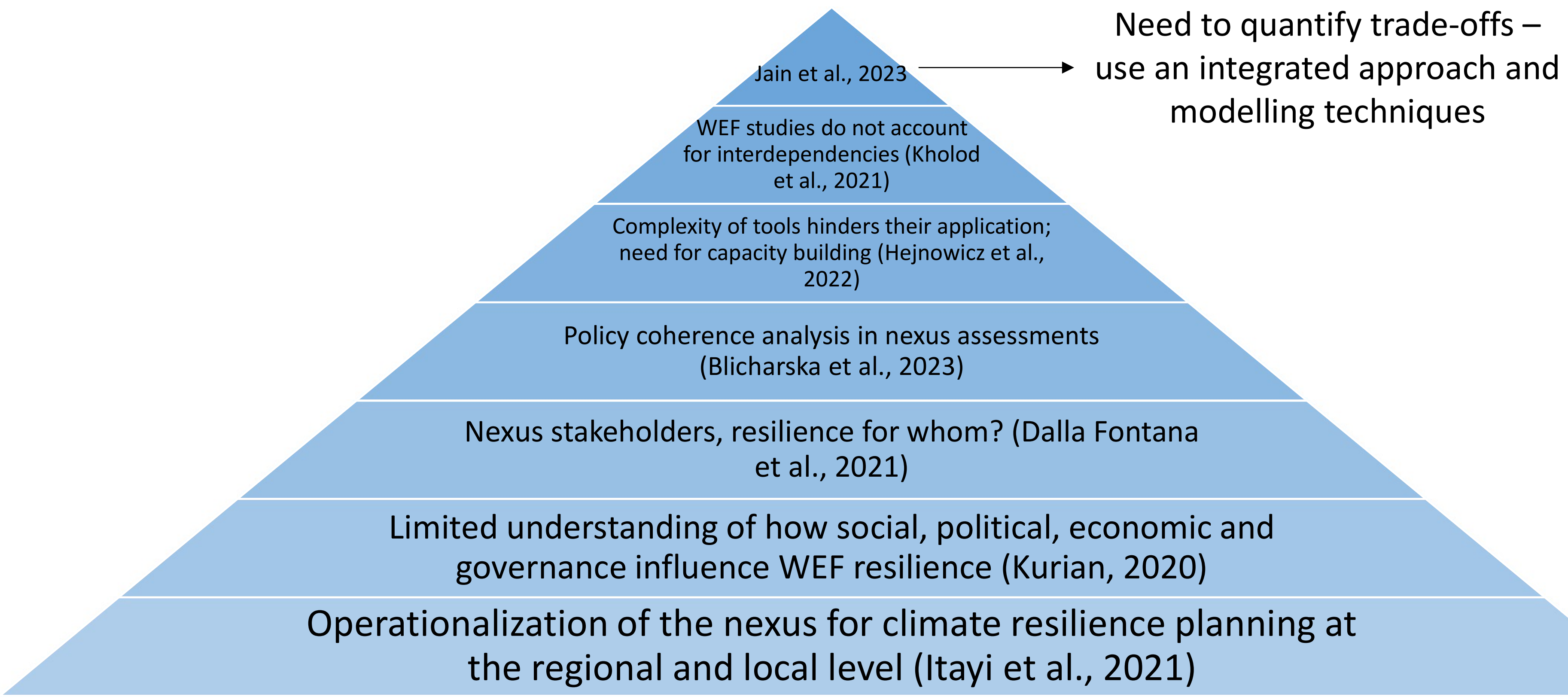
Examples of tools

Country/Region	Model/Tool	Reference
India	Global Change Analysis Model to identify water, energy and land stressed areas across the country	Kholod et al., 2021
	Pardee-RAND WEF approach to assess WEF security	Mondal et al., 2023
	NExus Solutions Tool (NEST) – integrate hydrological modeling and resource optimization techniques	Vinca et al., 2020
China	Simultaneous equation modeling (statistical model) for local-level nexus assessments	Huang et al., 2020
	Assessment-optimization modelling	T. Zhang et al., 2020
	Multi-level, fuzzy- interval credibility-constrained programming models to identify uncertainties in regional-scale plans	Yu et al., 2020
	Bayesian network analysis (a probabilistic graphical model)	Chai et al., 2020
	Sustainable Product-Service System and Distributed Economies applied to distributed WEF nexus and used a 11-dimensional canvas tool	Gao et al., 2022
South Korea	Water-Energy-Food Nexus Simulation Model (WEFSiM)	Wicaksono et al., 2020
	Spearman's rank correlation and network analyses	An, 2022
Ghana and Burkina Faso	MAXUS – spatial nexus model	Burger & Abraham, 2020
Tanzania	Multisector spatial modeling	Geressu et al., 2020
Japan	Ontology engineering to prepare nexus domain maps and identify causal linkages between sectors and key stakeholders	Endo et al., 2018
Sub-Saharan Africa	Agent-based models (simulations)	Bazzana et al., 2020
United Kingdom	Participatory scenario planning (a foresight approach that focused on vulnerability and adaptation)	Hoolohan et al., 2019
Nepal	Resilience thinking and nexus approaches were combined within a single framework: WEF-PIK (policies, institutions, and knowledges)	Stringer et al., 2018
México	Non-linear programming model	Núñez-López et al., 2022
	Multi-objective mixed integer nonlinear programing model involving multiple stakeholders	Sánchez-Zarco et al., 2021
Bulgaria	Water Framework Directive (WFD)—2000/60/EU and Canadian Complex Water Quality Index to assess water quality of WEF	Gartsiyanova et al., 2024
General	Life cycle assessment (circular economy approach)	Del Borghi et al., 2020
	Minimum cost of resilience (MCOR) and operation-based resilience metrics incorporated into in a multi-scenario mixed-integer linear program	Tsolas & Hasan, 2021

Insights from literature

- **Global Trends:**
  - Majority of studies are conceptual or descriptive.
  - Systems thinking and System Dynamics Modelling is rarely used; only 3–4 key examples globally (e.g., Chen et al., 2019; Laspidou et al., 2020).
- **Indian Context:**
  - Sectoral silos dominate WEF research – interconnection and interdependence is only theoretically described.
  - Resilience is under-framed; systems thinking and modelling is absent.
  - Lack of subnational modelling tools.

Unexplored areas in existing literature



Key gaps identified

Theoretical gap

- Limited integration of resilience theory into WEF for the Indian context

Population gap

- Poor representation of vulnerable demographic groups across India in existing WEF research

Methodological gap

- Absence of systems thinking and systems dynamics modelling of WEF nexus in India

Empirical gap

- Insufficient empirical studies or data at the sub-national level within the given research for contextualizing local WEF-based policies in India

Practical knowledge gap

- A gap in application of theoretical WEF knowledge in India

Knowledge gap

- A lack of understanding or information regarding the use of WEF and system dynamics models in India

Evidence gap

- A lack of available research data or empirical evidence on the risks, challenges and impacts of WEF policies for planning useful interventions in India

Why It Matters

- India is highly at risk to the impacts of climate change
  - High probability of occurrence of climate hazards
  - High exposure to these hazards, and
  - High vulnerability of its WEF systems and people dependent on them for their livelihoods and wellbeing
- Policymakers in India currently lack integrated tools to anticipate cross-sectoral outcomes.
- System dynamics modelling can inform evidence-based policy coherence to build resilience of the nexus and thus the adaptive capacity of the people dependent on it.

Next Steps in the Research

- Policy coherence assessment of water-energy-food policies at the sub-national level (pilot in one state of India, e.g., Odisha)
- Apply systems thinking and system dynamics modelling to simulate WEF policy scenarios in the state, under climate change
- Incorporate stakeholder-informed system maps and survey data covering indigenous knowledge
- Evaluate SDG alignment and ecosystem service trade-offs
- Deliver an open-access planning tool

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Thank you