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Editorial: Food-energy-water systems: achieving climate resilience and sustainable development in the 21st century

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Editorial on the Research Topic
Food-energy-water systems: achieving climate resilience and sustainable development in the 21st century

Introduction

Owing to the highly interwoven nature of food-energy-water systems (FEWS), climate change and the weather extremes associated with it will continue to challenge the capacity of these sectors to support human wellbeing, grow the economy, and sustain critical environmental services. The food and energy sectors alone contribute, respectively, 10 and 6 trillion USD annually, together representing about 20% of global GDP (World Economic Forum, 2022; International Trade Administration, 2023). To improve the future resilience of these three crucial strategic sectors, society will collectively need to better understand and then appropriately manage FEWS across a broad spectrum of spatial and temporal scales. Environmental stresses, economic pressures, and major technology transitions will compound the impacts of climate change, creating a complex analysis space. These issues thus constitute a quintessential interdisciplinary research challenge, which requires a well-structured science agenda.

Addressing this challenge will constitute the basis for decisions on sustainable FEWS development over the next many decades. The authors believe that supportive information services will be needed to translate fundamental research findings into actionable policies, which governments and other stakeholders ultimately can adopt. Given recent developments in the field of FEWS science, policy formulation can today build on integrated pathways developed from basic research findings, models, real-time information supply chains, and decision support systems. In addition, targeted workforce training and stakeholder

engagement will be essential to communicate the benefits and results of these approaches and to engage appropriate stakeholder groups in their implementation.

As the papers in this Frontiers Research Topic demonstrate, FEWS interactions can be highly complex. These interactions complicate the identification of FEWS sensitivities and the subsequent design of suitable FEWS adaptation measures. Decisions made today could create decade-to-century scale legacy effects (both positive and negative) and it is thus critical to take a systems view of how different FEWS are configured in terms of structure and processes, how these vary geographically, and how they can respond to changes in a resilient and sustainable manner. These realities motivated the assembly of papers into this current Frontiers Research Topic.

The goal of this Research Topic is *to present a collection of next-generation research studies on FEWS that are emerging from the scientific, integrated assessment, education, and policy domains and to assess the directions they suggest for future research and decision-making*. Collectively, the assembled papers discuss a broad suite of capabilities, including the design of suitable FEWS research frameworks that simultaneously advance modeling, data integration, assessment, and training capabilities. These frameworks, in turn, support both hypothesis-based research, assessments, stakeholder engagement, and the implementation of new management approaches.

The papers in this Research Topic were specifically solicited to encompass a full range of FEWS research questions. Thus, many papers address all of the FEWS sectors simultaneously and are therefore—essentially by definition—interdisciplinary. Others focus on two sectors to ensure at least some cross-sectoral linkages. Some papers in the Research Topic rely mainly (or exclusively) on biogeophysical perspectives, others on socio-economics, or some combination of the two. The Research Topic spans three critical areas of development in contemporary FEWS research:

- *Conceptual models, frameworks and data for climate-FEWS studies*, with specific topics that include: research characterizing climate stressors; research frameworks to analyze integrated systems; approaches to assess how climate trends and extremes disrupt single and multiple elements of FEWS.
- *Performance assessments of contemporary and future FEWS*, which: identify specific architectures of FEWS; perform evaluations of FEWS capacity to remain resilient under climate and environmental change; focus on urban domains, but also larger-scale regional assessments; identify gaps across scales; and, evaluate how climate-impacted FEWS produce major economic shocks or benefits.
- *Linking technical, educational, cultural, economic, policy, and regulatory responses to emerging FEWS challenges*. Studies in this Research Topic also make the transition from basic research to applications, through: tradeoff studies to recognize multiple and interacting planning options; quantitative, policy-relevant metrics and other decision-support information from a variety of sources (e.g., *in situ*, remotely-sensed, or survey data); approaches to stimulate productive interchange among scientists, decision makers, and managers; FEWS education; and, links to global public policies, including the climate agenda and the UN Sustainable Development Goals.

In this context, and while not fully comprehensive, we see this Research Topic as constituting a reasonable cross-section of the state-of-the-art in FEWS research. A total of 179 authors from all over the world contributed to 20 published papers. The resulting Research Topic is cast mainly as a set of Original Research Papers ($n = 17$), but also with contributions as Methods (1), Perspective (1), and Review (1) pieces. This Editorial contains active links to the original online publications, which can be found at: https://www.frontiersin.org/research-topics/32707.

Key findings

- Frameworks and associated modeling and data systems featured prominently across the set of studies, with many papers reporting on their design and use. These included the work by Yadav et al., which generated threshold-based indices of FEWS and affiliated human well-being, in a study in New Mexico (United States). An omnibus framework was described in the methods paper by Vörösmarty et al. and then applied to a suite of subsidiary FEWS assessment models (Bokhari et al.; Vörösmarty et al.; Chang et al.; Kicklighter et al.; Maxfield et al.; Zhang et al.). The effort described a loose confederation of FEWS models guided by hypothesis-testing based on single and multi-factor scenarios depicting contrasts in climate, land cover, and other categories of management, technology, and environmental regulations.

Several papers represented a recent trend in FEWS studies, that is, the engagement of its **social dimensions**. As part of this transition, the issue of human wellbeing has also been assessed in the context of physical flows of FEWS products in New Mexico (Yadav et al.). **Economic aspects** have been addressed to evaluate how biophysical flows can be converted into a monetary value for crucial FEWS products generated regionally by the Northeast and Midwest (Chang et al.). The valuation approach offers a more-or-less universally understood metric (money) that can be highly useful for engaging the public and policymakers on both the existence and importance of the FEWS-based production systems they may be charged with managing. Patterns of FEWS consumption have also been analyzed, and in the study of Daignault et al. this constituted a careful tracking of household demands and expenditures for FEWS products. The merging of life cycle analysis with household tracking data enabled the authors to explore how consumerism and household-level consumer behavior drives the demands for FEWS products. FEWS social dimensions research has also recently taken on the question of social equity—with a decided absence of environmental justice principles noted for most of the current literature (Stone et al.). Thus, the social risks associated with FEWS are forecast to rise, without sufficient consideration of economic equity and environmental justice.

Several papers focused on **FEWS infrastructure** and the affiliated contributions of **technology**. Sunny et al. explored solar-aided farming systems and showed how new technology adoption in Bangladesh is a multi-dimensional process involving biogeophysical realities, perceptions, and local economics. Zhang et al.

and Bokhari et al. executed in-depth analyses of electrical power and cooling technologies to explore how the impact of climate drivers produces inefficiencies in production and thermal pollution that can be mitigated by specific fuel mixes and cooling systems. The infrastructure constituted studies of traditional or new engineering systems (e.g., renewables) but also extended the notion to nature-based assets, as articulated by Vörösmarty et al. For example, the dynamics of natural and built infrastructure were assessed in Kicklighter et al., who demonstrated the impact of heat waves exacerbated by suburban land expansion, which in turn regulated the strength of carbon sequestration as an ecosystem service. Land-use and land cover change also figured prominently in the study by Williams et al., developing scenarios of future development based on contrasting water-saving strategies across the domestic, industrial, and agricultural domains (i.e., through irrigated landscapes).

Several papers also analyzed FEWS **tradeoffs**. Yourek et al. noted that Integrated Assessment Models are typically poor at capturing finer-scale regulatory and landscape management. However, they nonetheless were able to explore tradeoffs in irrigation and instream environmental flow, enabling an assessment of the impacts of climate versus land and irrigation management schemes in their study of the Columbia River Basin. Not unsurprisingly, increases in irrigation are typically met with reductions for water allocatable to nature. Additionally, they posited that water rights could be downscaled into land allocation policies, establishing another critical dimension to FEWS production tradeoffs. An analysis was also made of the ongoing and large-scale transition to renewables (Fekete et al.), essentially a tradeoff experiment evaluating the reliability of renewable energy transitions from fossil fuels. A primary limit on adopting clean energy technologies is the intermittency of renewables and the necessary energy storage solutions to balance the mismatch between demand and supply in short time horizons. Seasonal and longer time frame intermittencies also exist, and when considered, are found to convey substantial limits in our capacity to adopt a fossil fuel-to-renewable transition. Bokhari et al. demonstrated the value of reduced complexity modeling to analyze tradeoffs in electricity production, its thermal effluents, and other sources of water pollution. Such reduced complexity simulations reflect a high degree of computational efficiency, short set-up times, and capacity to easily develop, test, and communicate modeling results, particularly useful in the context of engaging stakeholders. A large-scale integrated assessment model was used to analyze tradeoffs in irrigated food and electricity production for the entire region of the Middle East and North Africa (Hejazi et al.). It demonstrated how fuel switching could lower tradeoff impacts that otherwise would have been in place with a heavier reliance on fossil fuels.

Stakeholder engagement was another aspect emphasized within the Research Topic. Williams et al. demonstrated how stakeholders engaged in designing scenarios. They revealed through this work the importance of the time horizons over which FEWS actions could be actualized as an essential determinant of user interest. Tuler et al. surveyed both researchers and stakeholders and discovered that they shared several perspectives in the context of joint FEWS research. For example, researchers incorrectly assumed that modeling results needed to be substantially simplified to be communicated to their stakeholders, yet in reality oversimplification was unnecessary, with the non-scientists in fact preferring a more complete—though admittedly more complex—reporting of modeling results. A study exploring the interactions between academic and NGO partners in a case study for Puerto Rico (Markazi et al.) recognized the importance of NGOs (at least in that specific regional context) in mobilizing the community, which in turn would enhance the overall institutional effectiveness to manage FEWS. While this work was context-specific, it could also find more general applicability.

Workforce development was the subject of the paper by Murray et al., who argued for the value of embedding experiential learning into doctoral training programs. Using confidence measures across the student body sampled, they aimed to facilitate interdisciplinarity and showed evidence of breaking down, traditional siloed barriers.

The Perspective piece by Khan et al. proposes that well-cast FEWS **Case Studies**, particularly those in the applied domain, are important for progress in the field but still generally lack a coherent strategy in their design and execution. However, several of the Research Topic papers were in fact case studies, although cast across a wide variety of scales, from large regional: MENA (Hejazi et al.), US Northeast/Midwest (Vörösmarty et al.; Vörösmarty et al.), Bangladesh (Sunny et al.); to smaller regions across the United States: New Mexico (Yadav et al.), Puerto Rico (Markazi et al.), Columbia River (Yourek et al.), Southwest Kansas (Ofori-Bah and Amanor-Boadu), Delaware River (Bokhari et al.); to locales: Magic Valley Idaho (Williams et al.), Lake County Illinois (Daignault et al.). The review of Khan et al., which also noted the lack of an overall approach to FEWS studies, then called for a **community of practice** to be established, which would help to standardize data, develop more applied case studies, and effect comparisons of modeling results.

What did we learn about resilience in the FEWS system in light of climate change and its extremes?

Four major cross-cutting themes helped to unite the papers presented in this Research Topic and give us some insight into building resilience across the FEWS nexus. The first is that operational context is important. From the various papers, it was shown that *in situ* climate conditions, the level of development in the country or region of interest, and its FEWS challenges are conditioned on specific biogeophysical and social dimensions. For example, the macro-regional challenges in managing water for FEWS in the arid to hyper-arid MENA region are dramatically different than for the U.S. Midwest and Northeast, yet both are large regional systems that must be managed with key macro-scale strategic factors in mind and in place across the domain of interest (e.g., energy sector production versus food production versus protecting public water supply).

Second, in terms of climate change, an adaptable response strategy—particularly in light of climate extremes—will be required in order to successfully apply the palette of new FEWS technologies, combined with better planning and coordination of land use change and management of inland waterways to maximize their intrinsic ecosystem services. A prime example is how increased

irrigation use may alter freshwater fisheries and concentrate extant pollutants due to competing demands for water. To be successful, resilient FEWS adaptations will need to simultaneously address the social dimensions of tradeoffs, often requiring choices which may impact one sector more than another, and thus the lives and livelihoods of large populations engaged as both managers and beneficiaries of FEWS resources.

Third, virtually all of the studies in the Research Topic had some notion of organized computation and data management to handle their FEWS tradeoff, sensitivity, and sustainability questions. We see the need for promoting fuller access to data and scientific results by researchers and stakeholders alike, and upon which an ongoing open exchange between these two critical groups can be sustained. Some papers suggested that past approaches at the community and larger government levels have been insufficient because their FEWS approaches have not been sufficiently operationalized. To fill this gap there needs to be a multi-scalar and multi-sectoral research infrastructure to perform the necessary background research and planning. To do so, we also need to improve the "culture" of FEWS research, where scientists maintain open and continuous exchanges with stakeholders.

Fourth, our educational system also needs to be upgraded to train a next-generation, interdisciplinary workforce in sustainability science. We will need researchers, engineers and policymakers who can address the many integrated FEWS challenges, which are not merely determined by the physical nature of the nexus setting but also by their social dimensions. New interdisciplinary training programs need to be formulated and tested.

From this Frontiers Research Topic, we see some immediate steps that should be taken to improve our capacity to address FEWS challenges through research. In the more than decade since the nexus concept first entered the sustainable development domain, definitions, data, and model needs have yet to be standardized. This not only will impede our progress on basic research but also delay optimal operationalization of the nexus. Efforts must therefore be invested in crossing the nexus divide and creating "common cause" with other FEWS researchers and practitioners. This would involve community-based mobilization to systematically evaluate and, where necessary, combine the diversity of existing data sets and models currently available.

We see immediate value in establishing a FEWS community of practice, which can host important intercomparison studies of archival, *in situ* monitoring network data, or remotely sensed FEWS-relevant knowledge resources. The partnership could first focus on the tools and analytics needed to characterize the basic nature, processes, and sensitivities of FEWS. Then, it could forecast potential future states of the nexus, driven not only by climate change but also the diverse spectrum of human actions that include management or mismanagement of land and water systems, pollution control, and economic and social policies. The authors view this as a grand, and likely long-lived, challenge for the FEWS research and applications community.

Author contributions

CV: Writing–original draft, Writing–review and editing. PC: Writing–review and editing. GJ: Writing–review and editing. RL: Writing–review and editing. DW: Writing–review and editing.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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