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Data for WEF Nexus Analysis: a Review of Issues

Bruce A. McCarl[1] · **Yingqian Yang**[1] · **Raghavan Srinivasan**[2,3] · **Efstratios N. Pistikopoulos**[4] · **Rabi H. Mohtar**[3,5]

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Abstract
Purpose of Review The purpose of this review is to discuss challenges regarding assembly and use of water-energy-food (WEF) nexus data.
Recent Findings WEF nexus analysis endeavors including nexus-wide-scoped data are relatively new although component data has been gathered for years. However, such data are not frequently comprehensive across all WEF sectors nor are they typically integrated into a WEF wide system database. Data systems covering the full set of WEF domains are evolving and there are challenges that must be faced to better support WEF system wide analysis.
Summary Nexus data must facilitate stakeholder and analyst understanding of nexus scope, locations, production, consumption, diversion, return flows, and conveyance possibilities along with costs. There is important need for data that supports efforts to understand system boundaries, and spatial dimensions, along with the origin and fate of WEF commodities plus cross-sector interactions and interfaces. A wide, rather comprehensive set of data are necessary across the full WEF scope as the nexus approach is about widening perspectives to unexplored levels. Additionally, WEF nexus data systems need to reflect study region uniqueness incorporating appropriate activities with contents varying as focus shifts from place to place. Challenges arise in representing appropriate scope, mix of enterprises, stochastic variation in water supplies, WEF commodity production practices, WEF commodity market prices, and costs and returns from ongoing and potential future technological choices. Data challenges arise due to proprietary interests, scale differences in analysis, model requirements, representation of unexplored possibilities, assembly cost, projections of the future, representation of stochastic variation, quick query and retrieval systems, and integration with visualization. Comprehensive, innovative procedures are needed for data collection, storage/retrieval and inference in support of high quality WEF nexus analyses.

Keywords Water-energy-food nexus · Commodity market price · Data systems · Model requirements · Stakeholder analysis · Stochastic variation

This article is part of the Topical Collection on *Nexus of Food, Water, Energy*

✉ Bruce A. McCarl
mccarl@tamu.edu

[1] Department of Agricultural Economics, Texas A&M University, College Station, TX 77843-2124, USA

[2] Department of Ecosystem Sciences and Management, Texas A&M University, College Station, TX, USA

[3] Department of Biological and Agricultural Engineering, Texas A&M University, College Station, TX, USA

[4] Artie McFerrin Department of Chemical Engineering, Texas A&M Energy Institute, Texas A&M University, College Station, TX, USA

[5] Zachry Department of Civil Engineering, Texas A&M University, College Station, TX, USA

Introduction

The water-energy-food (WEF) nexus [1•, 2, 3, 4••, 5, 6] is focused on complex interrelationships among systems that produce, deliver, and use WEF-related items. The purpose of considering the WEF nexus (which we will just call the nexus from hereon) in totality is to identify and capitalize on WEF synergies and benefits of coordinated actions relative to uncoordinated actions. Indeed, decisions based on the nexus-wide considerations rather than individual elements are likely to produce better, if not more informed, outcomes. Yet to achieve a better understanding of the relationships among nexus elements and capitalize on that relies on data covering the full nexus scope. Complicating matters are that data need to reflect changes over time. Desirable types of nexus data include items describing the following:

- Regional economics, income distribution, and jobs
- Energy, water, and food needs and prices
- WEF production practice technology mix
- Emissions of greenhouse gases, particulate matter, soil erosion, nutrients, and contaminated water
- Allocation of land and water
- Export possibilities and import needs
- Water treatment requirements
- Stocks of groundwater, agricultural land, oil and other fossil energy plus historic data describing depletion or increases and conditions under which that happened
- Potential alternative energy and water sources plus data on their cost, yield, and input usage
- Population location and projected growth plus associated WEF item demands.
- Links between past and projected climate change, water supplies, water diversions/withdrawals
- Aquifer elevations, reservoir conditions and river flows as they depend on precipitation locally or in distant recharge or upstream locations
- Energy use by irrigation, M&I pumping, water conveyance, power cooling, hydropower and hydraulic fracturing
- Water use and return flow for major diverters including energy, agricultural producers, municipal, and industrial concerns plus requirements for environmental health and preservation
- Regional weather for at least 20 previous years
- Agricultural crop and livestock yields, costs, water, energy, input, and other resource usages
- Movement patterns for water, agricultural commodities, and produced energy
- Budgets giving water use alternatives and their resource usage for relevant energy production enterprises including mining, oil/gas production, thermal and hydroelectric power
- Enterprise locations and water withdrawal points
- Locations of roads, railways, rivers, reservoirs, power transmission, pipelines, and WEF processing facilities
- WEF governance structures and degree or potential of coherence across these sectors
- Utilities pricing structure
- Possibilities for water, energy, and food conservation and potential consumer acceptance
- Technical possibilities for improving nexus management along with information on their cost, energy, water, and other input requirements. In addition, information on their robustness, which includes alterations in capacity under adverse weather conditions, shock, corrosion, and fouling and operator faults. Also, information on technology scalability and potential integration with existing regional industries and infrastructure

Such data if available, will generally exhibit varying degrees of resolution, quality, scale, and format. A challenge to the accessibility of these data is coherence across the scales and types used by an assortment of the nexus models and uses.

In addition, one must recognize that data supporting a family of models is likely needed and that different models have different requirements. As an illustration, Table 1 lists examples of models addressing different WEF components with a brief accounting of needed data and their geographic scope.

Classes of relevant data include those above plus the following items:

- Water extraction and conveyance;
- Crop/livestock mix;
- Crop management possibilities;
- Population growth;
- Climate change effects;
- Thermal, hydropower, fracking, bioenergy production;
- Energy conveyance mechanisms.

Some models require data at very fine time steps with others being annual or multi-year. This introduces the complexity of simultaneously supporting data needs of very fine time and spatially disaggregated models along with providing data on the total issue regionally and over multiple years. It also raises the need for a unifying overall data conceptualization and assembly procedure.

Key Challenges/Research Questions

The complexity and scope of the WEF nexus raises challenges for data development, retrieval, calculation, and use. Challenges also arise due to nexus issue scope, complexity, availability, use, and assembly. Generally, our experience shows data needs for the nexus modeling and analysis usually exceeds initial data availability and requires compromises for several reasons that will be discussed below.

Scope of Nexus Issue

A fundamental challenge involves properly establishing system scope. Decisions must first be made as to the geographic scope of the nexus issue and consequent analysis. The scope must reflect the fact that actions in one geographic region often influence and are influenced by actions in other geographic regions. Such influences arise via markets or natural linkages. For instance, in river systems such as the Colorado

Table 1 Models addressing WEF nexus aspects

Nexus aspects	Model example	Data used and geographic scope
Crop	EPIC [7] DSSAT [8]	Soils, climate, crop at field level
Hydrology	SWAT [9]	River basin description, naturalized inflows, urban and agricultural water diversion points and quantities, climate, regional crop mix at basin level
Economics of water diversion by WEF sectors	EDSIMR [10]	Municipal and industrial demand for water at diversion points, agricultural yield/cost/water relationships, agricultural prices and costs, water rights, water market conditions at regional level
Agricultural sector and market	FASOMGHG [11]	Dryland and irrigated crop input output, land use, demand for crops, international trade, resource endowments at mainly state level
Energy system	MARKAL [12, 13]	Energy production locations, enterprise resource use, costs and returns at regional or country level
Regional economic	IMPLAN [14]	Regional industry composition, production and input use characteristics at US county level
Groundwater	MODFLOW [15]	Aquifer characteristics, initial stocks, pumping locations and volumes for an aquifer
WEF nexus trade-offs	WEF NEXUS TOOL 2.0 [6]	Water, energy, food local portfolio; can include national, regional, and local (farm or factory level); prioritization of economic, social, and environmental indicators

or the Indus, water withdrawals in the upper reaches alter the availability of agricultural and hydropower water downstream. Alternatively, sectoral and resource scope are important. In an ongoing study around San Antonio, Texas, there are significant dimensions of ground and surface water, electrical energy production reliant on cooling water, little hydropower, hydraulic fracturing, rapid aquifer recharge, significant irrigated agricultural acreage, rapid regional population growth, dire climate change projections, alternative potential brackish and wastewater reuse water sources, and the possibility for interbasin water transfers that could affect the study. In a completed case study in Egypt, there are upstream water flows that need to be considered along with world markets for fruits and basic grains [16•]. In a US bioenergy production setting, one needs to consider how alterations in US agricultural commodities affect prices and in turn production elsewhere reflective of the indirect land use issue [17, 18].

Considering Full Complexity

Another challenge is appropriate data development and integration across diverse components. In the WEF nexus context, this could involve a need for data on ground and surface water hydrology, regional economics and environment, energy production, agricultural cropping and land use, urban growth and WEF commodity usage. Some of these data may be readily available in common databases, while other data will require large development efforts. The data system needs to support detailed models while also providing parameters to more aggregate models. It also needs to provide a place to store results for summarization and visualization.

The difficulty of assembling data is also impacted by the questions under investigation and its scope. For nationally scoped analyses, more aggregate data may be acceptable and consequently easier to find as compared to detailed site-specific scoped studies. Under these conditions, trade-offs arise between complexity–simplicity of data and modeling plus exploitation of the readily available but not ideal data sets against expensive and time-consuming data acquisition.

Rendering Data Useful for Decision Support and Dialog

In our experience, interactive and visually friendly means of data delivery increase communication ability and potential study acceptance. Development of effective ways of portraying data require dialog between those that build the database, and associated retrieval and visualization capabilities with analysts and decision-makers. Strong stakeholder and analyst involvement will also improve database content and end user interfaces plus subsequent use. We also have found that communication is greatly facilitated by strong visualization capabilities.

Also, in the decision support context, data developers must recognize that their data will rarely be complete enough or sufficient to provide definitive answers but rather constitute a basis for the provision of insights. In fact, data systems need to evolve and demonstrate capabilities for providing insights as the project evolves.

Representation of Variability

Characterization of variability in the data is critical. There will inevitably be year-to-year variations in water supplies, water diversions, and commodity prices. Additionally, there will be uncertainty in demand changes due to population growth, energy and commodity prices, and climate change incidence. Such variability needs to be described and organized to support treatments of variability by the analysis models and in data retrievals and visualizations.

Additionally, for data that vary, there is a need for average estimates as well as the degree of uncertainty in terms of maximum observations, standard deviations, and/or confidence bounds. A challenge also arises regarding representation of joint as opposed to independent, individual item, probability distributions. For example, there is often a joint distribution of interdependencies between crop yields, precipitation, temperature, extreme events, and river flow.

Data on Technological Alternatives

Nexus analyses are often performed in regions where there has been substantial water and energy planning wherein there are a number of suggested strategies. For example, the 2016 Texas Region L water plan [19] identifies 51 different strategies to cope with future water demand, providing data on strategy cost and water yield although not generally under stochastics water supply conditions. Nexus analysts will likely need to augment such data reflective of stochastic water availability. Furthermore, applicable data on energy capacity construction and operating costs may be difficult to obtain since that can involve regionally specific considerations. A major data challenge will be identifying transformational strategies systematically and developing estimates on their fixed and operating costs and water/energy yields and uses under varying conditions for weather, climate, and other sources of uncertainty. Regional stakeholder input on such items will likely be required.

Adding Consideration of Limits/Barriers

One needs to identify and assemble data on limits that influence strategy adoption. The 2014 IPCC report devoted substantial coverage to limits within [20, 21]. Across these pieces, the potential limiting or barrier creating factors are the following:

- Knowledge and awareness of possible strategies and as well as state of strategy related technology availability;
- Regional physical constraints such as topography, soil characteristics, and water source locations;
- Biological characteristics of vegetation and animals in the WEF nexus region
- Economic characteristics such as state of development, industry in region, extent of food production, incidence of water and energy dependent entities, regional income, economic stability, and macro-economic conditions;
- Financial constraints such as capital availability, and lending practices;
- Human resources availability and capability including sheer labor availability, labor skill, leadership capabilities, and educational attainment;
- Social and cultural influences such as societal values, world views, cultural norms and behaviors, perceptions of needs for action, and compatibility of strategies with life styles;
- Governance practices and regional institutions such as water allocation rules, property rights, land tenure, regulations;
- Competing values such as priorities for regional investment, alternative uses of resources that could be employed in WEF nexus enhancements and attitudes toward regional cooperation;
- Regional land, water, equipment, and infrastructure resources;
- Transaction, information, and adjustment costs encountered in finding and implementing strategies;
- Market failures and missing markets; and
- Uncertainty about effects of strategy implementation and the future.

Proprietary Data

Many WEF nexus situations contain parties with substantial proprietary interests. For example, companies who have developed innovative water and energy conserving practices may not wish to reveal data on cost, water and energy use. Additionally, when using census or other survey data at low levels of aggregation are often not revealed due to confidentiality agreements but are as level of aggregation increases. For example, localized data on large confined animal operations are rare given that there may only be one or two regional facilities. This often requires assumption-based data downscaling or creative inferential approaches.

Preservation of confidentiality when deemed necessary is also a challenge mandating development of security schemes and pledges that restrict access and convince data holding entities to make data available. A priori development and implementation of confidentiality agreements and security features may also be necessary to facilitate negotiations for proprietary data availability.

Granularity, Consistency, and Regional Heterogeneity

Models for different WEF nexus elements commonly address different scales. Hydrology models work on small watersheds, crop models on individual plants or fields, and economic models on counties or crop reporting districts. Data availability does not always match such scales. Often, some of the needed data like that on land use and soil type data are available at very fine resolution. However, economic data like crop budgets are frequently available only at a multicounty or state level and they vary from year to year. Downscaling and upscaling procedures are often needed to meet model data requirements, and when passing results among system and visualization elements. Appropriate implementation of downscaling and upscaling involves additional information, assumptions, and regionally tailored procedures leading to further data requirements, uncertainties and limitations.

Finally, data availability varies greatly geographically, which presents great challenges in the nexus analysis and modeling across focus regions, countries and settings.

What Has Been Done Versus What Could Be Done

Data obtained through surveys, interviews, or census means are typically reflections of what has been done in the past and not what could have been done. In particular, the set of production possibilities that are used are those that were judged to be the best given historical prices and resource availability. However, nexus actions, climate change, and population growth can alter prices or resource allocations in turn making other previously unutilized choices superior strategies. This raises the challenge of assembling data on prospective technologies. Sometimes, experimentation can be used, but more commonly, one may resort to use using data from other regions, raising the challenges discussed above under benefits transfer.

Governance Characteristics

Changing nexus behavior requires cooperation across many WEF actors who control usage, allocation, regulations, prices, etc.; or more generally those who are involved with governance. WEF governance data are available to some extent but are usually unique to a region. There is little data on the effect of different governance approaches on the success of WEF nexus actions. Developing or inferring such data is a challenge.

Cost of Data Collection Versus Accuracy of Data Engineering

The data requirements of many models often exceed data availability due to granularity and/or proprietary interests among other forces. This raises needs for new means of data assembly. Such means can include collection of primary observational data, developing data through experimental means, and/or performing data engineering where estimates are developed deductively. Challenges exist in terms of the cost and time acquired to generate observational data versus the accuracy of engineered data along with the time to develop experimental data.

Difference Between Production, Withdrawal, and Consumption

Description of water and energy flows raises substantial issues regarding net production and consumption. Flood irrigation is a famous example for using water with about 50% efficiency where there is a substantial difference between diversions and net water removed from a river after return flows are considered. Bioenergy production is another example where there may be substantial fuel used in bioenergy production and there is a consequent difference between total production and net production available. Intermediate use of WEF commodities along with return flows, their timing, and locations need to be reflected in the data.

Projections on Climate and Population

Regionally increasing population and climate change requires localized future projections. Population projections and variations based on differing assumptions (e.g., alternative levels of immigration) can often be obtained from state demographers. Climate change projections are available by grid cell, but localized use often involves downscaling. Projections of highly relevant phenomena such as incidence of drought, freezes, dry intervals, and extreme storms may not be reliably available. Incorporating data to represent these factors in the analysis will be a challenge.

Potential Transformative Solutions Needing More Research

Analyses of WEF nexus issues are a rapidly growing field and most of the challenges above require more research. The biggest transformative action is the demonstration of the gains to the nexus-related decision-making versus individual area decision-making, with such studies currently being in short supply, if not entirely absent. Comprehensive data collection, coupled with innovative retrieval and visualization procedures can help convey this. Additionally, there is a substantial need to understand how one can achieve broader acceptance of and participation in overall nexus solutions. This includes effectively integrating decision-makers from the separate WEF domains. Consideration of data collection, retrieval design, and visualization approaches are likely required to enhance nexus analysis and collaboration.

There is also substantial need for research on unifying data and models to both provide needed data for modeling and allow results retrieval and visualization to enhance decision support.

Impact on Science and Society

Nexus-related analysis and associated data support provides two distinct contributions to society and science. Firstly, the data developed can be used to inform stakeholders and policymakers on the scope and possible areas for action in the nexus arena. When successful, such an effort may be even more important than the data analysis results, placing capabilities in the hands of decision-makers to do their own assessment of potential nexus actions. Secondly, by disseminating information on innovative nexus data efforts that have potential for employment by other nexus analysts elsewhere, this can improve nexus analysis and beneficial strategy adoption beyond the case studies at hand.

Conclusions

WEF nexus analyses can help stakeholders and policymakers better understand the cross-sector scope and potentially lead to implementation of socially beneficial management alternatives. Since data is an essential part of such analyses, the data and its associated retrieval system also has value. In developing this data, a number of challenges arise as described above. Issues like appropriate scope, granularity, representation of complex interrelationships, proprietary considerations, characterizing uncertainty, data collection versus data engineering, previously unobserved technological alternatives, data evolution over time, representing resource, and government-based limitations, as well as a number of other issues should be considered. Data collection efforts within the WEF nexus analysis arena must move beyond individual sector-based data assembly to broader full nexus domain scoped efforts. The nexus data must also pay close attention to portraying the influences of climate and population growth.

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Compliance with Ethical Standards

Conflict of Interest Bruce A. McCarl, Yingqian Yang, Raghavan Srinivasan, Efstratios N. Pistikopoulos, and Rabi H. Mohtar declare no conflicts of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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