Adaptation Opportunities and Constraints in Coupled Systems: Evidence from the U.S. Energy-Water Nexus

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Abstract:

Over the past decade, adaptation has emerged as an important risk management strategy to address climate change and avoid adverse consequences. These endeavors overwhelmingly focus on actions within sectors and thus fail to account for coupled effects across systems. This paper focuses on adaptation constraints that arise from the interdependencies of coupled systems, and the opportunities that emerge when adaptation strategies integrate such interdependencies. Three general constraints to adaptation in coupled systems are identified and detailed using evidence from the United States energy-water nexus: insufficient data and information, path dependence, and institutional fragmentation and disorganization. Adaptation constraints within the energy-water nexus are especially difficult to avoid or overcome at local and regional scales owing to complex, but poorly integrated, governance structures. This indicates that some degree of national coordination is an important enabling condition to overcome constraints and enable adaptation throughout the energy-water nexus.

Key Words: climate change; energy; water; adaptation; decision-making; scale

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1. Introduction

Over the past decade, adaptation has emerged as an important risk management strategy to address climate change and avoid adverse consequences (Mimura et al., 2014). This was highlighted in the 2015 Paris Climate Change Agreement, which acknowledges adaptation as an essential response to climate change to protect people and ecosystems (UNFCCC, 2015). While adaptation efforts have increased recently, they generally remain focused on discrete sector-specific actions (Mimura et al., 2014). For example, numerous climate change publications including the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (AR) and the United States (U.S.) National Climate Assessment organize adaptation by sector (IPCC, 2014; Melillo et al., 2014), as do various adaptation plans (Hughes, 2015; Woodruff and Stults, 2016).

Inherent limitations to applying a sector-specific approach in the pursuit of adaptation exist (Adger et al., 2005). The concept of a sector is a convenient heuristic for organizing adaptation efforts and aligning information and actions to stakeholder groups, economic indicators, or jurisdictional elements. In practice, however, sectors represent complex systems of physical, social, political, and economic processes. These systems are often coupled – they interact, overlap and have effects on the inputs, constraints, and outcomes of each other. For example, the coupling of energy and agriculture systems is evident in the environmental, economic, and social consequences that stemmed from the implementation of U.S. federal incentives for bioenergy (Preston et al., 2015). These incentives exacerbated competition for corn which led to rapid increases in ethanol-related corn production, particularly compared to food-related corn production, and contributed to decade-level high prices for corn and ethanol during the 2012 U.S. drought (Preston et al., 2015).

This paper focuses on adaptation constraints that arise from the interdependencies of coupled systems, and opportunities that emerge when adaptation strategies integrate such interdependencies. This paper argues that such interdependencies are the norm, not the exception, and thus the dominant framing of adaptation responses as sector-specific is a “failure of understanding” that must be addressed in the development of robust adaptation responses (Preston and Kay, 2010 based on Clark, 2002, p. 115). In contrast, reorienting framing toward *holistic adaptation*, or adaptation concerned with complete systems, has the potential to identify mutually beneficial adaptive responses to climate change and to produce more effective outcomes than adaptation focused on a single system.

This paper proceeds with a theoretical review of consequences that arise when adaptation planning does not consider coupled systems. This is followed by a review of the foundational literature on adaptation constraints to establish context for subsequent discussion. The practical implications of coupled systems for adaptation are then explored by using evidence from the U.S. energy-water nexus (EWN). The paper concludes with a discussion of pathways to overcome constraints and pursue opportunities related to adaptation implementation within the U.S.-EWN and lessons that can be applied to adaptation more broadly.

2. Adaptation within coupled systems

Despite the need for a holistic framing of adaptation, there is little academic literature and few practical examples detailing adaptation approaches within coupled systems (Moser, 2009). Moser (2009) notes widespread acknowledgement that cross-sector adaptation is necessary but that most entities have postponed this challenge. Examples of adaptation efforts show the narrow focus of adaptation implementation: Norwegian municipalities used the past to guide adaptation efforts (Amundsen et al., 2010); U.S. federal lands pursued adaptation within units without integration (Jantarasami et al., 2010);

and Swedish municipality efforts lacked sectoral coordination (Storbjörk, 2010). Failure to consider coupled systems in adaptation efforts can result in four consequences: unrecognized tradeoffs, maladaptation, ineffective outcomes, and missed ancillary or co-benefits of strategies.

Externalities lead to unrecognized tradeoffs when adaptation efforts are not holistic. The IPCC-AR5-Working Group 2 reported examples of potential tradeoffs that may occur when adaptation planning does not consider multisystem interactions (Table 1). For example, while increased pesticide use may adapt crops to new conditions, it also creates externalities in related systems including increased: costs for farmers, pollutants to the environment, human exposure to pollutants, and greenhouse gas (GHG) emissions (Klein et al., 2014). The distribution and severity of unrecognized tradeoffs displaced onto related systems may be unequal and unjust which will exacerbate existing inequalities or create new ones.

Table 1. Potential adaptation tradeoffs: selected examples from Table 16-2 in Chapter 16 of the IPCC-AR5 (Klein et al., 2014, p. 918).

Sector	Adaptation Objective	Adaptation Option	Real/Perceived tradeoff
Agriculture	Maintain yields; suppress pests/invasives	Increase chemical fertilizers/pesticides	Adverse impacts of pesticide use on non-target species; increased: GHG emissions; human exposure to pollutants; discharge of nutrients/chemical pollution
Biodiversity	Enhance regulations for at-risk species	Protect critical habitat	Addresses secondary not primary pressures; property rights concerns; regulatory barriers to development
Coasts	Protect assets from inundation/erosion	Sea walls	High direct/opportunity costs; equity concerns; coastal wetland ecological impacts

A second consequence of sector-specific adaptation is maladaptation, which is defined as adaptive actions that adversely impact or increase vulnerability in other systems or groups (Barnett and O'Neill, 2010, p. 211). Barnett and O'Neill (2010) use the construction of the Wonthaggi desalination plant for Melbourne to detail five types of maladaptation: 1) the energy-intensive desalination process increases GHG emissions; 2) the contested Aboriginal-owned location of the plant and increased utility costs overburden vulnerable populations; 3) the aforementioned social costs and environmental costs such as reduced flows of the Murray river create opportunity costs; 4) the use of seawater for desalination masks freshwater availability and undermines conservation efforts; and 5) the scale and permanence of the project create path dependence. In Melbourne, the sole-pursuit of ensuring water availability is achieved at the expense of related systems that must then manage the resultant maladaptation. When multiple, related systems pursue adaptation singularly, maladaptations transfer onto other systems thereby increasing vulnerability and not effectively reducing climate risk across systems. Additionally, when adaptive actions that generate maladaptation are coupled, effects on related systems become even more pronounced.

The case of the Wonthaggi desalination plant also details ineffective outcomes of adaptation focused on a single system. For one, the plant has never been used – the first water order was announced in March 2016 amid calls that it was unnecessary, and as of December 2016, the plant has not initiated the month long process to begin operation (Willingham, 2016). Despite never operating, plant owners are paid 1.8 million dollars per day to ensure operability (Willingham, 2016). While the plant is often referred

to as a water “insurance policy” (Willingham, 2016), other measures that consider coupled systems like pursuing treated wastewater, captured rainwater, and conservation could enable more effective water savings and ensure water availability for less cost (Barnett and O’Neill, 2010) even when shortages are not dire.

In addition to negative consequences of single-system adaptation, ancillary or co-beneficial adaptation opportunities are often missed. For one, low-regrets and demand-management actions are frequently overlooked in favor of supply-management and infrastructure-based actions (Pittock, 2011). Emphasizing the latter neglects opportunities to lessen system and resource demand through conservation or efficiency measures. For example, pursuing energy efficient retrofitting in U.S. homes could reduce household energy demand by as much as 40% (Council on Environmental Quality, 2009). These efforts have multiple co-benefits including: reduced GHG emissions “by up to 160 million metric tons annually”; potential annual cost savings of 21 billion dollars on household energy bills (Council on Environmental Quality, 2009); more jobs (U.S. building energy efficiency investments could create “3.3 million cumulative job years of employment” – Fulton, 2012, p. 3); avoided energy supply expansions; and lessened water demand for electricity generation. Second, considering coupled systems in adaptation helps identify opportunities for synergistic technologies like utilizing waste heat “for desalination and combined heat and power”, using water systems “for energy storage or electricity demand management”, and capturing “energy generation in man-made water conduits” (U.S. D.O.E., 2014, p. x, 129). While holistic adaptation could help avoid negative consequences and realize multisystem benefits, it will also experience constraints.

3. Current Discourse on Adaptation Constraints

The concept of adaptation constraints has emerged within the climate change adaptation literature to describe “*factors that make it harder to plan and implement adaptation actions*” (Eisenack et al., 2014; Klein et al., 2014, p. 907). The term ‘constraint’ is often used to describe an impediment to adaptation, while ‘barrier’ and ‘obstacle’ are contextualized similarly (Klein et al. 2014, p. 906). Constraints are essentially simplified constructs that help clarify why adaptation is difficult (Biesbroek et al., 2014). Constraints are not exclusive to adaptation and often emerge within complicated policy-making situations (Biesbroek et al., 2014).

Constraints originate from three fundamental sources: the actors that are adapting, the context in which adaptation occurs (e.g. the socioeconomic, environmental, and institutional details of the situation), or the system at risk to climate change where the adaptation occurs (Moser and Ekstrom 2010; Ekstrom and Moser 2014; Eisenack et al. 2014). Often the agency, scale, and scope of adaptation dictates which constraints are encountered (Adger et al., 2009; Moser and Ekstrom, 2010). Constraints occur at different stages of adaptation and are not fixed in time; rather, as some are overcome, others may emerge and a few become persistent (Porter et al., 2015). For example, British local governments prioritized climate information constraints in the early 2000s, but years later funding and staff deficits were identified as the most significant adaptation constraints (Porter et al., 2015).

Given a broad range of constraints are identified in the literature, some effort has been made to structure the discourse through categorization (Biesbroek et al., 2013; Eisenack et al., 2014). Table 2 provides a snapshot of selected adaptation constraints from recent literature. This table was constructed iteratively using a convenience sample from relevant peer-reviewed literature, government reports and a Google Scholar™ search for articles published from 2010-2015 with “barriers” OR “constraints” AND “adaptation” in the title that yielded 151 results when citations were excluded. Google Scholar was

chosen because comparatively, it captures a wider array of literature than other databases (Preston et al., 2015a). In light of Porter et al. (2015) and the timeliness of constraints, 2010 was chosen as the earliest publication year in an effort to identify recent adaptation constraints. The table itself was iteratively constructed. Constraints were identified while reading articles and then were grouped together in a table. The search and resultant table illuminate the breadth of adaptation constraints mentioned in recent literature, but are by no means exhaustive of relevant sources or adaptation constraints.

Table 1. Barriers to adaptation mentioned in selected literature from 2010-2015.

Barrier	Example/Description	Citation(s)
Adaptation Deficits		
Lack of resources/information/knowledge/data	Stakeholders desire useful/understandable information (Bierbaum et al., 2013).	Amundsen et al., 2010; Biesbroek et al., 2011; Ekstrom and Moser, 2014; Jantarasami et al., 2010; Jones and Boyd, 2011; Moser and Ekstrom, 2010; Porter et al., 2015; Storbjörk, 2010
Lack of willingness to act/change	Unwilling to change strategies despite recognizing changes (Jones and Boyd, 2011).	Jantarasami et al., 2010
Lack of awareness/communication	Unclear “responsibility, leadership...lack of agreement over options and goals” (Ekstrom and Moser, 2014, p. 65).	Biesbroek et al., 2011; Porter et al., 2015; Storbjörk, 2010
Lack of knowledge of climate change impacts	Municipalities wanted information on impacts in unfamiliar situations (Amundsen et al., 2010).	Ekstrom and Moser, 2014; Porter et al., 2015; Storbjörk, 2010
Lack of capacity/continuity (knowledge loss)	“Years pass between...floods and risks are forgotten...we have been taken by surprise many times” (Storbjörk, 2010, p. 245).	Amundsen et al., 2010; Carmin et al., 2012
Lack of integrated/cross-sectoral planning	Inadequate contact between officials/units across sectors (Storbjörk, 2010).	Amundsen et al., 2010
Lack of stakeholder consideration	Opposing views/erosion of trust enabled the Rotterdam “Water Plaza” cancellation.	Biesbroek et al., 2014
Decision-Making Barriers		
Stakeholder fear/distrust	Aboriginal communities fear views are not adequately considered.	McNamara et al., 2012, p. 12
Focus on historical trends	Cities without historical experience of impacts are less likely to adapt.	Amundsen et al., 2010; Storbjörk, 2010
Conflicting climate information/decision-making timescales	“Changes in the climate system and...impacts are difficult to relate to the dynamism of societal changes and short-termism in decision-making.”	Biesbroek et al. 2011: 4
Perceived opposition	Insufficient public support for adaptation.	Jantarasami et al., 2010
Previous conflicts	“Actors interpret...events that happened in previous projects...as priors to other decision-making processes”	Biesbroek et al., 2014, p. 114
Safety/public health	Drowning concerns regarding the Rotterdam	Biesbroek et al., 2014

concerns	"Water Plaza".	
Institutional Barriers		
Biesbroek et al., 2011; Eisenack et al., 2014; Ekstrom and Moser, 2014; Jantarasami et al., 2010; Jones and Boyd, 2011; Moser and Ekstrom, 2010		
Uncertain/unclear roles/responsibilities	Administrative re-organization split erosion management creating confusing/hindering action	Amundsen et al., 2010; Biesbroek et al., 2011
Fragmentation/un-coordination	Deficit of connection/coordination of institutions/organizations/individuals/policies (Biesbroek et al., 2011 p. 6).	Biesbroek et al., 2013; Evans et al., 2012
Void (Lack of leadership/unclear guidance)	Deficit of institutions enabling/facilitating/stimulating adaptation (Biesbroek et al., 2011, p. 5).	Ekstrom and Moser, 2014; Moser and Ekstrom, 2010; Storbjörk, 2010
Risk-aversion	Gendered risk perceptions enabled reluctance to accept aid (Jones and Boyd, 2011).	Porter et al., 2015
Operating procedures	Moving/reintroducing populations go against U.S. National Park Service operating procedures (Jantarasami et al., 2010).	Storbjörk, 2010
Cultural/Social Barriers		
Attitudinal	Opting to wait-and-see/inaction due to hurt political interests (Ekstrom and Moser, 2014).	Eisenack et al., 2014; Porter et al., 2015
Socially constructed gender/race/ethnicity /class/caste barriers	Limited political power/land access increased Janajati caste member's vulnerability to flooding.	Jones and Boyd 2011
Legal Barriers		
External environmental laws	Some land managers feel the U.S. Endangered Species Act hinders options.	Jantarasami, Lawler, and Thomas 2010
Outdated management plans	Inadequate Murray-Darling Basin water-sharing inter-flood interval guidelines.	Jenkins et al., 2012
Land ownership mosaic	Ownership of land alters the governance of land.	Jantarasami, Lawler, and Thomas 2010: 8
Financial/Economical Barriers	Dalit caste members lack access to loans/assistance (Jones and Boyd, 2011).	Amundsen et al., 2010; Eisenack et al., 2014; Moser and Ekstrom, 2010
Market barriers	Global market integration creates costs.	Evans et al., 2012
Technological Barriers	Some technologically advanced options may be beyond planner's knowledge creating uncertainty (Amundsen et al., 2010).	Jones and Boyd, 2011
Political Barriers	Elected officials may delay adaptation because of costs/complexities/perceived consequences (Eisenack et al., 2014).	Amundsen et al., 2010; Ekstrom and Moser, 2014; Moser and Ekstrom, 2010

4. Adaptation constraints within coupled systems: The U.S. Energy-Water Nexus

Energy and water systems are inextricably linked. Most forms of energy production need water, and water distribution and treatment is dependent on access to available and affordable energy

(Goldstein et al., 2008). The U.S.-EWN is complex and spatially varied, with distinct regional differences (Tidwell et al., 2014a, 2013) that are dependent on multiple factors including: energy demand and production, water demand and supply, population density, use characteristics, energy fuels, infrastructure, biophysical characteristics, policies, regulations, and management practices (Tidwell et al., 2013). U.S.-EWN connections demonstrate the complicated nature of coupled systems and highlight the need to pursue adaptation holistically.

Adaptation constraints within the U.S.-EWN are seemingly endless and can easily become over-contextualized. This paper does not attempt to identify every adaptation constraint in the U.S.-EWN. Rather, this paper concentrates on constraints that are present across, or emerge from, the U.S.-EWN. In other words, constraints attributed to the interaction of systems. This focus aligns with the current call within adaptation literature to move towards generalized approaches that produce outcomes across cases to better inform adaptation (Biesbroek et al., 2013; Eisenack et al., 2014; Ekstrom and Moser, 2014; Moser and Ekstrom, 2010; Moser, 2009). *General adaptation constraints* are present across systems, are difficult to solve at local or regional scales, and require multilevel governance approaches to overcome. When overcome, general adaptation constraints can potentially eliminate multiple context-specific constraints and enable adaptation decisions in energy, water, urban and agriculture systems. Three general adaptation constraints prominent in the U.S.-EWN are discussed next.

4.1 Insufficient data and information

Data and information needs are frequently highlighted as constraints to adaptation (see Table 2), emphasizing a broad need for information across systems. Insufficient data constraints within the U.S.-EWN involve missing, unconsolidated, conflicting, uncertain, proprietary, and confidential data challenges (Goldstein et al., 2008; Hussey and Pittock, 2012; Macknick et al., 2011; Tidwell et al., 2014b; U.S. D.O.E., 2014, 2011). Hussey and Pittock (2012) note that nearly all articles in a EWN special issue of *Ecology and Society* cite data issues as major impediments to research and decision-making. Additionally, Stillwell et al. (2011) and Perrone et al. (2011) identify data barriers as their largest obstacle for EWN studies in the state of Texas and the city of Tucson.

Data gaps exist across the U.S.-EWN particularly regarding water consumption, energy use in water services, hydraulic fracturing, saline and brackish aquifers, stream flow, annual/monthly time series water demand, and hydropower operation; as well as population, industry, agriculture, climate, environment, and energy projections (U.S. D.O.E., 2014). Many public U.S.-EWN data are difficult to integrate because data are typically collected by an agency for a specific purpose, and are often outdated, aggregated, or unstandardized (Goldstein et al., 2008; Perrone et al., 2011). For example, the U.S. Energy Information Administration (EIA) relies on power plants to report water use without providing reporting standards. These data are incomplete, inaccurate (GAO, 2009a), and do not correlate with calculations, particularly at regional levels, largely due to unreported and low-quality data (e.g. standard water use recording mechanisms are not required; estimates are used when data are lacking but no estimation methodology is used/documented; combinations of fuel/cooling technologies are unaccounted for) (Averyt et al., 2013). Additionally, certain fuel technologies, cooling systems, and combinations thereof lack adequate water use calculation methodologies (Macknick et al., 2011). The inclusion of these data into models increases uncertainty, and may be counterproductive, particularly at local and regional scales.

Sharing data across the U.S.-EWN has complex human dimensions. First, difficulties arise due to the proprietary and confidential nature of some data (Goldstein et al., 2008; U.S. D.O.E., 2014). For

example, reservoir data are necessary for basin-scale models, but these data are often classified or inaccessible (U.S. D.O.E., 2014). Additionally, some consulting companies hinder data sharing across the U.S.-EWN by claiming ownership over information, some of which is explicitly public (Goldstein et al., 2008). Competing interests also stall data sharing – many water sector stakeholders believe that sharing pumping and storage data creates disadvantages when negotiating with other water providers (Goldstein et al., 2008). When data are shared, it is often via personal relationships on a case-by-case basis (Goldstein et al., 2008). These practices reinforce existing affiliations and conflicts within the U.S.-EWN and inhibit research, model development, and the creation of information for decision-making.

Information-related constraints within the U.S.-EWN principally relate to the production and utilization of information. While a proliferation of climate adaptation information is available, this knowledge may be unhelpful when actors require specific information for decision-making (de Bremond et al., 2014; Nordgren et al., 2016). Typically, adaptation information is organized by sector in assessment reports focused on hazard descriptions and their potential consequences that are then funneled to decision-makers (Cash and Moser, 2000; de Bremond et al., 2014; Nordgren et al., 2016). Sorting through this uncoordinated information and finding much of it un-useful for specific decisions may hinder adaptation action (Nordgren et al., 2016). Additionally, evidence suggests that the “models, tools and methods developed by the research community have either not sufficiently evolved or have not been effectively delivered to guide adaptation” (Preston, 2013; de Bremond et al., 2014; Klein and Juhola, 2014; Preston et al., 2015a, p. 482). Conventionally, climate information research assumes that translation for decision-making is unnecessary because information is “useful and usable” (Dilling and Lemos, 2011, p. 682); however, in practice, conceptual divides between stakeholders and researchers exist and can hinder understanding (Feldman and Ingram, 2009; Meerow and Stults, 2016). For example, adaptation research prioritizes vulnerability assessments or general plans; whereas energy stakeholders want information that incorporates specific needs and multiple potential factors, driving forces and policy responses at decision-relevant scales to be actionable (de Bremond et al., 2014; Nordgren et al., 2016). Without these elements of utility, the decision-maker will not utilize the information.

4.2 Path Dependence

Path dependence, defined as “the dependence of future societal decision processes and/or socio-ecological outcomes on those that have occurred in the past” (Preston, 2013), is a key process influencing adaptation (Klein et al., 2014). U.S.-EWN stakeholders often favor decisions that create path dependence like investing in large, long-term infrastructures, and technical and engineering-based solutions (de Bremond et al., 2014). Alternatively, flexible and low-regrets measures like wetlands conservation, floodplain restoration, energy-efficient water systems, water-efficient energy systems, and sewerage-sourced power systems are often overlooked because they are typically less familiar and perceived constraints hinder implementation (Pittock, 2011). For example, in de Bremond et al. (2014), southeastern U.S. energy stakeholders prioritized incremental upgrades and expansions of infrastructure while ecosystem-based options and transformational adaptations were avoided.

Continued reliance on water-intensive thermoelectric generation (Scott et al., 2011; Sovacool and Sovacool, 2009) exacerbates constraints across the U.S.-EWN and hinders adaptation. This path could create “tradeoffs between the water needed to cool new power plants and the water needed for drinking, irrigation, fisheries, and agriculture” (Sovacool and Sovacool, 2009, p. 2771). For example, recent fuel changes have occurred in the U.S. energy sector in partial response to swift natural gas development and a focus on curtailing carbon dioxide (CO₂) emissions (U.S. D.O.E., 2014). While these

changes may result in fewer CO₂ emissions, they could also increase other GHG emissions and constrain water supplies. Some low-carbon technologies like pulverized coal with carbon capture, concentrated solar power, and nuclear power consume large amounts of water (Macknick et al., 2011; Tidwell et al., 2013). These technologies reinforce the need to consider the water implications of adaptive strategies within the energy system.

Some U.S.-EWN constraints could be avoided by overcoming path dependence in water allocation systems. The arid western U.S. is highly adapted to support agriculture with infrastructures and institutions in place that support irrigation based on past economic and climate conditions (Libecap, 2010). Some of these systems encourage inefficient water use (U.S. D.O.E., 2014) and are ineffective in light of diversifying demands and uncertain supplies (Libecap, 2010). Additionally, path dependence to cheap freshwater withdrawals persists (Sanders, 2015) making it an attractive source for thermoelectric cooling even though using multiple water sources could decrease the percentage of western U.S. watersheds with projected water use exceeding total water availability from 61% to 8% (Tidwell et al., 2014b). Path dependence, by definition, is difficult to overcome and requires institutional coordination; however, U.S.-EWN institutions are fragmented and disorganized.

4.3 Fragmented and disorganized institutions

Often cited as an adaptation constraint, the fragmentation and disorganization of institutions within the U.S.-EWN creates numerous constraints at local and regional institutional, jurisdictional, management, and economic scales. Generally, U.S. energy and water sectors are regulated and managed independently, with research and interest regarding the U.S.-EWN growing over the past decade (Bazilian et al., 2011; Hussey and Pittock, 2012; Stillwell et al., 2011; U.S. D.O.E., 2014, 2006). U.S.-EWN decision-making takes different forms across policy frameworks which creates inconsistent legislation and inadequate implementation, information, and integration across institutions (Hussey and Pittock, 2012). These institutional inconsistencies exacerbate information-related constraints and enable the proliferation of uncoordinated information across institutions (Averyt et al., 2013; GAO, 2009b; Goldstein et al., 2008; Perrone et al., 2011). The complex institutional environment of the U.S.-EWN is concerning because, for many stakeholders, adaptations are most influenced by policy, governance, and shifting demands – not climate change (de Bremond et al., 2014). Additionally, institutional inconsistencies enhance stakeholder uncertainty (de Bremond et al., 2014), which reinforces path dependence because stakeholders with little institutional guidance on adaptation outcomes typically rely on pre-existing methods and plans (Patt et al., 2010). For example, the concept stationarity was declared “dead” within water management (Milly et al., 2008), but an alternative has yet to be widely accepted so it remains (Lins and Cohn, 2011; Marlow et al., 2013). Therefore, institutional complexity, path dependence, and information-related constraints are tightly coupled constraints making them particularly pervasive.

The often-unique structure of the U.S.-EWN muddles adaptation planning, especially regarding who has the authority and resources to make decisions. U.S.-EWN management occurs across scales from the local level to river basins and larger, crossing multiple administrative, jurisdictional, and institutional boundaries leading to territorial mismatches at administrative and physical levels (Goldstein et al., 2008; Perrone et al., 2011; Preston et al., 2015; Scott et al., 2011). Efforts to integrate U.S.-EWN planning has been limited with no coordinated federal or state approach (Hussey and Pittock, 2012; Sovacool and Sovacool, 2009).

When U.S.-EWN decision-making is fragmented, externalities may increase one sector’s efficiency while creating demand in another (Hussey and Pittock, 2012). Consider the following projected U.S.

energy sector changes. First, primary generation fuels are shifting away from coal and towards natural gas (60% of added capacity), renewable energy (29%), and nuclear energy (four plants totaling 8%) (U.S. D.O.E., 2014). Second, Section 316(B) of the Clean Water Act, implemented in May 2014, requires that water intake technologies at power facilities represent the “best technology available” (U.S. E.P.A., 2014). While dry-cooling and hybrid systems are possibilities, their cost and efficiency create adoption barriers (Macknick et al., 2011; Sanders, 2015; Tidwell et al., 2014a, 2014b). Therefore, most water intake technologies will be recirculating systems, which withdraw less, but consume more water than the once-through systems they are replacing (Macknick et al., 2011; Sanders, 2015; Tidwell and Pebbles, 2015; U.S. D.O.E., 2014). Third, new power plants will use a greater variety of water sources compared to existing systems, which mostly use surface water (75%) – 30% of planned power plants will use groundwater sources as compared to 13% of existing systems (U.S. D.O.E., 2014).

From the perspective of the energy sector, these changes reduce vulnerability (de Bremond et al., 2014; Tidwell et al., 2014a), decrease CO₂ emissions, and lessen impacts on aquatic species (U.S. D.O.E., 2014); however, they create externalities in related systems. These changes are particularly concerning in the southeastern U.S. because: primary generation fuels are moving towards natural gas and water-intensive nuclear power; thermoelectric cooling systems increasingly utilize groundwater (U.S. D.O.E., 2014); and thermoelectric cooling technology changes occurring mostly in the eastern U.S. will double the amount of water used at most plants (Macknick et al., 2011). These modifications are additionally coupled with increasing population and increasing hot and dry days further constraining water supplies and leading to less efficient energy and water systems. The projected changes in the southeastern U.S. will create externalities in water and land systems that are difficult to examine without a holistic consideration of related systems.

5. Discussion

Adaptation within the U.S.-EWN is necessary to avoid adverse climate change consequences. However, constraints to U.S.-EWN adaptation exist. Additionally, change-enabling elements are absent: adverse impacts occur disparately across the nexus (Sovacool and Sovacool, 2009) complicating who should adapt; climate-related vulnerabilities remain unseen for decision-makers that utilize historic information for planning (Bazilian et al., 2011); and even when vulnerabilities are acknowledged, decision-makers are unlikely to respond to climate trends – rather, policy, regulatory, or economic changes enable adaptation (de Bremond et al., 2014). However, adaptation may appear unnecessary before 2050 if economics are the primary decision-making criteria (Adger et al., 2005; O’Neill and Handmer, 2012; Preston, 2013). These factors, aided by path dependence, create systems unlikely to change without regulatory or policy reform.

Reform will be most effective from the top down, led by national (i.e., federal) action. The U.S.-EWN is rife with well-documented vulnerabilities, and dependent on inefficient paths and adaptations initiated in the context of stationarity (Hussey and Pittock, 2012; Libecap, 2010; Perrone et al., 2011; Pittock, 2011; Sanders, 2015; Scott et al., 2011; Sovacool and Sovacool, 2009; Stillwell et al., 2011; Tidwell et al., 2014b; U.S. D.O.E., 2006, 2014). These elements describe the conditions for transformational adaptation: “large vulnerability...and severe climate change that threatens to overwhelm even robust human-environment systems” (Kates et al., 2012, p. 7158). However, national-level U.S.-EWN reform will require huge investments in thoroughly planned infrastructures and the overhauling of institutions to focus on multisystem holistic adaptation. These transformations are unlikely in the current U.S. national governance context.

Absent national-level leadership, U.S.-EWN adaptation will occur at smaller scales, within discrete systems, and will therefore be less efficient and effective. At best, sub-national U.S.-EWN adaptation will be fragmented, much like U.S. urban adaptation (Bulkeley, 2010). This comparison may be too optimistic, as urban scales have clearer governance structures than the U.S.-EWN (Goldstein et al., 2008; Perrone et al., 2011; Scott et al., 2011). However, sub-national opportunities exist. A first step could be addressing the constraints mentioned previously. First, the availability and quality (collection, geolocation, methodologies) of relevant U.S.-EWN data needs improvement (Averyt et al., 2013; Macknick et al., 2011). Additionally, more hydropower, hydraulic fracturing, water demand/availability, and system resource consumption data is needed (U.S. D.O.E., 2014). Third, researchers and stakeholders should be able to access and analyze U.S.-EWN data alongside projections of decision-relevant systems and scales.

Next, efforts should focus on creating and disseminating actionable information. Actionable information needs: human agency (includes specific stakeholder needs/perspectives/context); should be useful at decision-relevant scales; and must incorporate multiple factors, driving forces, and policy options (de Bremond et al., 2014). Stakeholder engagement and participation is essential to create actionable information (Bierbaum et al., 2013; de Bremond et al., 2014; Liu et al., 2008). This engagement should be integrated across development stages (Bierbaum et al., 2013) so information is iteratively co-produced and customized (de Bremond et al., 2014; Lemos et al., 2012). Information should be credible, legitimate (understandable/transparent), and salient (contextually relevant) to be effective (Cash et al., 2003). These attributes are prioritized through “boundary management” which requires communication (inclusive/frequent/two-way), translation (shared terminology/criteria for credibility), and mediation (multiple perspectives, transparency, rules of conduct/decision-making) (Cash et al., 2003; Feldman and Ingram, 2009; Liu et al., 2008; Tribbia and Moser, 2008). In order for these efforts to be effective and scalable, funding agencies and institutions must support analyses, timelines, and outcomes that create and utilize actionable information (O’Brien, 2012; Preston et al., 2015b).

Actionable information is essential to holistic adaptation, but it is not a panacea to constraints. Rather, it is most beneficial in systems that have consistent and coordinated institutions and funding (Nordgren et al., 2016; Porter et al., 2015). However, U.S.-EWN institutions are uncoordinated, and funding levels vary across the nexus (Hussey and Pittock, 2012; Scott et al., 2011; Sovacool and Sovacool, 2009). Integrated, multisystem planning is ideal when efforts involve new infrastructures or increased resource consumption to explore synergistic technologies or locations. Regional Transmission Organizations, state utility commissioners, or state environmental and energy offices could coordinate integrated planning efforts at decision-relevant scales (Tidwell and Pebbles, 2015). Multisystem efforts could occur in proactive regions, but integrated planning is unlikely throughout the U.S.-EWN without national-level coordination (Bierbaum et al., 2013).

Single-system holistic adaptation may occur quicker than multisystem efforts because sector-specific adaptation information and planning is prevalent (Adger et al., 2005; Mimura et al., 2014; Nordgren et al., 2016). Single-systems should prioritize increasing resilience and flexibility through conservation, efficiency, and ecosystem restoration (Pittock, 2011); pursuing low-water energy fuels, locations outside stressed watersheds, or alternative thermoelectric cooling systems (especially in eight percent of western U.S. watersheds that are severely water-constrained) (Tidwell et al., 2014b); and considering related resources (Tidwell and Pebbles, 2015) and systems early enough to avoid constraints. In accordance with holistic adaptation, all single-system adaptations should avoid dependence pathways by neither exacerbating climate change nor limiting future adaptation options.

6. Conclusions

Considering coupled systems in adaptation is essential as multiple emerging threats are encountered, not only climate change (Klein et al., 2014), and as adaptation progresses from planning to implementation (Mimura et al., 2014; Woodruff and Stults, 2016). Examples of adaptation actions highlight the considerable effort actors undertake to overcome constraints: grants are combined to create the longevity needed for successful knowledge co-production (Bartels et al., 2013); adaptation actions depend on a champion actor (Porter et al., 2015), and most adaptation actors come from well-resourced locales (Hughes, 2015). Currently, the little adaptation implementation that occurs happens autonomously, often in response to previously experienced impacts (Klein et al., 2014; Mimura et al., 2014). Prioritizing holistic adaptation now before implementation is prevalent may increase synergistic actions and avoid negative consequences in related systems. These lessons apply beyond the U.S. – developed countries could focus on efficient multisystem transitions, while developing countries have the opportunity to avoid committing to unsustainable system-level pathways.

Challenges to holistic adaptation exist. Divides between researchers and stakeholders (Feldman and Ingram, 2009; Meerow and Stults, 2016) and intellectual and institutional path dependence keep adaptation information and planning either too general or sector-specific (Amundsen et al., 2010; Nordgren et al., 2016; Storbjörk, 2010). Additionally, diverse and disparate physical, jurisdictional, administrative, and institutional scales complicate analyses and planning (Goldstein et al., 2008; Perrone et al., 2011; Scott et al., 2011). Also, the approach and availability of funding for adaptation generally, and multisystem adaptation specifically is unclear (Nordgren et al., 2016; Porter et al., 2015). These obstacles must be overcome for holistic adaptation to succeed beyond well-resourced systems with motivated actors (Bartels et al., 2013; Hughes, 2015; Porter et al., 2015; Tribbia and Moser, 2008).

Notable gaps in the literature include uncovering essential elements of actionable information, understanding how researchers influence actionable information, and analyzing multisystem adaptation options with generalizable methods that include information on costs, benefits, and impacts on related systems across scales. Future research should address the aforementioned gaps and additionally focus on analyzing multisystem adaptation efforts at sub-national scales, identifying opportunities to improve researcher and stakeholder interactions, and assessing adaptation options based on flexibility and dynamism to minimize path dependence.

Adapting energy systems to climate change without considering water systems and vice versa creates unseen consequences that make achieving even modest adaptation objectives difficult. Holistic adaptation – adaptation concerning complete systems – is presented as a path forward to maximize benefits and minimize costs of adaptation actions. Failure to adopt a holistic approach to adaptation reinforces the focus of adaptation benefits on a single system and displaces costs that may exacerbate climate change and its consequences onto related systems.

VITAE

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