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Review

Resilience of Interdependent Water and Power Systems: A Literature Review and Conceptual Modeling Framework

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Abstract: As increasing pressures of population growth and climate change arise, water and power systems (WPS) are becoming increasingly interdependent. This interdependency has resulted in an increased potential for cascading failures, whereby the service interruption of one system can propagate to interdependent ones. This paper makes four contributions. First, we present an extensive literature review in the field of integrated water and power resilience, leveraging both institutional and technical literature research landscapes. We compare various modeling approaches used to model interdependent WPS and discuss the different metrics and definitions that are typically employed to quantify and define resilience. Relevant challenges and gaps related to modeling tools and metrics are also discussed, and appropriate recommendations are made. Second, the paper presents a visualization prototype for interdependent WPS to showcase water and power system interdependencies and reveal co-managed resilience strategies that can be used to improve resilience under different types of common threats. Third, we provide a conceptual decision support framework that simultaneously optimizes a portfolio of co-managed resilience strategies in the face of multiple, uncertain threats and addresses WPS interdependencies. Finally, we present future trends regarding digitalization, integrated planning, collaborative governance, and equity needs for building more resilient WPS.

Keywords: integrated water and power resilience; resilience metrics; modeling tools; resilience framework; visualization prototype

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1. Introduction

Decision-support tools, increased collaboration, and targeted research are needed to improve the resilience of the nation's water supply and power systems. The interdependencies between water and power systems (WPS) are well-documented [1]: energy is used in a wide range of processes delivering water (e.g., water heating, drinking water treatment, center-pivot irrigation), and water is withdrawn or consumed for many energy-related processes (e.g., thermoelectric cooling, hydropower, oil and gas extraction). Much of the past and current research on the energy–water nexus focuses on opportunities to reduce operating costs [2], improve efficiency and reliability [3], and reduce environmental impacts [4] by accounting for these interdependencies. Recently, however, the concept of resilience has become an objective in the water and power sectors, as a wide range of compounding influences, such as increasing populations, aging infrastructure, cybersecurity threats, and climate change, increasingly threaten the ability of WPS to persist and continue to provide essential goods and services with acceptable levels of reliability and cost over the long term.

Although separate resilience research efforts have been or are underway in the water and power sectors [5,6], the interdependence of WPS presents opportunities for achieving higher levels of resilience at lower cost through economies of scale, shared investments, and potentially through the identification of new "win-win" resilience strategies designed with both sectors in mind. For example, water reuse is a resilience strategy that applies to both the energy sector for cooling thermoelectric power plants and the water sector for human applications in regions facing water shortages. The concept of co-managing water and power for resilience has been discussed in both sectors, and key challenges and opportunities have been identified [7], but widespread progress and standardization of common practices have yet to be made.

A literature review may provide insights as to why progress in this area has been slow. Co-managing resilience in the water and power sectors is extremely complex, not only because it is a multisector problem, but also because it is a multiscale challenge, spanning engineering, operational, and investment decision timescales (e.g., minutes or hours to many years), in addition to physical and spatial scales (e.g., plant, utility, interconnection) [8]. For example, water system dynamics that occur over the power grid spatial domain have temporal scales spanning from hours to multiple years. This could result in the inaccurate matching of service interactions with respect to time and system state, such as matching power consumption (in watts) to water consumption (in liters) [8]. Similarly, resilience hazards manifest at multiple temporal scales, e.g., in the order of minutes (cybersecurity events), days (floods, cold and heat waves), weeks to months (droughts), and years (hydrological droughts), and can propagate across different spatial scales. Resilience strategies can also be deployed and evaluated at multiple scales spanning from local (e.g., plant-level or microgrids) to interstate (e.g., transmission line hardening) solutions. In addition, existing institutional structures within each industry perpetuate siloed planning processes and management strategies. Indeed, each sector has its own core statutes and regulatory agencies that enforce them. Even in countries or municipalities where water and power utilities may more easily forge cross-sector relationships (e.g., countries in the Gulf Cooperative Council), planning for resilience will still require enhanced coordination to strategize resilience improvements against potential investment costs. These are some of the underlying reasons why no planning framework exists through which the sectors can coordinate.

This paper provides an extensive literature review in the field of integrated WPS resilience studies to define critical and increasingly relevant research areas around the resilience of interdependent infrastructures. This review sheds light on the current treatment of integrated WPS resilience, predominantly related to U.S. efforts, leveraging studies from the institutional and technical literature research landscape. The paper compares various state-of-the-art modeling approaches used to model interdependent WPS and discusses the different metrics and definitions that are typically employed to quantify and define resilience. In addition, we discuss challenges and gaps related to modeling and metrics of interdependent WPS and make relevant recommendations. Furthermore, we develop a visualization prototype for interdependent WPS to showcase water and power system interdependencies and reveal co-managed opportunities between water and power utilities to face common threats. We also present a conceptual decision support framework for co-management of resilience as a means of optimizing a portfolio of resilience strategies in the face of multiple, uncertain threats and while addressing the interactions between the sectors. The proposed modeling framework aims to provide a foundation for a more extensive analysis of integrated WPS resilience opportunities and increase the awareness of the broader scientific community. Finally, we present future trends regarding digitalization, integrated planning, cybersecurity, and collaborative governance and equity considerations for building resilient WPS.

2. Literature Reviews

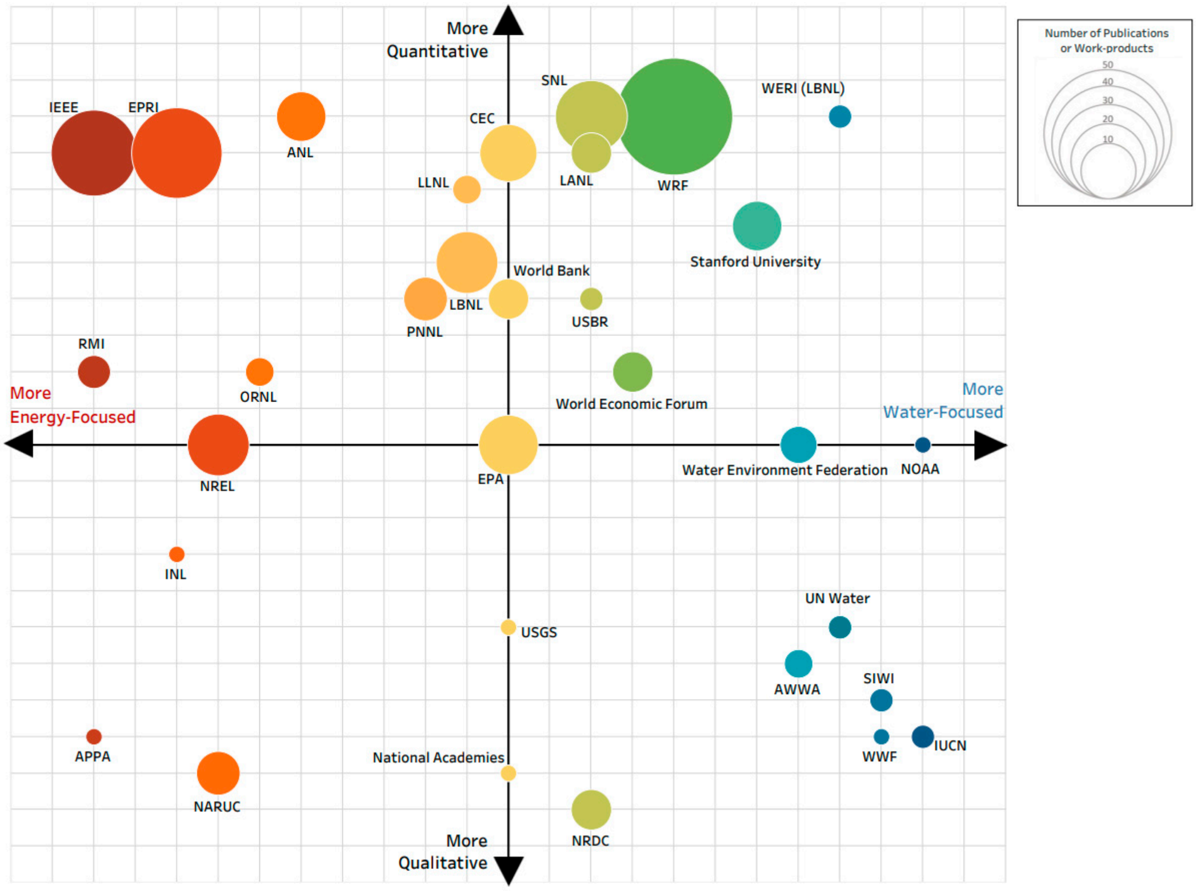
2.1. Institutional Landscape Assessment

To better understand today's landscape of water–energy interconnection and resilience research, we searched for technical reports, projects, and other grey literature to find common research and publication themes. This review included looking at technical reports within the national laboratory space (U.S. Department of Energy [DOE]-funded), and a broad range of institutions external to U.S. DOE that have investigated issues related to the intersection of water, energy, and resiliency. Only items published within the last ten years were documented, subject to publication date availability. Themes that consistently appeared on the topic of water and energy included disaster analysis and climate change, water-energy opportunities and tradeoffs, and water resource planning. The number of publications, projects, or initiatives by these institutions in each of these topics was accounted for, in addition to information on the methods utilized to answer their research questions. Documents or projects that appeared in the search were reviewed, and those with no relevance to water and energy were not included in the total.

For the national laboratory search, we surveyed the U.S. DOE Office of Scientific and Technical Information database of DOE-funded technical reports under key words related to water and energy and their interconnections, such as "water energy nexus." This search resulted in approximately 100 technical reports covering a broad variety of topics related to water and energy. Most technical reports by national laboratories were found to focus on the topics of environmental sciences; energy planning, policy, and economy; energy conservation, consumption, and utilization; and climate change.

To obtain information outside the national laboratory sphere, a landscape assessment was conducted across 30 external institutions. Institutions included were those that came up in searches with high frequency or those cited often by other institutions. These included government agencies (e.g., U.S. Environmental Protection Agency [EPA]); private research foundations and think tanks (e.g., Water Research Foundation [WRF], Climate Resilience Center); and universities (e.g., Stanford University). It is worth noting that, although the final list of institutions included both international and U.S.-based organizations, those most frequently appearing in searches were often in the latter group. Although we have included a variety of international institutions in our literature review, additional institutions could expand our knowledge of the research coverage in the water–energy space and provide new insights. Future research looking into these sources may shed more light on country-specific treatment of the water–energy nexus due to the regulatory and spatial differences resulting from the different policy, climate, geography, and operation conditions. For the complete list of external institutions used in this paper and related references with links to the institutions, please see Table S1 of the Supplementary Materials.

Figure 1 demonstrates our literature review results and provides an overview of whether a significant amount of the water–energy nexus research found in the literature is mostly quantitatively- or qualitatively-focused and whether that research is predominantly water- or energy-oriented. More specifically, Figure 1 presents a quadrant graph of both the national laboratory and external institution research in the water–energy space. Based on the information gathered, the graph demonstrates the extent of an institution's focus on energy versus water research (left to right) and the extent to which their research is more focused on qualitative versus quantitative assessments (bottom to top). For example, a dot placed on the far right of the graph indicates that the institute had a research product that was predominantly water-focused (e.g., water treatment) and covered only a few energy-related topics. Institutions in the middle were found to study water and energy in equal measure or had a research product that simultaneously considered both and/or their relationship. An institution near the bottom of the chart focused its research on discussion, literature review, or similar with little to no experimental, analytical, or computational approaches. A dot at the top of the figure indicates the use of quantitative analysis in the research. The size of the dots indicates the quantity of publications found related to that institution's water–energy space. Thus, Figure 1 provides insight into where research appears to be aggregating—quantitative vs. qualitative and energy focused vs. water-focused—providing a broad perspective of how research is distributed across the water–energy space and identifying relevant research gaps. Based on the institutional landscape overview, more work products focus on quantitative analysis than qualitative. Additionally, although institutions in the research space were found to be evenly distributed between energy and water spaces in overall placement, fewer institutions were found to have balanced research coverage internally, i.e., reside away from the middle of the quadrant graph as opposed to left or right. This result shows that although there may be good coverage of water or energy topics individually, fewer institutions consider them jointly or evenly. This finding appears to be especially true in the qualitative research (i.e., lower half) part of the figure, indicating that fewer institutions are leading discussions, panels or promoting policies addressing water-energy interdependencies. Institutions that appear closer to the middle include U.S. EPA, World Bank, the California Energy Commission (CEC), U.S. Geological Survey (U.S.G.S), and the National Academies.



Acronyms: Argonne National Laboratory (ANL); American Public Power Association (APPA); American Water Works Association (AWWA); California Energy Commission (CEC); U.S. Environmental Protection Agency (EPA); Electric Power Research Institute (EPRI); Institute of Electrical and Electronics Engineers (IEEE); Idaho National Laboratory (INL); International Union for Conservation of Nature (IUCN); Los Alamos National Laboratory (LANL);Lawrence Berkeley National Laboratory (LBNL); Lawrence Livermore National Laboratory (LLNL); National Association of Regulatory Utility Commissioners (NARUC); National Oceanic and Atmospheric Administration (NOAA); Natural Resources Defense Council (NRDC); National Rural Electric Cooperative Association (NRECA); National Renewable Energy Laboratory (NREL); Oak Ridge National Laboratory (ORNL); Pacific Northwest National Laboratory (PNNL); Stockholm International Water Institute (SIWI); Sandia National Laboratories (SNL); United Nations (UN); U.S .Army Corps of Engineers (USACE); U.S. Bureau of Reclamation (USBR); Water Energy Resiliency Institute (WERI); Water Research Foundation (WRF); Water Utility Climate Alliance (WUCA); World Wildlife Fund (WWF)

Figure 1. Coverage of the water–energy research sphere based on institutional landscape assessment results.

Figure 2 below expands on Figure 1 and shows the literature broken down by topic and source. Data was gathered on whether an institution was found to have at least one work product or publication on a given topic. Figure 2 shows which topics are covered with the highest frequency (disaster analysis, climate change, water resource planning, and water use efficiency) and the lowest frequency (national security and other nexus linkages) by the institutions included in the search. Figure 2 shows that a small number of institutions covered a broad range of topics, such as the Water Environment Federation and the Electric Power Research Institute (EPRI). Both institutions had work products on nine of the topics included in the list, whereas others were more focused on particular topics in this research space.

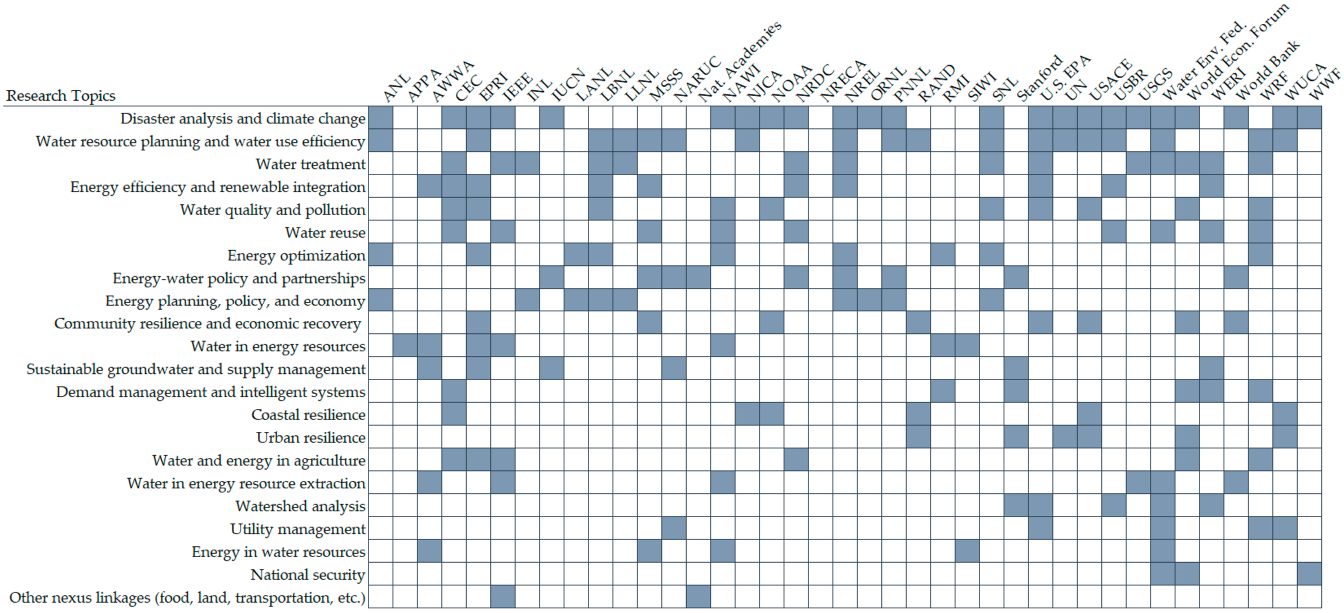


Figure 2. Research topic coverage by institution.

Additional takeaways from the institutional landscape assessment include:

- As indicated by the breakdown in topic coverage, nearly two-thirds of the institutions included in the investigation had a work product that revolved around disaster analysis or climate change assessment.
- There is considerable coverage of water-focused research across the external institutions, looking at topics from water resource planning, water reuse, water treatment, water quality, and water in energy resources specifically, each of which appeared in 23–40% of all external institutions identified in the search for water and energy projects and reports.
- When looking at the breadth and depth of research in the water, water resiliency, and water–energy nexus space, the WRF stood out as one of the more prevalent institutions with regards to both the number of publications and the variety of topics [9–13].
- The U.S. EPA was found to have a substantial amount of research broken out among different programs, such as human health and climate change [14] and water and climate change [15]. They were also one of the few institutions found to have research more evenly balanced between energy- and water-related topics.
- National laboratories, although consistently conducting more quantitative-based research, typically focus on the topic from an energy perspective as opposed to a water perspective compared to other institutions.
- Many publications or work products of the institutions discussing climate change were related to planning: water utility planning, water supply planning, infrastructure planning, and risk assessments. A few examples include WRF [12], EPA [16], and [17].
- There does not appear to be a significant amount of research by national labs or external institutions in recent years on the topics of water recovery, desalination, multi-jurisdictional analyses, or regulatory policy and assessment.
- Although there is decent coverage of water or energy topics overall, fewer institutions study them jointly or evenly. This finding appears to be especially true regarding qualitative research, indicating that there are fewer institutions leading discussions, panels, or promoting policies addressing water–energy interdependencies.

Overall, the institutional landscape assessment revealed both the depth and breadth of research currently conducted in the energy–water space, who is conducting most of that research, and the gaps that are yet to be filled.

2.2. Literature Review of Resilience Definitions and Metrics

We performed a review of the peer-reviewed literature regarding resilience definitions and metrics. The concept of resilience first emerged within the field of ecology [18] and has subsequently been adopted in many domains, including infrastructure planning [19] and operations [20]. Most of the resilience definitions originate from [18], which defined resilience as a system's ability to persist over time with the same basic structure. The concept was later expanded to include the ability of the system to face and adapt to changes after a disruption [21,22]. More recently, resilience is defined as the combined ability of a system to resist (prevent and withstand) any possible hazards, absorb the initial damage, and recover to normal operations [20]. In such a view, resilience is a multifaceted capability that encompasses avoiding, absorbing, adapting to, and recovering from disruptions. For our research, we identify three main types of capacity for resilience: absorptive, restorative, and adaptive [23]:

- Absorptive capacity is the ability of the system to absorb the impact of the disruptive event and, hence, minimize the system damage/disruption.
- Restorative capacity is the ability of the system to rapidly recover to normal or satisfactory functionality with minimal effort (e.g., cost, time).
- Adaptive capacity is the ability to learn from disruptive events and modify system operations, configurations, functions, and system planning to enhance future absorptive and/or restorative capacity.

Each of these system capacities represents a different temporal resilience phase, which are often visualized through the disturbance and impact resilience evaluation (DIRE) curve [24] that can vary in shape (linear, exponential, or trigonometric).

From a systems interdependency perspective, however, defining resilience is an ongoing challenge [25]. Even though interdependencies can improve the efficiency of network functionality, this type of complex coordination may also increase vulnerability to disruptions. For example, as a result of the interdependency, a disruption in some components of one system could lead to a dysfunctionality in the undisrupted components of the other dependent system and could result in a series of cascading failures among the whole infrastructure network system [26]. Interdependencies may also have a significant role in post-disturbance restoration, in which the efficiency of restoration efforts of a system can be substantially affected by the efficiency of the restoration efforts of other systems. Indeed, the co-managed scheduling of restoration strategies could improve the utilization of resources, time, and funds. In this context, the sequence of restoration tasks can be scheduled and optimized by considering these interdependencies among WPS, which can help improve the effectiveness of restoration tasks. Consequently, understanding the level of interconnectedness and interactions between WPS at each resilience stage is a key element towards defining and quantifying resilience.

Several metrics have been proposed to measure the resilience of water and power systems in isolation [27,28]. These metrics reflect different perspectives of various stakeholders and may not yield congruent results when applied to the assessment of the integrated WPS resilience. Examples of these metrics include: (1) time-based system metrics that utilize the area of the DIRE curve to quantify the absolute resilience of the system with respect to each resilience phase (e.g., pre-event, outage, restoration) [24]; these metrics have been tested in a number of infrastructure systems including water distribution systems [29–33], wastewater treatment systems [34–37], and power systems [20,38–40] ; (2) graph theory-based metrics (also referred to as network or topology metrics) that incorporate the system's topology such as the number of nodes and arcs, the average degree of nodes, and the average critical path length [41,42]; (3) probabilistic-based metrics that incorporate the impacts of uncertainties (e.g., component failure) on a system's performance [40,43,44]; and (4) cost-based metrics that quantify resilience based on costs associated with recovering system performance or lost opportunity costs due to system outages [38,45]. Performance measures used in this context are based on asset operability, network connectivity, network capacity, satisfied demand, and the value of services provided [46].

Some recent quantification efforts have focused on developing surrogate metrics that combine characteristics of multiple infrastructure networks, including water and energy. A surrogate metric is proposed in [47] that quantifies resilience as the ratio of the energy required to deliver the design water demands to the total input energy used by the pump stations. In [48], resilience is quantified as the weighted sum of the bus voltage magnitude, transmission lines' thermal limit, thermoelectric cooling water demand satisfaction, water supply-demand satisfaction, and power supply-demand satisfaction. The weights, which are recognized as quantities pertaining to the operation of both water and power systems, are determined through a sensitivity analysis that assesses the effect of each parameter on the overall performance of the power system. In [49], a graph theory-based metric is developed for resilience evaluation of an interdependent network, comprising three key infrastructures of water, energy, and transport. The metric is computed as a function of the number of users (of all interdependent networks) that remain in service, whereas the connection between networks is represented as interdependency links (e.g., distribution lines, water pipelines, roads). A metric is proposed in [50] that quantifies the social vulnerability for a given community as a function of the socio-economic conditions of the community (e.g., population, social group) and is applied to three interdependent infrastructure networks: water, natural gas, and electric power distribution systems.

Surrogate metrics, although they contain interdependent WPS characteristics in their analysis, primarily focus on quantifying the absorptive stage rather than the entire life cycle of disaster events, such as the restorative stage, in which the interdependencies also play a significant role. Therefore, there is a critical need for robust assessment metrics that can assess multisector dynamics at each resilience stage. Moreover, there is a need to investigate whether the impacts on WPS interdependencies vary over different stages of the life cycle of disturbance events. If impacts vary by resilience stage, there is a need to identify and explore different strategies that can be used in WPS decision-making to improve and quantify resilience.

2.3. Modeling Considerations

From a modeling perspective, there is a growing interest in investigating the integrated resilience of coupled water and power systems and of interdependent infrastructures in general [51]. These efforts typically rely on empirically-based approaches that analyze interdependencies according to historical accident or disaster data [52]; agent-based approaches that model the behavior of each system as an agent and track how each agent interacts with other agents and its environment based on a set of rules that help analyze the cascading effects associated with system interdependencies [53]; economic theory approaches that measure the interdependencies among infrastructure sectors by economic relationships [54]; and network-based approaches that model the interdependencies of networks by interlinks, providing intuitive representations along with detailed descriptions of their topologies and flow patterns [55]. The interdependency modeling approaches have also been categorized according to the mathematical method, modeling objective, scale of analysis, quality and quantity of input data, targeted discipline, and end-user type [56].

Each of these approaches has its own strengths and weaknesses. Empirically-based models cannot account for the effects of non-stationarity. Agent-based approaches [53] usually focus on one aspect of the interdependent WPS, such as the electricity consumed by pumping stations. In addition, they do not model dynamic system constraints (e.g., changes of water/energy flows within the arcs and transfer capacity limits) that are attached to the deliverability of services (e.g., water, energy) and can be violated under extreme events. Economic theory-based approaches [54] depend on the choice of the supply and demand functions, which become difficult to validate when the relevant data is scant, especially in cases where system perturbations have a significant impact on some economic sectors. Finally, network-based models [55,57,58], although they capture the topological features of interdependent systems and dynamic interactions, are relatively complex to develop and computationally intensive when applied to large-scale networks.

Existing modeling limitations call for additional research on developing modeling approaches for interdependent WPS. Current modeling practices fail to establish a true co-managed relationship that: (1) captures all types of interdependencies and the level of interconnectedness between WPS relative to different temporal and spatial levels and different physical, economic, and institutional realities; (2) accounts for multiple competing objectives across energy and water stakeholders; (3) simultaneously optimizes a portfolio of resilience strategies to be implemented across one or both sectors in the face of multiple, uncertain threats and addresses the interactions between the strategies over system lifetimes; and (4) allows for modeling multiple threats and their impact on both water and power systems. Therefore, integrated multiscale, multiobjective, and multiuser platforms for integrated modeling and stakeholder coordination are needed to address integrated WPS resilience based on the needs of resource decision makers to understand threat scenarios, their impacts, and the effectiveness of restoration strategies. Thus, additional research is needed to develop co-managed modeling frameworks that can inform multisector entities (e.g., water and power utility operators) about co-design strategies to mitigate the impact of natural and manmade threats on their operations. These optimization frameworks should be able to capture the level of interconnectedness between sectors to reflect performance relative to different temporal (e.g., short-term, seasonal) and spatial (state, regional, national level) levels.

The broader integration of co-managed modeling frameworks would also require exchanging a plethora of equipment status (e.g., level of damage), environmental (e.g., wind, solar, water), and system state (e.g., voltages, pressurized water) information between water and power systems. To achieve such integration, it is crucial to establish appropriate communication protocols that can ensure the reliable and safe exchange of information and data between multisector operators, while handling large amounts of data and translating them into understandable decision actions (e.g., opportunities to provide demand flexibility). Finally, computational complexity typically becomes prohibitive with greater spatiotemporal resolution or increased scope in such co-managed modeling frameworks. Several tradeoffs across data availability, model fidelity, and computational burden are areas in which impact assessment and strategies representations and interactions can and must improve to enhance our understanding of how complex systems co-evolve and to develop robust opportunities for resilient systems.

3. System Interdependencies and Relationships to System Threats and Restoration Strategies

This section presents a visualization prototype that can help us better understand, interpret, and communicate the interrelationships emerging from the complex operation of interdependent WPS. The goal of the visualization prototype is twofold: (1) to provide a holistic view of the WPS interconnections and interdependencies at all system scales (e.g., power transmission and distribution, water treatment and distribution) and (2) to reveal co-managed opportunities for water and power system operators to improve resilience under different threats. We developed the visualization prototype using the MindManager software licensed by Mindjet [59] and leveraged the interdependencies found in our literature review.

Figure 3 illustrates the water and power flows between interdependent WPS. Power flows are shown in red and water flows are shown in blue. Clearly, water and power flows are complex and have many interconnections and interdependencies. Water is used in the power sector for fuel and bio-fuel production, thermoelectric cooling, hydropower, and marine generation. Power is used in the water sector, primarily for pumping and treating public supply and wastewater. Note that water infrastructures (e.g., wastewater, water treatment, water supply systems) are usually connected to power distribution systems rather than power transmission systems. Power transmission systems are where large power generating stations are connected and convey power at high voltages over long distances. Power distribution systems are lower voltage systems that deliver power to end users. Power distribution systems have different reliability standards and power equipment thresholds (e.g., transformer nameplate capacity, voltage limits, etc.) than transmission systems. Resilience in interdependent WPS therefore depends on an understanding of these network components and relationships, and how, where, and when threats may strike. A resilience strategy applied to the power transmission system can improve the resilience of the water supply system if it improves the reliability of electricity delivered through the power distribution system to pumping stations. Similarly, depending on the level of interconnectedness, a hazard that affects the water supply system may propagate to the power transmission system through the power distribution system. For example, a sudden change in the electricity consumption of the water supply system's pumping stations could cause power quality issues in the power distribution system (e.g., voltage drop/rise, frequency drop/rise) that could propagate to the power transmission system.

Another important aspect when assessing the integrated resilience of WPS is water quality. Depending on the water contamination levels or contamination event (e.g., hazardous materials release), water quality can negatively affect the various water sources and the water supply system in general. For example, a highly contaminated water source will require more energy for the treatment necessary to meet human domestic, agricultural, and industrial needs. This increased demand would raise the level of interdependence between WPS and the overall impact on the grid. By comparison, in cases where no significant treatment is required, as in applications where non-traditional waters could be used, the level of interdependence between WPS could be reduced, providing additional flexibility to cope with a hazard event. To this end, monitoring the physical, chemical, and biological parameters through appropriate sensing and telemetry techniques is crucial to preventing water quality resilience threats [60].

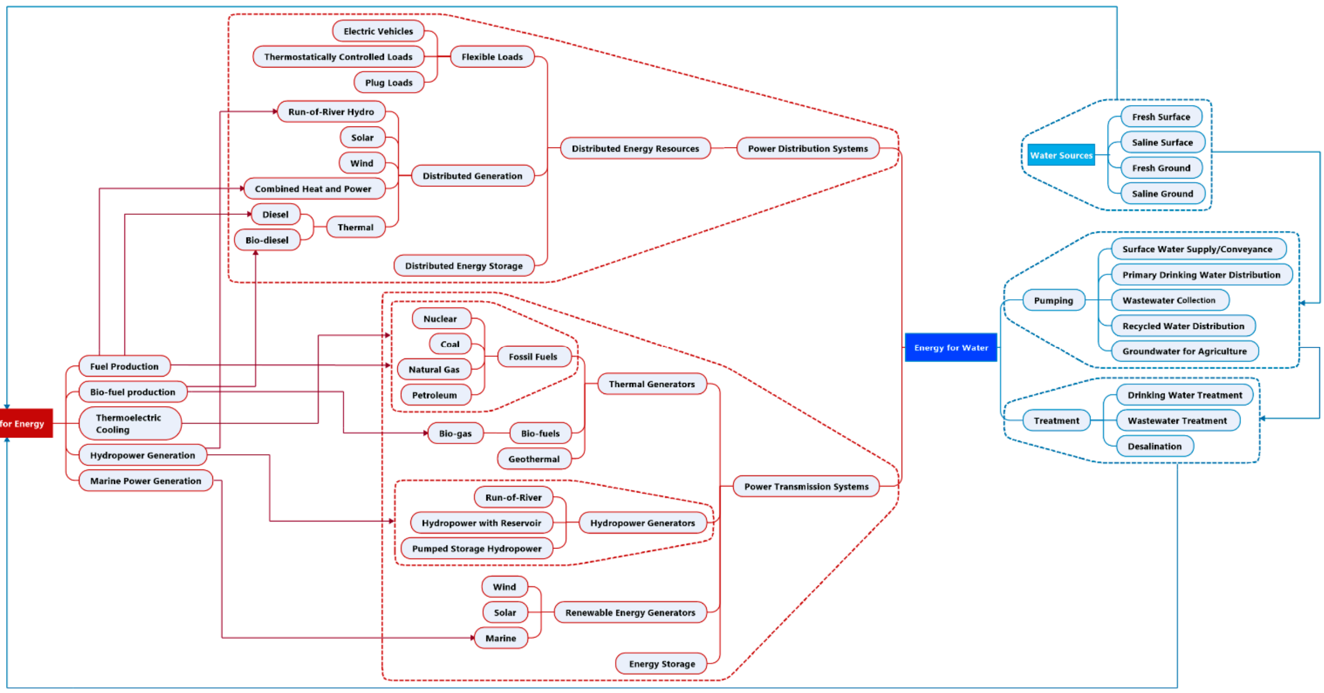


Figure 3. Visualization of WPS interdependencies.

We can use representations of this systems-of-systems interconnectivity, such as those shown in Figure 3, to help identify opportunities for co-management of resilience in WPS. Modifying the visualization shown in Figure 3, Figure 4 shows how a combined climate change threat, i.e., drought and heatwave (shown in orange), affects the generation of hydroelectric facilities connected to both power transmission and distribution systems (energy sector), the thermoelectric cooling levels of thermal generating units (energy sector), and the resource adequacy of water sources (water sector). Climate change threats can vary in duration, spanning from days to months to years, and in impact, causing short-term power outages as in the case of heatwaves or long-term water and power supply shortages as in the case of droughts. To mitigate this type of threat, Figure 4 also shows three co-managed resilience strategies (shown in purple): (1) capacity improvements; (2) the use of non-traditional waters; and (3) microgrids.

Capacity improvements are planning decisions that water and power stakeholders can collectively take to better co-manage potential climate change threats. Such decisions could include adding new or increasing existing storage and/or process capacity of key WPS facilities, such as the water storage capacity (surface or groundwater) of water supply and treatment facilities, the water reservoir volume of hydroelectric dams, the energy storage capacity of battery storage facilities, the pumping capacity of pumping facilities, and the treatment capacity (i.e., processing rate) of treatment facilities. For example, water storage or "water banking" of excess fresh or reclaimed water near the point of use can be called upon during drought seasons, when less water is available and the power grid is under stress to meet the increased electricity demand.

The use of nontraditional waters (e.g., brackish or saline groundwater, desalination brines, and industrial or municipal wastewater) for energy (e.g., thermoelectric cooling, hydropower) or human applications is another co-managed resilience opportunity in regions facing the probability of chronic freshwater shortages. For example, S&P Global Market Intelligence estimates that for the year 2030, 98.2 gigawatts of coal capacity will be at risk due to water stress [61]. The deployment of nontraditional waters can reduce the withdrawals from major surface reservoirs and help maintain reservoir levels for hydropower generation during drought seasons.

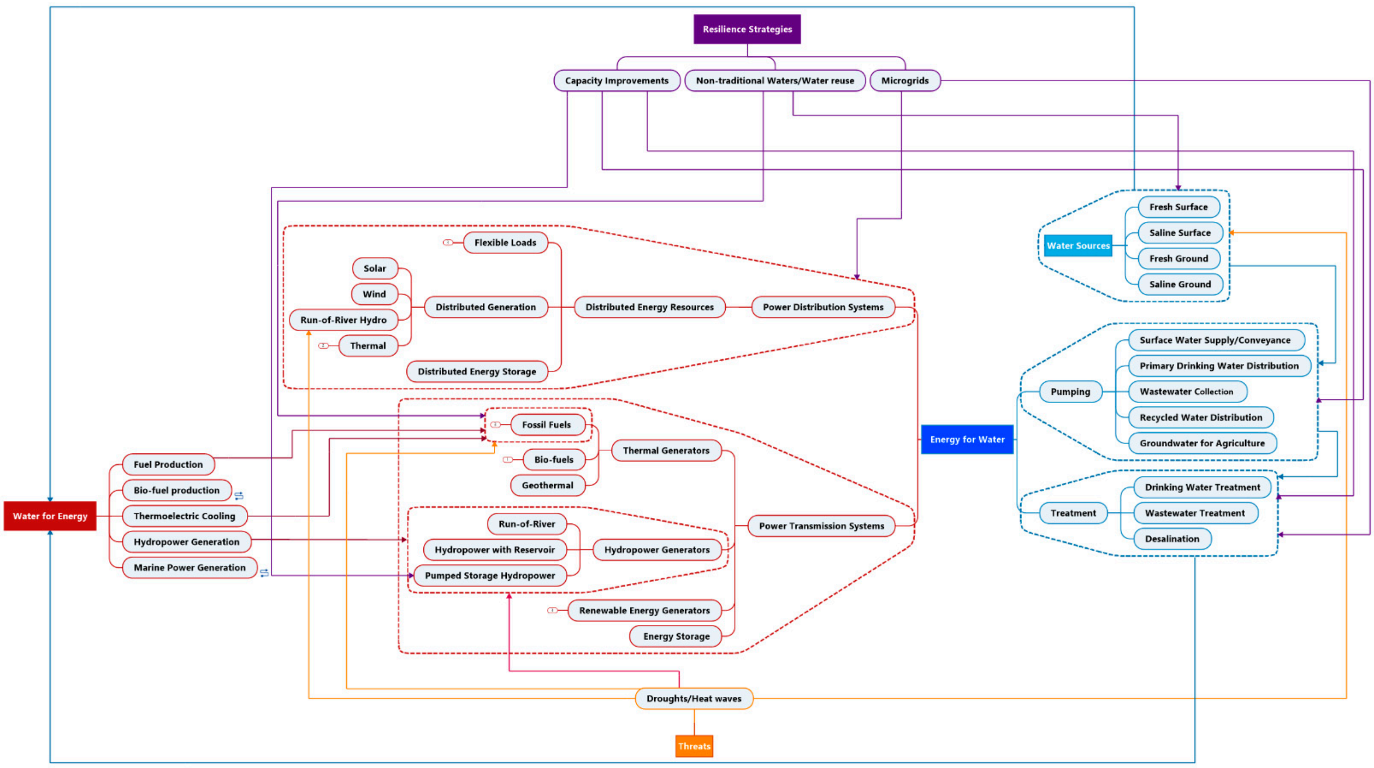


Figure 4. Visualization example of co-managed WPS opportunities and threats.

Water-power microgrids are another co-managed resilience strategy of interest. Water-power microgrids are small-scale interdependent water and power distribution systems that can selectively disconnect from the main power grid during a disruptive event and operate autonomously without affecting the reliable supply of electricity and water. To enable this autonomous operation, water-power microgrids use dispatchable distributed energy resources (i.e., solar units, small wind turbines, battery storage, combined heat and power generators, diesel generators, run-of-river hydro, flexible demand loads, etc.) that provide independent power to designated critical loads, including pumping loads, and sectionalized switchers that disconnect and reconnect the microgrids from the main grid. Water-power microgrids can be co-managed by water and power operators through a central controller that monitors water and power system operating parameters (e.g., voltages, water/power flows, head pressure, etc.), balances power/water supply and demand, and enforces the transition between autonomous and interconnected mode during power grid outages. Although the concept of water-power microgrids has been thoroughly studied [62–64], their actual implementation is still at the experimental level.

While "win-win," co-managed resilience strategies for WPS appear feasible, several challenges hinder collaboration, such as understanding the probability of extreme events, funding of joint mitigation strategies, and the fair allocation of operational and investment costs of these mitigation strategies across water and power utilities. Indeed, lack of cost-benefit valuation data and shared systems understanding can inhibit the allocation of costs and create difficulties when accounting for cross-sector benefits. This can be especially troublesome in communities that face high poverty levels when rates need to be increased to fund resilience investments. Although federal funding is available post-disaster, federal support funds are not typically available to pro-actively fund resilience investments.

The complete visualization prototype that contains all potential combinations of co-managed resilience strategies between interdependent WPS when impacted by different hazard threats can be found in Figure S1 of the Supplementary Materials.

4. Resilience Decision Support Framework for Interdependent WPS

Integrated modeling tools can help decision-makers better understand the dynamics and complexity of the system and avoid ineffective responses and poor coordination for rescue, recovery, restoration, and mitigation. Our literature review shows that many decision-support tools exist for examining resilience from the water system perspective or from the energy system perspective, but not from the perspective of co-managing these systems for resilience. The concept of co-management is described in the literature, but widespread progress does not appear to have been made, aside from the development of tools used to co-manage WPS to maximize revenues and minimize costs. True co-management for resilience would simultaneously optimize a portfolio of resilience strategies to be implemented across one or both sectors in the face of multiple, uncertain threats over the lifetimes of these systems and address the interactions between the strategies.

Considering the interdependent nature of water and power systems, appropriate frameworks need to be developed to evaluate how different resilience strategies will influence the restorative, adaptive, and absorptive capacities of integrated water and power systems under different types of threats and subsequently how these capacities will improve integrated system performance, recovery duration, and cost. In addition to capturing the operational benefits of resilience improvements for specific disruptions, it is critical that a resilience decision framework use a lifecycle analysis approach to evaluate strategies that involve capital investments in addition to operational costs and to capture the benefits of such strategies in the face of multiple threats over a system's lifetime. We present a conceptual resilience decision support framework that fulfills these criteria in Figure 5, using an influence diagram [65,66]. An influence diagram is a graphical representation of decisions and their associated uncertainties that explicitly reveals dependencies (influences) and the flow of information [66]. Influence diagrams visualize the structure of a model in a compact fashion while also having a formal mathematical interpretation. Figure 5 shows the resilience strategy decisions with squares, influences with arrows, uncertainties with ovals, and the evaluation of the decision with the hexagon.

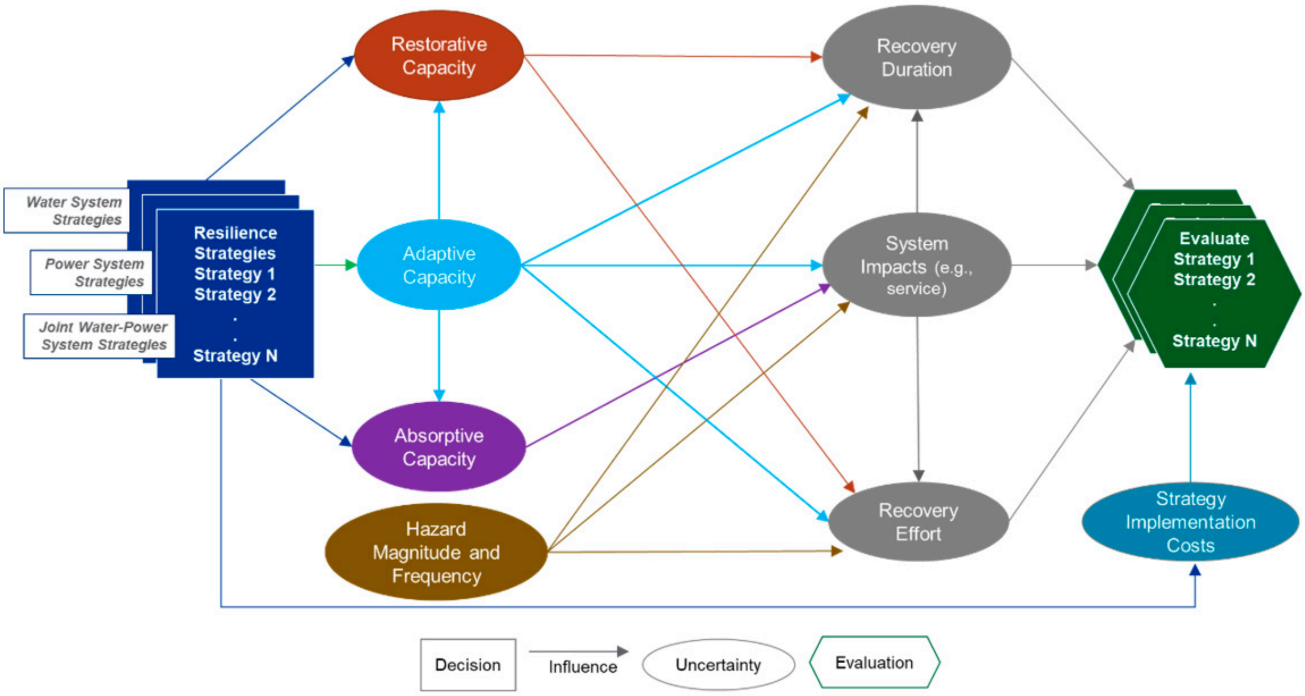


Figure 5. Influence diagram of conceptual WPS resilience framework.

This resilience framework evaluates (the hexagon) resilience strategies as a function of their implementation costs and their impact on the system performance, recovery effort, and duration over the relevant course of the system's lifetime as it is exposed to various hazards/threats. A strategy's ability to reduce hazard impacts is a function of its ability to provide restorative, adaptive, and/or absorptive capacity in the water and/or power components of the WPS. The "system" encompasses the integrated WPS modeling characteristics, such as pumping stations, pipelines, generators, and transmission lines, that are affected by the resilience threat(s) and the resilience strategy itself, as illustrated in Figure 4. System "performance" may include monetized in addition to non-monetized impacts, such as water quality degradation or customer dissatisfaction, and would then require the evaluation node to incorporate a multiobjective evaluation approach.

Because the influence diagram explicitly represents uncertainties, it facilitates modeling the return frequency and intensity of each hazard occurring during the system's lifetime, the uncertainty in hazard impacts, and the uncertainties in the costs and effectiveness of each strategy. This, in turn, allows strategies to be compared on an expected value basis or in terms of their risk profiles so that decision makers' risk attitudes can be considered. It also allows strategies that are sector-specific (e.g., water) to be evaluated with respect to the interdependent sector (e.g., power) to understand how resilience benefits may propagate between sectors.

5. Future Trends

Future trends in resilient WPS include digitalization, integrated planning, collaborative governance and equity, telecommunication, and cybersecurity. These should be considered when applying the resilience framework or developing potential resilience strategies.

5.1. Digitalization

Digitalization refers to using digital technologies and digitized data to support decision-making and improve business operation, efficiency, and resiliency in infrastructure systems. Digitalization in water and power sectors is poised for explosive growth through field sensors, computer models, and assessments coupled with predictive software, supervisory control, and data acquisition (SCADA) systems, Internet of things [46] architectures, communication protocols, geographic information systems (GIS), power/water flow and/or power/water quality data analysis, computerized maintenance management systems (CMMS) and operations management systems (OMS), in addition to customer information systems (CIS). The right combination of these technologies, when properly integrated, will fuel digital WPS transformation [67]. Machine learning, artificial intelligence, digital twins, and advanced data management will help transform the water and energy industries as big data processes are implemented and scaled. Such technology-enabled systems and processes can contribute to enhancing operational efficiency, decision-making capability, performance predictability, maintenance planning and optimized workforce needs, and consumer experience. In addition, digitalization may be used to improve resilience by rapid detection of failures and timely application of co-optimized recovery solutions that aid response to extreme weather events such as droughts and floods.

Evidently, the successful implementation of digitalization would also require accessing and exchanging high-quality data between the various water and power stakeholders. Thus, the digitalization of the water and power sectors comes with cybersecurity threats [68]. Such cybersecurity threats have various attack types, from compromising sensitive or private information to disrupting physical components, which can lead to operational failures (e.g., pump inactivation and system shutdown, generator or transmission lines outages), physical failures (e.g., pipe breakage from hydraulic transient, power substation breakage), and water contamination. In the United States, cybersecurity incidents have increased over the last five years in both the water and power sectors [32]. Thus, cybersecurity has become a growing concern for interdependent WPS, with the threat of data theft and operational disruptions demanding the need for greater system security and resilience. To the best of our knowledge, cybersecurity threats remain an understudied field in interdependent water and power infrastructure. Work needed in this area includes software vulnerability detection, cybersecurity architecture and protocol development, cybersecurity training, and cybersecurity roadmap development for integrated infrastructures.

5.2. Integrated Planning

Integrated resource planning is the process used by utilities to project future customer needs and identify the resource mix that is most likely to meet those needs while balancing cost and risk and addressing environmental, legal, and regulatory considerations. In this type of planning document, "integrated" typically refers to accounting for both supply- and demand-side resources, not necessarily integration with other sectors. Water and electric utilities have not traditionally developed their resource plans collaboratively. However, as noted previously in this paper, climate change and other hazards affect both sectors, and some electric utilities are explicitly considering water availability in their integrated resource plans (IRPs). Memphis Light, Gas and Water (MLGW) [69], Arizona Public Service [70], and Tennessee Valley Authority (TVA) [71] all include water availability for thermoelectric cooling as a metric in their IRPs as part of their metrics for selecting preferred portfolios of generating resources. MLGW included water availability as one of three components of a sustainability metric in their 2020 IRP [69]. APS included water use in 2035 as a metric in their 2020 IRP [70]. TVA included water usage as one of several metrics used to evaluate portfolios in their 2019 IRP [71]. Utilities in the Pacific Northwest, such as Tacoma Power, Idaho Power, and Portland General Electric, routinely consider water availability and timing for hydroelectric production as variables in their IRP analyses [72–74].

A joint integrated resource planning process that addresses water and electricity planning in an integrated fashion may provide benefits [75]. These benefits include holistic watershed planning, ensuring electric utilities have the cooling water they need while water utilities have access to the quality and quantity of potable water they need. Joint IRPs may also support collaboration on renewable resources, energy efficiency projects, or demand management, such as timing water pumping during off-peak grid periods.

Cross-regional IRPs may also help utilities respond to climate change. Changes in water availability in one region can trigger responses in other regions, and these regional dependencies are critical to evaluating climate change impacts. Regional forces shape grid and market conditions that can impact resource adequacy and risk. A shared modeling framework and integrated planning processes between water and electric utilities may help reduce costs and risks while increasing reliability and resilience, particularly in the face of climate change.

5.3. Governance, Equity, and Resilience

Governance is the act of conducting the policy, actions, or affairs of an organization and locality. Governance is what brings people and organizations together to engage in decision-making. The governance structures around power systems in the U.S. are more straightforward than those for water. For investor-owned electric utilities, state utility regulators regulate the generation, distribution, and intrastate transmission, whereas the federal energy regulatory commission regulates the interstate transmission of electricity. In most cases, municipal and cooperative electric utilities are governed by city councils and local boards, respectively. In many places in the U.S., there are multiple levels of water governance (i.e., states, counties, cities, watershed districts, departments of natural resources, state and federal environmental regulators, and agriculture departments), which can create stalemates and hinder progress. Governance structures for decision making at the energy–water nexus are even more muddled, but as climate change effects impacting both sectors become more acute, clear and effective governance structures together with good data and accurate system models become even more critical.

Governance is also essential for resilience and equity issues, particularly when problems arise, such as who receives water and power in contingency situations. Such contingency situations are more prominent in communities that lack resources to recover economically after a disaster. Although resilience strategies emphasize the role of engineering solutions and strategic planning efforts, societal inequities and exclusions have not yet been resolved. At a local level, existing disparities in communities are exaggerated in the face of a natural disaster. Communities that are underserved and socioeconomically vulnerable typically face significantly larger challenges. Not only are they most often located on precarious geographies such as steep slopes and in low-lying areas, but they also often lack the capacity to recover and rebuild. These stark imbalances illustrate the urgency of why we need to address equity and resilience together to create urban environments that are resilient, equitable, and fair.

6. Conclusions

This paper makes four contributions to address the challenges of resilience planning for the interdependent water and power sectors. First, we present an extensive literature review on integrated water–power resilience studies concerning different modeling tools, metrics, challenges, and gaps identified in the technical literature and institutional research landscape. Second, we provide a visualization prototype to illustrate water and power system interdependencies and reveal co-managed opportunities for water and power stakeholders. Third, we propose a conceptual decision support framework that simultaneously optimizes a portfolio of resilience strategies in the face of multiple, uncertain threats and addresses the interactions between the strategies. Finally, future trends regarding digitalization, integrated planning, collaborative governance and equity, and cybersecurity are presented for building more resilient and socially fair WPS. The main findings of this paper are summarized below:

- Reviewing the literature from private and public institutions addressing the interconnections between water and energy shows that climate change and disaster analysis are the most common topics covered.
- Institutions that had reports or initiatives focused on climate change and disaster analysis were found to focus predominantly on the topic of planning, rather than

operations. This focus ranged from water supply planning to infrastructure planning, in addition to risk evaluation. The institutional landscape assessment also revealed that research gaps remain in regulatory policy and water recovery practices and on promoting research that jointly addresses water–energy interdependencies.

- From a WPS interdependency perspective, no standard definition or metrics for resilience exist. Therefore, there is a critical need for developing robust assessment metrics that can assess resilience in an interdependent, multisectoral context.
- Existing modeling limitations call for additional research on developing modeling approaches to evaluate resilience strategies for interdependent WPS. Future modeling platforms should allow for integrated multiscale, multiobjective, and multiuser analyses. Stakeholder engagement is also crucial to ensure any modeling addresses the needs of resource decision makers regarding key threat scenarios, their impacts, and effectiveness of restoration strategies.

With respect to future research trends around WPS resilience, we explored several topics around digitalization, telecommunication, cybersecurity, integrated planning, and collaborative governance and equity. We found that better use of existing data coupled with new sensors, information integration, and data analytics may boost coordination between water and power utilities via building new, data-driven solutions for effective asset co-management, efficient operations, and remote system management, reducing operating costs and improving resilience. However, most WPS utilities have a long way to go with digital sensors, communications, and data analytics before reaching the desired future state as a digital WPS utility and addressing cyber-physical threats. We identified joint IRPs as a promising approach to address resilience co-management for WPS. Finally, communities that are underserved and socioeconomically vulnerable typically face significantly larger resilience challenges. Therefore, resilience strategies should be carefully designed to be fair and non-discriminatory.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/w13202846/s1. Figure S1: Visualization of co-managed opportunities and threats. Table S1: Percent of External Institutions in Landscape Assessment Covering Given Topic.

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