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Integrated water-power system resiliency quantification, challenge and opportunity

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ABSTRACT

Resiliency has been studied in the power and water systems separately. Often the resiliency study is not so comprehensive as to understand interdependent, integrated water and power systems. This research outlines the relevant factors necessary to understand and advance quantification of such integrated systems. It also presents a review of integrated water-power systems resiliency. Based on literature survey and identification of challenges, the authors present quantification and computational steps needed to understand integrated water-power systems resiliency. A conceptual framework is proposed to quantify integrated water-power system resiliency. Finally, the authors presented an opportunity for improved water and power system resilience.

1. Introduction

Power and water systems are interdependent. Water depends on power to extract, process, and distribute water while power depends on water to generate electric power, refine fuel and cool power generator system. In the U.S., thermoelectric cooling system withdraws most of the water nationally while agriculture consumes most of water [1]. Interdependent water-power systems are also observed in industrial, business and residential sectors. These sectors used signification amount of power for pumping and heating, while water is used significantly for cooling systems. Water variability caused by fluctuation of weather poses a major challenge in the power systems Vulnerability in the water in an interdependent water-power system may pose a major challenge in the power system. For example, disruption in water system caused by storm, flood and sea-level can damage power system infrastructure. Colorado experienced such case in September 2013 when a flood disrupted natural gas and power stations infrastructures, and oil and gas companies were forced to shut down their operations [2]. Water system disruption in the US caused by draught in the 2102 affected petroleum and coal transportation by barge as well as damaged bioenergy crops utilized for biofuel [3]. Intentional attacks—physical, cyber, chemical/biological targeting of pipes, pumping stations, water tanks, and other facilities on water infrastructure—may disrupt interconnected water and power systems.

Power and water systems are critical infrastructure, responsible for providing society with diverse services that are coupled in many instances (Fig. 1). This coupling means that the resilience of one subsystem—i.e., either the water or power components—impacts the resilience of the other. The number and diversity of critical water and power systems that are integrated is significant. They include municipal water supplies; thermal energy generation, where water is used for cooling; agricultural, where pumps are required for irrigation; hydropower generation, where reservoirs store water for other uses; and health services such as hospitals, which are required to have backup power generators, but not necessarily backup clean-water supplies. Because disturbance to one system can impact the other, resilience considerations of these systems must understand their interdependencies and propagation of events.

Both power and water systems have been studied with regard to resilience; often these analyses are not comprehensive with respect to timescales or resilience formulations. Power resilience is typically considered over shorter timescales, ranging from microseconds to the duration of the fuel supply (e.g., water in a reservoir, pipeline capacity, or burnup of nuclear fuel). Longer time frames of repair, maintenance, and improvement after a significant event that impacts infrastructure may also be considered. Water resilience typically connotes

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considerations such as seasonal deviations from normal levels (e.g., a short-term drought) through centuries (e.g., climate change impacts to normal levels). Water resilience is often also considered in the context of natural disasters, but not necessarily a suite of disturbance events.

The magnitude of interactions between water and power systems is enormous. For example, US used 148 billion kWh of electricity for heating water, and over 738 billion liters of water per day for thermoelectric cooling [4,5]. Nearly 322 billion gallons/day water were used in the US during 2015 [6]. About 4% of the US electricity is used for moving and treating water and wastewater (1.6% is used for wastewater treatment) [7]. About 80% of the power in drinking-water plants is used for motor pumping [4] in the US. Disruptions to either power or water can therefore propagate significantly and in impactful ways. The impact disruption on interconnected power and water systems can be understood by assessing their resiliency. Resiliency assessment of interconnected power and energy systems is beneficial many ways. First, it can help to understand interconnected energy systems' ability to absorb a disruption and to recover quickly to a normal state. Second, it will help clarify required infrastructure and modernization needed to improve resiliency. Finally, the opportunity of various research and development (R&D) activities to improve the resiliency can be identified.

This research presents a detailed, intensive review of integrated water-power systems resiliency reported in the literature. This research outlines the relevant factors necessary to advance quantification of integrated water and power systems. The objective is to put forth a framework that is implementable for irrigation systems, to demonstrate quantification of resilience in this context. It was realized, however, that this type of quantification requires a broader understanding of water and power system resilience and corresponding landscape. Therefore, the approach in this research is to leverage existing resilience concepts from power and water literature and apply them to integrated water and power systems. Finally, the authors proposed a conceptual framework to assess integrated water-power system resiliency.

2. Interdependent water and power systems

Assessing the resiliency of water-power systems required understanding of interdependent water and power systems. Generalizations can be drawn about water and power system dependencies despite the heterogeneities in the form and substance of the specific instances

Table 1
Power water dependency mapping by identifying power input to water grids and water inputs to power grids [8].

Integrated coupling	Linkage	Examples
Power required for water system	Acquisition	Pumping from well; intake actuation
	Treatment	Chlorination or UV sanitation; nutrient removal
	Transport	Pumping to pressurize pipes; valve actuation
	Storage	Monitoring; reservoir gate control
	End-use	Manufacturing (chemical production); cleaning (hospitals); municipal allocation and metering
Water required for power grid	Cooling	Thermal generator heat exchangers; server warehouses
	Direct generation	Hydropower; marine hydrokinetic
	Energy storage	Pumped storage hydropower; thermal storage

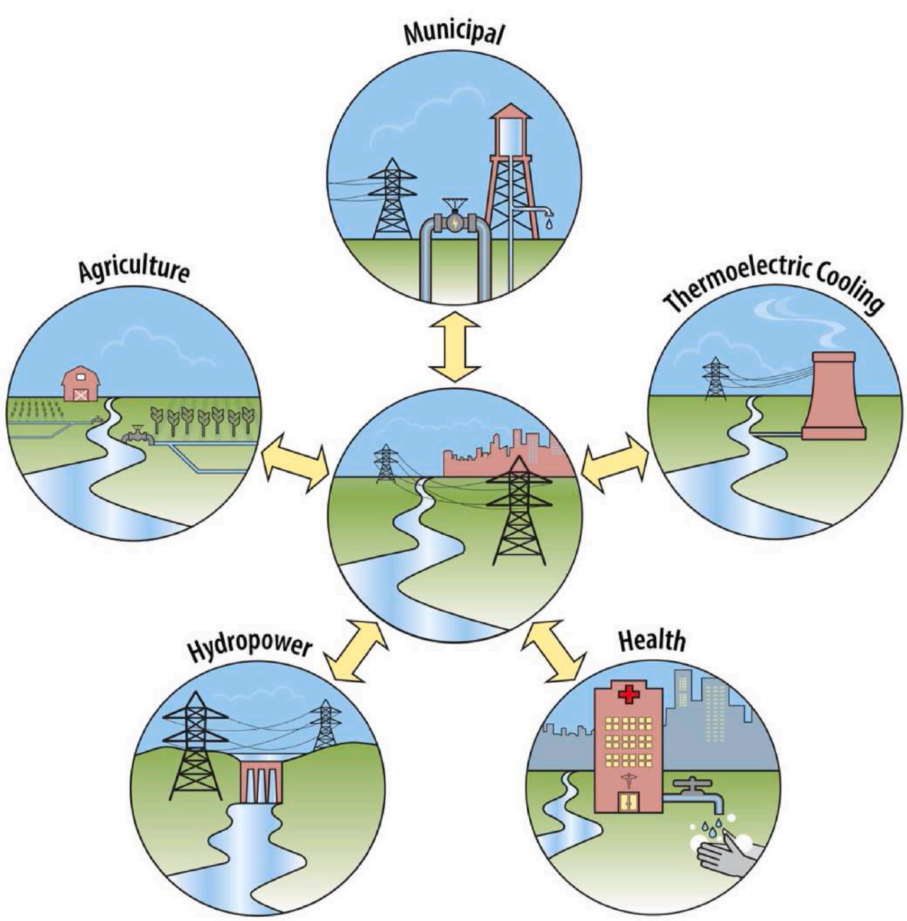

Fig. 1. Water and power systems are integrated for variety of uses that are critical to society.

(Table 1). The section present a set of lists to understand components of the water and power system and where dependencies exist. A detail explanation of power and water interdependency in the irrigation system is presented.

2.1. Irrigation system

In the western U.S., irrigation is the largest use of freshwater resources [9]. Irrigation is a consumptive use because the water is extracted from a natural waterway but not returned. Instead, this water enables photosynthesis of the crops, which results in evapotranspiration, and infiltrates into the ground, which can eventually recharge aquifers. Electricity is coupled with irrigation systems through the use of pumps, with generation in conduit hydropower, and with electronic irrigation infrastructure control systems. While different in form and function, these two instances of water-power dependencies can be connected via the water and power sources—for example, natural waterways and bulk power system generation. The water-power dependency of irrigation system is elaborated below:

2.1.1. Water system dependencies

Irrigation systems utilized the following water infrastructures to transport water:

2.1.1.1. Dams and reservoirs. In irrigation districts with water-storage rights, this part of the infrastructure is responsible for storing water. Water is provided by rainfall or snow melt and released during periods of low precipitations.

2.1.1.2. Diversion structures and headgates. Diversion structures are responsible for diverting water into a pool from a source, such as a stream or river, which is used to supply the conveyance canals. The water flow into the canals is controlled by headgates, the operation of which is dependent on available water rights.

2.1.1.3. Fish screens. This element is responsible for blocking fish and debris from the water to be used in farms. Fish screens provide a way to guide fish back to the source from which water was diverted.

2.1.1.4. Canals and pipelines. Canals are the main channels to transport water in the irrigation system, which provide water for its final distribution. These open channels were usually built by ground excavation and expose water to evaporation, absorption into the soil, and contamination from external agents, affecting water supply to farms. Underground pipelines can be used as a solution to transport water, mitigating all these effects simultaneously and improving water quality.

2.1.1.5. Laterals and weirs. Laterals refer to small channels that take water from a main canal to deliver it to a section of the service area. Weirs are used to control water that flows from the lateral to a specific end user, and these are adjusted according to irrigation-district requirements.

2.1.2. Power-system dependencies

2.1.2.1. Pumps. In some irrigation systems, the water source (a river or a dam) is at a lower elevation than the location of distribution channels and end users. Pumps are required to carry water from its main source to a delivery chamber. From that point, distribution is through gravity-fed canals, relying on the available hydraulic head to supply the amount of water need at each water demand.

2.1.2.2. Sprinkler irrigation. This system is used to provide a rainfall-like irrigation to the crops. Water is distributed by pumping. The pump unit provides pressure, and the mainline and several lateral lines distribute the water along the crop. Finally, sprinklers are used to pour water on vegetation. This technology saves water and ensures a more-uniform water distribution; it also provides a mechanism to add fertilizers.

2.1.2.3. Drip irrigation. This is a modern solution which distributes pressurized water through a network of valves, pipes, tubing, and emitters. It is designed to place water directly into the root zone, reducing water loss from evaporation.

2.2. Power and water system interdependency in other sectors

Other sectors which show strong power and water interdependency are: thermoelectric cooling of nuclear or fossil, pumped-storage hydropower (PSH) and municipalities. Table 2 summarizes the primary power and water system interdependency in these sectors.

2.3. Power requirements for water distribution, water supply, water conveyance, on-site water treatment for end-use

Power is required for following water processes: (1) water supply, (2) water conveyance, (3) water-supply treatment, (4) water distribution, (5) on-site treatment for end-use, and (6) wastewater treatment (Fig. 2). Table 3 shows an example of power usage in the water processes.

3. Understanding power and water system resiliency

The underlying resilience concepts for understanding water and power system resilience are quite similar even though the processes, associated infrastructure, timescales, and objectives of these systems and corresponding resilience studies are quite different. While exact definitions of resilience vary, a useful definition put forth by the Federal Energy Regulatory Commission (FERC) is “the ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such events” [17]. A complementary resilience conceptualization more explicitly bins resilience by attribute definitions (Fig. 3) [18]:

1. Reconnaissance: ability to be aware of system and potential threats.
2. Resistance: intrinsic ability to withstand or reduce disruption or its impacts.
3. Response: ability to change operations during an event.
4. Recovery: ability to return to a normal state or original posture to absorb another impact.

Table 2
Primary power and water system interdependency in other sectors.

Sector	Primary water system dependencies	Primary power-system dependencies
Thermoelectric cooling of nuclear or fossil	Use of water for thermoelectric cooling of nuclear or fossil energy	Use of power to be cooling water supply and treatment
Pumped-Storage Hydropower (PSH)	Water is purely a “fuel” for generation	Water is pumped by PSH [10] and stored in the water tanks in the water system to benefit from lower rates of electricity price in the power system during off-peak periods
Municipalities	Capture water from pristine sources, such as municipality-owned watersheds or alternative sources, such as large rivers or aquifers [11].	Require significant power for pumping, desalination of brackish water [12]

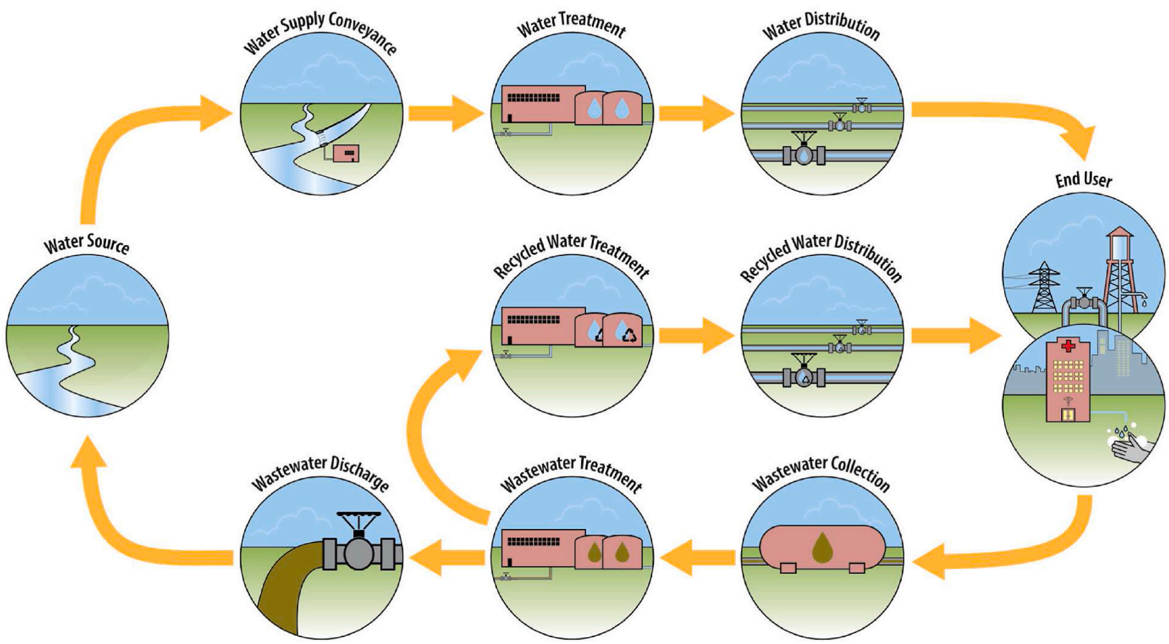

Fig. 2. Interdependent water system that require power for supply, distribution, conveyance, treatment, and end use.

Table 3
Example of power requirements for water distribution, water Supply, water conveyance, on-site water treatment for end-use.

Water processes	Power needed
Water Supply	In regions with water scarcity, especially during dry periods (summertime), additional water is obtained from underground reservoirs through pump [13]. Desalination of brackish water needs extra power
Water Conveyance	Power is required for long-distance water transportation [14]
Water Supply Treatment	Power is needed at the treatment of seawater and brackish groundwater to meet water quality specified by water act [15]. Typically treatment of seawater and brackish groundwater is more energy-intensive, compared to the power required for treating surface water [16].
Water Distribution	Pumps may be required to maintain adequate pressure levels in pipes, which ensures the water level of storage tanks and adequate pressure head to supply the water demands.
On-Site Water Treatment for End-Use	Power is needed for additional treatment such as heating, cooling, and softening prior to consumption,
Wastewater Treatment	Power is needed at various processes of wastewater treatment such as aeration, pumping and solids processing.

5. Restoration: ability or process wherein degradation caused by the event or use of assets is repaired or system is maintained. An analysis of this stage would yield information about additional needed investments.

A general resilience index for infrastructure can defined as an integral of the performance curve over time, standardized as a percentage (Eq. (1)) [19]. In this equation, $Q(t)$ represents the system performance level as a function of time. For $Q(t)$ the system's performance can be measured across any of many different dimensions, provided it's normalized to a differentiable equation, with a positive minimum value. The notation t_0 represents the time at which the disruption event of interest starts, and t_1 represents the end of the disruption event of interest. As performance degrades due to a disruption event, the integrals value decreases. The act of resisting, recovering and restoring service would increase the system's performance, thus increasing the value of the resilience index.

$$\frac{\int_{t_0}^{t_1} Q(t)dt}{100(t_0 - t_1)} \tag{1}$$

3.1. Power system resilience

Resiliency concept in power systems revolves around response time of available assets following a disruption that maintains continuous service. Adaptive capabilities, such as seamless islanding, fast load restoration, and fast resynchronization add resilience to power systems. Systems may also have intrinsic properties that slow down the effects of a disturbance. One such property for the electricity grid is the rotational inertia of bulk-power generators, which slows down the divergence of grid-frequency loss of generators or large loads. Resiliency of a given power system is also dictated by system's ability to sustain a set of unknown failure event and to return to stable running conditions [20]. Cyber-physical resilience concepts measures system's ability to identify, adapt to, and absorb disruption in a timely manner [21]. Another useful way to characterize grid resilience is to evaluate the magnitude and duration of a disruption which can be sustain without falling below a minimum operating performance [22]. There is abundant literature in the power-grid resilience methods [23] and quantification [24].

Some of the innovations in power grids that can improve resilience are distributed energy resources integration [25], microgrid incorporation [26], and line hardening [27]. Current R&D investments to enhance power grid resiliency include [28]: (1) computational tools for grid transmission and distribution system planning and dynamics over a variety of time and spatial scales, (2) novel technologies to control and coordinate millions of assets for grid operations, (3) novel sensors, advance communication devices and analysis to enable 100% observability, (4) new devices and components for improved reliability/resilience, (5) cyber-physical solutions and real-time response technologies and systems, and (6) decision support tool for regulator, utility, and grid operator. Table 4 summarizes different key grid resiliency metrics adapted in the literature and relevant research.

As an example of researchers seeking novel resilience measures or proxies for them, Wallnerstrom et al. [32] introduced a new Risk Index category. The new Risk Index category (Eq. (2)) captures the average number of outages that exceed T hours over the course of a single year

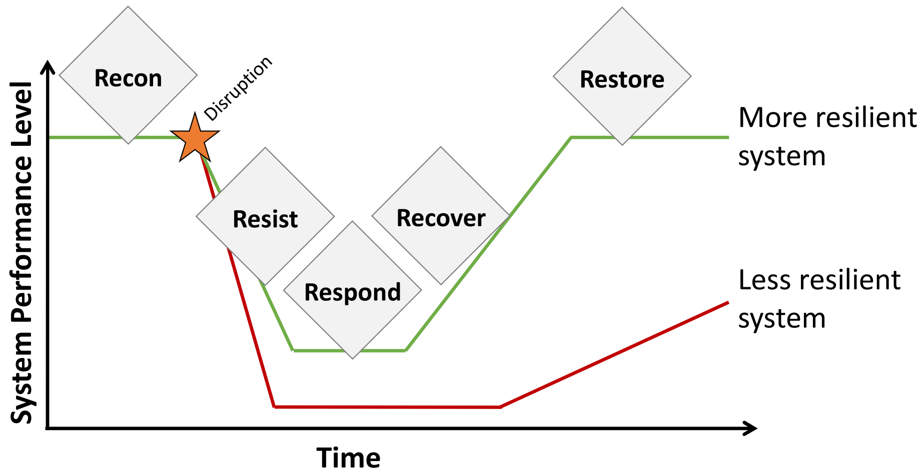

Fig. 3. Notional depiction of resilience performance of a system in the context of a disturbance event.

Table 4
Key power-system resiliency metrics appeared in the literature.

Area	Metric definition	Study
Power system cyber-physical resilience	Cyber-physical resilience is the combined resilience of cyber and physical components.	Arghandah et al. (2016) [21]; Jufri et al. (2019) [29]; Bie et al. (2017) [30]; Jena et al. (2020) [31]
Vulnerability measure/ Resiliency improvement	Vulnerability is a system's inability to respond to disturbances to its processes.	Wallnerstrom et al. (2012) [32]; Zhu et al. (2014) [33]; Yuan et al. (2014) [34]; Salmeron et al. (2004) [35]; Johansson et al. (2010) [36]; Eskandarpour et al. (2017) [37]; Ouyang et al. (2014) [38], Schneider et al. (2019) [39], Dong et al. (2018) [40]
Hardening	Hardening refers to making electrical components physically stronger to reduce vulnerability.	Mitra et al. (2007) [41]; David et al. (2014) [42]; Panteli et al. (2017) [43]; Wang et al. (2019) [44]; Lin et al. (2018) [45]
Restoration planning	Restoration planning measure the level of preparedness to get a system running again after a major disturbance.	Safaei et al. (2012) [46]; Gao et al. (2016) [47]; Yao et al. (2019) [48]; Arab et al. (2015) [49]; Wang et al. (2015) [50]; Zhang et al. (2018) [51]; Chen et al. (2018) [52]
Security and Protection	Components should be protected to either through personnel or technology to prevent disturbances.	Ren et al. (2017) [53]; Jin et al. (2017) [54]; Ren et al. (2018) [55]; Azzouz et al. (2018) [56]; Mo et al. (2015) [57]; Ma et al. (2018) [58]; Hussain et al. (2018) [59], Dong et al. (2019) [60]

per 1000 customers.

$$R_T = \frac{\sum_i \left(\lambda_{\geq T,i}\, N_i\right)}{\sum_i N_i} \tag{2}$$

where $\lambda_{\geq T,i}$ represents the instances of outages per year of duration T or greater and N_i is the number of customers in the region of interest. This example is specifically designed for flexibility in implementation to allow users to account for different regulations and laws of different regions, while still providing meaningful insight into the reliability of customer services.

3.2. Water system resilience

Resilience of water systems can be physically characterized as an ability to return to their former state following a disturbance; however, the notion of impact on uses of that water is also paramount. From the strictly physical definition, water resilience can be interpreted and quantified from the start, duration and end time of a water-deficit period [61]. Extension of water deficit period caused by extended water restrictions have impact on water resiliency. The conditions that cause water deficits depend on the specifics of a region and type of water system. Typically, a water-deficit period is determined from the time when waster level falls below an acceptable level. Another definition of water resiliency involves measuring the average duration of a water system is under a limited restriction [62] or the fraction of time that a water system is below an acceptable state [63].

Water resilience in social-ecological systems is measured based on the ability of water to safeguard and sustain a social-ecological system at certain level [64]. The ability of water to safeguard and sustain a social-ecological system characterized by the stability of regional weather systems, biosphere and earth system along with stable water supply. Appropriate spatial scales for considering water resilience vary, but can range from the Earth system down to local scales of communities, buildings, or households. Water resiliency definition and quantitative approach varies by type of waster infrastructure [65].Table 5 summarizes different water resiliences and their application in the literature.

Water systems take a similar approach to resilience indicators as power systems described in the previous section. As an example, Schoen et al. [70] uses Eq. (3) below to indicate resilience (*Re*) using performance over time through the failure and recovery profiles (*F, R* respectively).

$$Re = \frac{\left(T_i + F\Delta T_f + R\Delta T_r\right)}{\left(T_i + \Delta T_f + \Delta T_r\right)} \tag{3}$$

In the above equation T_i is the time of system operation until the disruption, ΔT_f is the duration of the failure, and ΔT_r is the duration of the recovery activities.

4. Existing research on integrated power and water systems

Integrated water and power system resilience has been investigated in a few different contexts. This section highlights the major studies in the literature that aim to address various challenges in the integrated power and water systems.

Table 5
Key water system resiliency metrics appeared in the literature.

Metric name	Definition of Metrics	Study
Water infrastructure network-based indicators	The graphical representation of structure of system of interconnected nodes and pipes to highlight vulnerabilities in the system.	Porse et al. (2016) [66]; Soldi et al. (2015) [67]; Candelieri et al. (2015) [68]
Water infrastructure performance-based indicators	Measuring the performance of the system to assess it robustness.	Ayyub (2014) [69]; Schoen et al. (2015) [70]; Baroud et al. (2014) [71]
Water infrastructure technological indicators	Technology is utilized to measure a system's characteristics and response capability to extreme events.	Hammond et al. (2015) [72]; Lennon (2015) [73]; Mugume et al. (2015) [74]
Transportation infrastructure network-based indicators	The transportation network topology is studied to assess the system's vulnerabilities.	Zhang et al. (2015) [75]; Xu et al. (2015) [76]; Liao et al. (2018) [77]
Transportation infrastructure performance-based indicators	Features related to traffic flow are examined to gauge reactions to system disturbances.	Nogal et al. (2017) [78]; Wang et al. (2019) [79]; Donovan et al. (2017) [80]
Cyber infrastructure	Different metrics are used to quantify a system's ability to anticipate and recover from cyber security threats.	Oughton et al. (2019) [81]; Smidt et al. (2018) [82]

4.1. Mapping interdependent water-power system

Mapping interdependent water-power systems characterizes interconnected water and energy flows and their landscape [1]. The literature emphasizes the relationships among geo spatial characters, power, and water, as well as the associated impacts on environment [83]. For example, the transfer of different types of water (e.g., freshwater, rainfall, wastewater) to the U.S. electric grid are studied [84] and show that the changes in interdependent water-linkage structure affect the overall volumes of freshwater consumption. Several other studies show that large water withdrawals of thermal power systems creates a vulnerability to climate [85,86]. The connection of solar and wind energy with water is studied in a drought resilience and groundwater sustainability study [87].This research shows that groundwater sustainability is benefited from solar and wind energy. A water-energy nexus analysis in China shows that lack of water-resources would force consumers to use more renewable energy-sourced power to ensure reliable power supply as well as economic development [88]. A study in Washington state stresses the importance of considering social factors, in addition to nexus factors, when designing systems for resilience. They examine how nexus management decisions in the Yakima River Basin yielded unequal outcomes for different populations being served, predominantly informed by wealth class. They conclude from this that without considering the social aspect, the power status quo is often naturally maintained, even if not intentionally [89].

Mapping interdependent water-power systems is conducted in the literature by mapping input-output in the integrated water-power system. The study [90] uses linkage analysis and input-output modeling to examine energy and water consumption and their implications among different economic sectors in Beijing. Critical nodes in the chain include agriculture and food processing, real estate (consumer of both), logistics and transportation (provider of both, made possible by real estate), and the service industry (substantial consumer of both). Another study in China [91] compiled the different types of water consumption used for energy production and vice versa. In analysis of these networks, researchers were able to model regional control and dependence relationships all over the country, and these models can be used in future work to help bridge gaps in resource management [91]. The proposed framework [92] identifies vulnerable links in the chain (provinces/regions) to improve overall resilience. Table 6 summarizes mapping of interdependent water-power system.

Table 6
Summary of literature mapping interdependent water-power systems.

Mapped inter-dependent water-power system	Study name
Thermoelectric cooling of nuclear or fossil	Pourkiaei et al. (2019) [93]; Tidwell et al. (2012) [94]; Tidwell et al. (2016) [95]; Zhu et al. (2019) [96]; Long et al. (2010) [97]
Irrigation system	Li et al. (2019) [98]; Zhao et al. (2020) [99]; Espinosa-Tasón et al. (2020) [100]; Cremades et al. (2016) [101]; Serrano-Tovar et al. (2019) [102]; Jobbins et al. (2015) [103]
Hydropower system	Basheer et al. (2019) [104]; Hennig (2016) [105]; Zhou et al. (2019) [106]; Amjath-Babu et al. (2019) [107]; Zhang et al. (2018) [108]; Shang et al. (2018) [109]
Municipalities	Mo et al. (2013) [110]; Valladares Linares et al. (2013) [111]; Nogueira Vilanova et al. (2015) [112]; Marzooq et al. (2018) [113]; Al-Mutrafi et al. (2018) [114]; Ma et al. (2020) [115]
PSH	Hunt et al. (2018) [116]; Bhattacharjee et al. (2019) [117]; Ak et al. (2019) [118]; Ramos et al. (2014) [119]; Hunt et al. (2020) [120]
Power requirements for water distribution, water supply, water conveyance, on-site water treatment for end-use	Smith et al. (2018) [121]; Kyung et al. (2013) [122]; Santana et al. (2017) [123]; Wakeel et al. (2016) [124]; Kenway et al. (2019) [125]; Wu et al. (2015) [126], Oikonomou et al.(2018) [127,128], Singh et al.(2019) [129],

4.2. Co-optimization of water-power dispatch

Co-optimization water-power dispatch has focused on optimal dispatch of water and power within interdependent water-power system. For example, an integrated power and water system of the local municipal utility that uses multiple power, water, and coproduction facilities to meet power and water demand can co-optimize water and power dispatching decisions [130]. Co-optimization of regional water-power systems centers on hydropower-reservoirs and aims to allocate water resources optimally between irrigation and hydropower. This research aims to maximize irrigation productivity while minimizing power generation costs. The co-optimization method identify reservoir operation rules that is beneficial for interdepended water-power system [131].

Beside irrigation systems, co-optimizing within integrated water systems analyzes efficient operations and sourcing of energy. A study [132] on micro-water-energy systems develops three different models to minimize the usage of electricity: (1) standalone operation of the power system without optimizing water overdemand, (2) optimization across both variables, but with the microgrid taking precedence over the water demand (bi-level), and (3) optimization across both variables concurrently (co-optimization). This study finds that the most-efficient use case was the co-optimization method with battery storage. A study used a mixed integer nonlinear program to optimize the water and power use for temperature control of buildings in a microgrid during occupied and unoccupied hours [133]. It was found that the ideal single fixed temperature was 25 °C while the most economic strategy was to range between 20 °C and 25 °C between occupied and unoccupied hours. A study in the Iberian Peninsula aims to optimize the economic burden of thermal energy with respect to plant cooling constraints and energy production, among other variables. In Iran, a method for optimizing operating rules for a multireservoir system with respect to power and water demands was developed using network flow and linear programming. The model was flexible enough to derive different operating rules by adjusting the objective and constraints, and it was found that keeping the reservoirs' water levels as high as possible actually increases total energy production and reduces water deficits better than the standard operating policy [134].

A case study in China attempted to optimize the operating rules for pumped water storage by utilizing a multiobjective optimization model to simultaneously minimize water shortages and maximize revenues from energy production and comparing the results to this parallel reservoir system. The resulting curves indicate that, with small water supply flow, parallel reservoirs are more efficient than pumped water storage, but once the flow becomes large enough, pumped water storage becomes increasingly more efficient [135]. On isolated islands, excess intermittent wind power is usually simply lost, while the islands also tend to rely heavily on desalination for fresh water, which is a process that requires electricity. A study of the island of Sao Vicente in Cape Verde proposed multiobjective optimization method that utilizes excess wind power for desalination and pump hydro storage to create an integrated water and power supply system that minimizes the lost wind power. Using this method to optimize the size and scope of the integrated system, by way of minimizing costs, maximizing that percentage of energy use that is renewable, and minimizing wind power loss, they were able to reach 84% renewable energy penetration while decreasing costs by 27% [136].

4.3. Climate change impacts at large-scale

Research assessed the vulnerability of existing interdependent water-power system (e.g. thermoelectric power plant) to changing climate [137]. Climate and water infrastructure change can bring volatility in electricity market as shown in the case study in the interdependent water-power infrastructure [138]. This study emphasized the need of investment in climate-proof infrastructure to reduce electricity price fluctuations. The drought study in Texas, U.S., investigated the complexities associated with interdepended water-power systems by studying drought vulnerability of thermoelectric generation. It proposed long-term strategies to enhance drought resilience [139]; for example, this study proposed to reduce water demand of thermoelectric power plants by increasing natural gas plants.

Renewable technologies used for pumping and heating, can mitigate the impacts of climate change and can also greatly reduce overall costs for the integrated water-power system of thermoelectric generation [140]. California study [141] focuses on uncertainty principles, interdependence of the sectors, climate change and generalizability and monitored of seasonal and annual environmental changes, and how these impact the optimal strategy. It finds that, in seasons of high water demand, the system will rely more heavily on renewable water and energy sources (at an average rate of ~92%). A study of over one thousand thermoelectric plants across the country models their behaviors under climates from 2035 to 2064, both individually and in 19 collective regional groupings. The research shows a need for region-specific climate-resilience strategies because the plants will be affected differently, but by the same token, the study goes on to show that focusing only on larger regions, as opposed to individual plants, still paints an inadequate picture of the overall needs of the systems [142].

Rising temperatures will both reduce crop yields and increase water and energy consumption in areas that are dry and where irrigation depends on power [143]. A study of Great Britain's thermoelectric power plants investigates the economic impact of cooling water shortages caused by droughts brought on by climate change. The effects of climate change will raise short-term costs for risk mitigation efforts [144]. A study that compares river discharge from three major sources (the Columbia and Colorado Rivers and the western slope of the Sierra Nevada mountain range) of freshwater and hydropower in the Western U.S., found that dry conditions coincide between at least two of them more frequently than ordinary probability would predict, including six instances of all three experiencing dry conditions between 1906 and 1999. These occurrences make it difficult for the varying regions to reliably pick up each other's slack in times of need, and it is expected that climate change will make these occurrences even more frequent [145]. A worldwide hydropower water network study examines the climate change impacts through the 2080s [146].They recommend to plan future power-plant technologies and locations based on water usage and temperature rise [146].

4.4. Decoupling water and energy codependence

Technological innovation and evolution of economic policy are driving changes in the energy sector to lead to less dependence on water. An energy system that does not rely on water means that it would not depend on the reliability of the water system in addition to its own systems, which is clearly beneficial to the system's overall resilience [147]. Many consider decoupling these two systems' interdependence to be a necessary step in ensuring the resilience of the individual systems. Currently the water industry accounts for about 4% of global electricity consumption [148]. Similarly, most countries' second largest use of water after irrigation is thermoelectric power generation. A study in China on water usages by their thermoelectric energy sector between 2000 and 2015 revealed an absolute decoupling for water withdrawal and a relative decoupling for water consumption. This means that despite the expansion of thermoelectric energy production, the freshwater withdrawal rate declined, and the rate of growth of electricity generation was higher than the improved rate of efficiency of water consumption. This is largely due to the use of air and seawater cooling, which help to alleviate the need for freshwater withdrawal and consumption [149]. A study in Abu Dhabi clearly outlines the need to decouple water desalination and power generation processes to make the system more flexible. In the desert climate of the UAE, this is especially pertinent because, in the winter, they could otherwise shut down some power plants completely [150].

Decoupling water and energy codependence has been studied in irrigation, thermoelectric plants, and solar-powered water-pumping systems. A study of water demand for power generation in the southwestern U.S. found that, in times of water scarcity, extracting and purifying brackish groundwater can be as little as one quarter the cost of withdrawing surface water. Dry cooling, on the other hand, is much less efficient and would only become economically viable at much higher average costs for water withdrawal [151]. A study of 1178 thermoelectric plants in the U.S. aimed to determine whether it were more cost effective to use dry or wet cooling with brackish groundwater or municipal wastewater. Based on their least-cost estimates, the study determined that 807 of the plants would save money by retrofitting to using wastewater while 140 could use brackish groundwater and 209 could convert to air-cooling technologies [152]. A study of plants in developing parts of Asia has determined that dry cooling, while alleviating the power sector of its dependence on water availability, also leads to losses in thermal efficiency to the tune of 12–15% of electricity generated in hotter and more-humid regions [153]. One study simulated a completely self-contained solar-powered water-pumping system, disconnected from any power grid. By the researchers' calculations and testing, they were able to mathematically confirm this possibility [154]. Another study implements a different kind of photovoltaic water pumping system in Guinea-Bissau. The system employs design decisions that sacrifice some environmental friendliness and the converter's expected lifespan in favor of more control under unexpected changes in solar radiation. The experimental system succeeded despite the harsh conditions of the region [155].

4.5. Integrated resilience to disruption

Resilience improvement in the integrated water-power distribution system is defined as ability to increase the users' water and power demand after natural disasters [156]. For example, the decision framework to improve resilience of a power-water-distribution network of connected microgrids against natural disasters finds the best operation to restore disrupted loads in the damaged water-power-distribution networks [156]. The integrated water and power systems study of a major metropolitan areas in the US examines the performance of integrated water-power supply systems before and after a major disruption, such as an earthquake [157]. Dynamic resilience is used to quantify the resilience of a multipurpose reservoir system under disruption [158]. In this method, the dynamics of the resilience under multiple disruptions at different times is captured through a system-dynamics simulation approach.

Several studies in the literature investigate mitigation strategies to improve integrated water-power systems under disruption. A 2016 study in Australia's Whitsunday Region investigated susceptibility to increasingly intense tropical cyclones. It spent six months researching strategies to mitigate climate change that resulted in a year-long experiment in solar power. After a tropical cyclone pulverized the Bowen Water Treatment Plant in 2017, a new setup with solar power was finally instituted in 2018, and the study found that this not only helped sustain the water supply that relies on the power, but it actually reduced electricity costs by about 40% [159]. A study focusing on hybrid power systems outlines the utility of integrating renewable energy sources into grids with existing fossil-fuel sources, which rely heavily on water cooling. This can help increase overall resilience of the system while still maintaining the utility of the power plants already in place, while also gradually moving to replace them outright. The need for this is presented as a response to disasters such as the nuclear plant explosion in Fukushima caused by earthquakes and tsunamis, costing about $188 B in repairs and radiation cleanup [160]. One study suggests that building resiliency into the water system requires the implementation of a smart water grid, which can control devices and automate monitoring, as well as creating a network across all linked components. These smart grids can contain sensors to detect and prevent damage caused by flooding through the deployment of smart valves and pumps, which can be operated automatically as needed [161].

4.6. Quantification methods

Wide range of quantification methods are adopted in the literature to assess interdependent water-power system. The quantification methodology involves simulation, combined simulation-optimization, predictive modeling, stochastic system modeling, and multi-objective optimization. System dynamics simulations were used to model climate and water resource change [142], drought and climate change [144], and social system dynamics [162]. Climate and water-resource change simulates coupled water balance, thermoelectric power, and thermal pollution [142]. Social-system dynamics simulates social drivers and outcomes of food, energy, and water systems at different scales [162]. Multiobjective optimization was used to optimize operation of pumped water storage [135], solar and wind energy [87], and wind-powered desalination and PSH [136]. Agent based simulation is used to model droughts and heat waves [85], water–energy modelling [86], and planning of the energy-water-food nexus [138]. Table 7 summarizes various quantification method adopted in the literature.

5. Challenges in quantitation of resiliency of integrated water-power system

Resiliency assessment of the interconnected power and water systems requires a thorough of the relationships between a disruption, its impacts, and the resulting consequences throughout the system. Such understanding is critical to (1) define the boundary of the system and its resiliency assessment and (2) inform decisions that could lead to performance improvements. However, quantitation of resiliency is not without challenges, given the broad extent and dimension, large number of stakeholders and sectors, data requirements, and diverse threat and consequence landscapes, among others, all of which challenging to capture [199]. Key challenges are described below:

Table 7
Different state-of-the-art quantification methods to assess interdependent water-power systems.

Quantification Method	Studies
Linear optimization Multiobjective optimization	System-level resilience of thermal power generation [163], operating rules of pumped water storage [135], solar and wind energy [87], wind-powered desalination and PHS [136], large-scale interdependent water energy optimization [164], optimized pumping operations [165]
Large scale nonlinear optimization Mixed integer nonlinear Stochastic programming	Interdependent water energy supply [130], economic dispatch water-energy microgrids [166], multipurpose reservoir systems [131], scheduled water-distribution pumps [167], optimal water–power flow-problem [168], water network-demand response [169], multi-supply spreading basin systems [170], planning water-energy nexus system under uncertainty [88]
Discrete event simulation Long-term time-domain simulation	Drought within interdependent water power [171], decoupling water and power dependency [149], power-system resilience in interdependent water-power [172]
System dynamics	Asses climate change and water resource [142], drought and climate change [144], social-system dynamics [162], restoration measures [173], disaggregated simulation model [174]
Agent-based modelling	Droughts and heat waves study [85], water–energy modelling [86], water energy nexus planning [138], water and related energy behavior [175]
Combined optimization and simulation	The integrated resilience computation method [176], integrated state-estimation framework [177], gas water supply chain [178], irrigation system design [179], multisector water energy [180], surface irrigation [181], real-time pump and valve operation [182], implicit stochastic optimization framework [183]
Statistical analysis	Southern Africa's interdepended water, power and food [140], California's water and hydropower systems [145], resilience of integrated power and water systems [157], brackish water use [151], water withdrawal for thermoelectric generation [152], power plant vulnerability [153]
Decision theory	Multidivisional planning model [184], integrated food, power, and water systems under climate change [141], energy, water, and climate-change nexus [185], biology into the energy-water nexus [186]
Generic simulation methodology	Static and dynamic resilience comparison [158], battery-less photovoltaic water-pumping system [155]; multi-reservoir systems operations [134], photovoltaic solar technologies [187]
Input-output model and linkage analysis	Water-energy nexus of city [90], water power nexus analysis [83], water-energy scarcity nexus risk [92], regional water-power systems modeling [188], global change-assessment model [189]
Machine learning	Pumping station reliability [190], hydropower reliability [191], grid-outage prediction [37], big data [192], nexus in households [193], climate sensitivity [194], groundwater-potential mapping [195], micro-hydropower energy recovery [196], dam-leakage flow prediction [197], real-time pump control [198]

5.1. Different temporal and spatial scales

In power systems, electricity must be balanced at all times, and sudden changes (e.g., generation tripping offline) can have instantaneous impacts on frequency stability; therefore, the emphasis is typically on timescales of cycles to months (i.e., the duration of the fuel supply). While there is expectation that water be available instantaneously in the tap, there is typically sufficient storage that resilience is thought of on longer timescales, such as days to years [200].

In some instances, disruptions to one system may immediately propagate to another. If there is sufficient storage, the impacts may be delayed in one or both directions, leading to longer mitigation times. The following qualitative examples highlight differences in spatial and temporal scales of dependencies:

5.1.1. Agriculture and irrigation

Demand scenarios are different in the integrated power and water systems of irrigation agriculture and hydropower production. Hydropower produces energy on a second-by-second basis, and water demand for hydropower needs to be met each second. Water demand for irrigation is seasonal and depends on the hydrological water network. Hence, water demand for irrigation is highly variable across the year. In the presence of disruption of the integrated power and water system of irrigation agriculture and hydropower production, water demand for hydropower would require near real-time response. Depending on the arrival of the disruption, water demand for irrigation systems may not require real-time demand response.

5.1.2. Municipal

The nexus of a city freshwater and power systems is an example of the relatively immediate impacts of a disruption or degradation on the other system. Consider the integrated power and water system of a local municipal utility, where power and water demands must be met on a continuous time basis. Given the need to dispatch both power and water in the presence of disruption, an interdependent power and water utility that simultaneously meets electrical power and potable-water demand needs near real-time response to increase the resiliency of the interdependent system. A decision that impacts the resiliency of such a system is the dispatching strategy of water production and power generation.

5.1.3. Climate impact

The temporal resolution of integrated water-power systems to assess climate impact ranges from years to decades [137]. Climate variability measured via heat waves and droughts [201,202] may take years to understand impact on water resource [203,204] and thermoelectric-power generation [205,206]. Large temporal- and spatial-scale resiliency assessment is needed to understand linkages among climate, water resources, and power system and to identify critical regions. Because climate change does not have near-term impact on water demand for hydropower and thermoelectric-power generation, mitigation options to enhance the resiliency of integrated power and water systems are not near term.

As shown in the cases above, joint resiliency assessment interdependent water and power systems is challenging because of the differences in their spatio-temporal scales. Power systems requires short response time because of lack of technology to store large amount of electric energy. . In contrast, water systems allow flexibility to a certain extent to balance supply and demand because water system spatially defined by a catchment area, comprises of natural and man-made hydraulic entity. Moreover, technology is not a barrier to store water as natural water reservoirs (e.g. ground water, lake) and other water infrastructure is serving as water storage entity. Coarse spatial and temporal resolutions may exhibit inaccurate assessments of resiliency.

5.2. Water energy nexus metric

Water-energy nexus resilience literature presents a picture of a notion with a wide spectrum of interpretations and diverse formulations across disciplines [207]. This conceptual dissonance causes multiple characterizations, seemingly with no path toward a unified quantification metric. This may hamper synergy and trade-off studies, which could only partially provide insights on cross-system dynamics and joint resilience. Efforts currently made consider metrics explicitly function of power or water systems operation. Given the differences in the systems operations, these metrics can only point to the strengths and weaknesses of each system, separately. An overall resilience quantification reflecting the interdependent water-energy system operation, using weighted average of metrics [208] may be an avenue for exploration. However, the issue of weight determination, time and scenario dependence would appear daunting tasks in scoping resilience.

5.3. Integration of different model types

Although interdependent, water and power systems are composed of different elements, interacting not only among themselves, but also across their respective system boundaries. For example, hydro sources are linked to both water (water treatment, irrigation, etc.) and power systems (power generation, water cooling, etc.). Such an integrated structure requires models that capture, both all relevant components and their interactions.

A model has three main attributes: fidelity (how close the model is to reality), resolution (how granular the model is), and scale (how big/small the system it represents is) [209]. In attempting to capture the structure, dynamic behavior, and emergent properties of the multiscale interactions described earlier, modelers have to specify these attributes. This is where the challenges lie. Power system models mimic systems that are interconnected network of power generation, transmission, distribution systems, for the electricity delivery to consumers at minimal costs. Similarly, water systems model mimic systems that are interconnected networks of water supply, transportation, treatment, distribution systems, for water delivery to consumers, also at minimal costs. Modeling tools to estimate integrated water-power systems resilience would need to capture these factors, at the relevant level of details and scales. Irrigation systems for instance, would require models that establish the relationships among crop-water requirements, groundwater availability, water constraints, and crop growth. The model scale can change if the modeling landscape is extended to consider environmental impacts consideration, or economics. In such case, physical earth system or economics factors representation will be needed in the model.

These multi -scale and -layered interactions may make the efforts to develop a unified modeling platform to quantify resiliency of integrated water-power systems virtually impossible, that is, if this is where the research community is heading. One approach to address this challenge may be to modify existing tools to enable them to effectively quantify and estimate the resilience, as presented by Ref. [199], using metrics specific to the original purpose of the model. An alternative may be energy and water system dynamics modeling at compatible scales. That is, investigating systems where disruption impacts are seen at a similar time scale.

5.4. Integration of nexus thinking and resilience

While many studies have shed light on resilience and the water-energy nexus, a clear need to improve the understanding of resilience across or in the water-energy nexus remains. In investigating the implications for larger, more-complex systems—integrated water-power systems for instance—it is essential to go beyond the boundaries of systems, to understand the configuration of feedback relations, and to assess precisely any joint vulnerabilities. Most previous studies, focused on the "water for energy" side of the nexus, instead of the "energy for water" side [210], do not facilitate full knowledge and comprehension of water and power systems integration. Hence, applying resilience thinking in addition can only exacerbate difficulties in understanding.

5.5. Large-scale computation

High resolution of integrated water-power system resiliency requires large-scale computation. For example, if resiliency quantification couples grid conditions, power markets, and multipurpose reservoir systems, simulation and modeling the entire landscape would require integration of interdependent water-power systems at different spatial and temporal resolution. Depending on the varying temporal and spatial resolution, computational complexity can increase exponentially. Stochasticity and variability in parameters (e.g., changing precipitation nature and temperatures, uncertainty in water, increasing climate variability and disrupted power production and distribution) further increase the computational complexity.

5.6. Data integration from a diverse set of actors

Data integration from a wide range of actors with both overlapping and conflicting interests can be challenging. A wide range of stakeholder are involved in an integrated water-power system. Because diverse stakeholders have overlapping, but also conflicting interests, high-resolution resiliency analysis will require sufficient data to capture relevant factors necessary to quantify integrated water and power systems.

6. Framework to assess resilience of integrated water and power systems

A current gap in the understanding of resilience of integrated water and power systems is a framework that is sufficiently general to be broadly applicable, yet specific enough to be quantifiable. The initial application of this framework will be for irrigation systems. Nevertheless, a comprehensive framework for evaluating integrated resilience is possible through cataloging the fundamental linkages and applying foundational resilience principles. Spatial and temporal variability in power and water linkage also add complexity to resiliency assessments, but fundamentally, the principles can be applied across timescales of interest. The framework proposed here is independent of specific metrics, and can be used as a basis for calculating a large range of resilience metrics most relevant to the system of interest.

The conceptual framework to assess integrated water-power system resilience follows these steps:

Step 1. Identify objectives and priorities of the objectives of the water and power systems

This step provides meaning to the process by clearly identifying the system objective and performance measurement. Defining optimal operations versus a minimum set of objectives required to perform the design function is necessary to evaluate the system under when under various levels of duress. As an example—optimal: supply all residents with clean water for drinking and irrigating of gardens and lawns; minimum normalcy: supply hospitals and local incident-recovery centers sufficient water with rationed delivery to residents. Identifying the system mechanisms that are available to mitigate incidents by slowing the consequence (resisting), responding, and assisting in recovery to a nominal or near-normal state.

Step 2. Map dependencies between the water and power systems

This step identifies the linkages between water and power systems. Potential linkage includes hydraulic connections between water and power and water allocations between the power and agricultural sectors. Output from this step would be a network representation of integrated power and water systems that links various components in the systems. The network representation consists of source nodes, sink nodes, conveyance nodes, and arcs. The network representation of power- and water-system dependency can be completed by mapping power input to water grids and water inputs to a power grid.

Step 3. Identify the mechanisms for failure and response within an appropriate boundary for the system

This step evaluates of where failures or degradation in energy or water impact ability to meet the objectives of other systems and describes properties or capabilities that are intrinsic or designed into the system which provide mitigation and response capabilities. The step determines existing practice and approaches that decide the allocation of water resources between power production and other demands, such as irrigation. Existing water management based on irrigation and other water demand can be identified. The operating characteristics (e.g., mean inflow, capacity, minimum and maximum storage) of existing hydropower are measured.

A boundary of the coupled system should extend to a distance where impacts can be evaluated at a reasonable scale. For example:

6. Small hydroelectric (e.g., run-of-the-river or irrigation-generation) systems would depend on both the constraints on water resource and the existence and health of the electric distribution system. The boundary must be appropriately set with respect to the water resource and the electric grid. That is, the model would not need to incorporate the entire North American watershed or power system.
7. Freshwater supply of a municipality would need to consider water storage and the availability of power to assets such as pumps. The extent of boundary conditions depends on vulnerabilities that effect that availability. As an example, if a problem at an important transmission substation can make the normal path of electricity delivery out the boundary, the model should include that.

This step allows for consideration of natural and man-made threats to the system and consideration of controls that mitigate them. For example, cybersecurity could be considered where elements of control are connected to digital devices or are dependent on electronic communications. The controls and capabilities should be assigned to one or more timeframe given by the Rs of resilience.

Step 4. Generate a dependency-impact profile by simulating disruptions to the business-as-usual case

In this step, the resiliency profile of power and water systems can be generated for various disruptions by understanding the vulnerability and system recoverability of integrated power and water systems under disruption (Fig. 4). A simulation will be needed to understand the transient behavior of the water and power system under disruption. For example, if water demand for power and the water irrigation system are vulnerable to water availability, disrupted and system-recovery states can be identified by simulating the power and water system based on existing recovery strategy. Note that the disrupted state of a power and water system may vary based on temporal and geospatial location and depend on integrated water-power networks, including their hierarchical levels, such as equipment, plant, regional, and city levels. Resiliency of power and water system to a disruption can be quantified by comparing the loss of service at disrupted and recovered state with business-as-usual scenario under no disruption. Major output from this step are the resiliency of power and water systems under disruption, based on recovering strategy in the business-as-usual case (Fig. 5).

The depictions in Fig. 4 are general and notional for the general dependency of a water system on the electric grid. This can be reversed for generation examples in which the dependency is on water to support the generation objective. For special cases where there is a mutual dependency, simple loops would occur and need to be resolved. A tangible form of the metrics for the power system has been offered in prior art [22]. A similar metric that considers water-side storage and a mapping of metrics to the water resource remains a need for this domain. The metrics can first be created to consider design or investments for stakeholders in a human-led analysis and/or to apply a more-sophisticated method, as described in the next step. The metrics can also be used in an operational sense to provide operators of the two systems with a situational awareness of the state of the system such that contingency analysis and mitigating actions can be considered on a day-to-day basis.

Step 5. Develop optimization model to improves the resiliency of power and water system

Because current water-power system decision-making under a

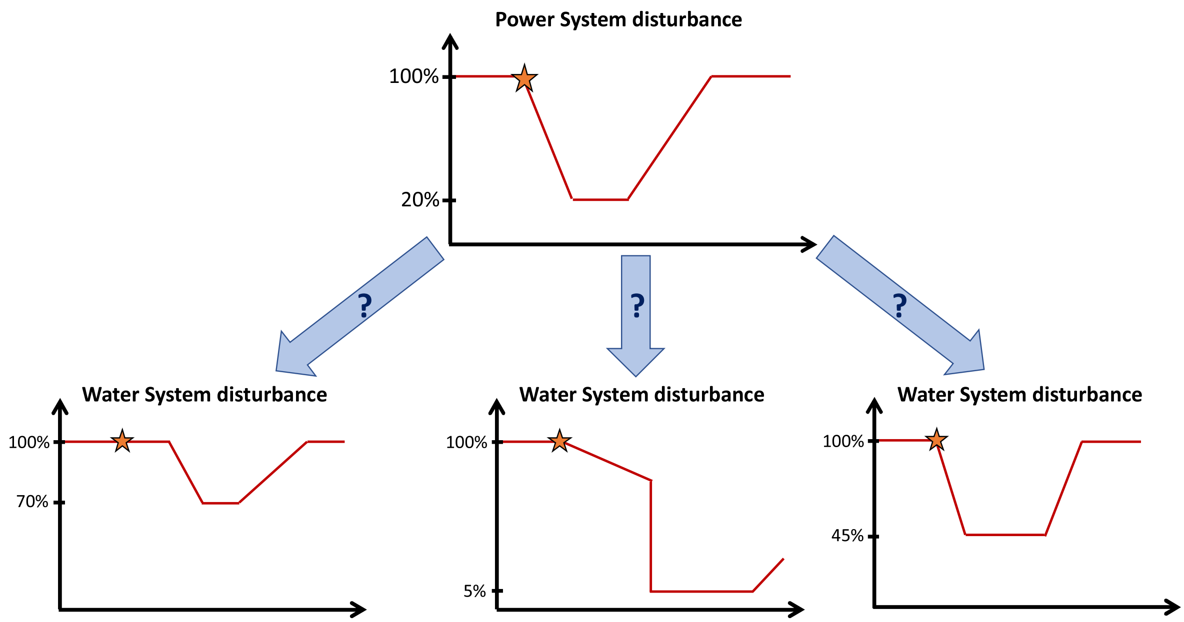

Fig. 4. Propagation of an event between water and power systems may vary depending on system-specific interdependencies, system state, and disruption. The inverse of this figure (prorogation from water to power systems) is also true.

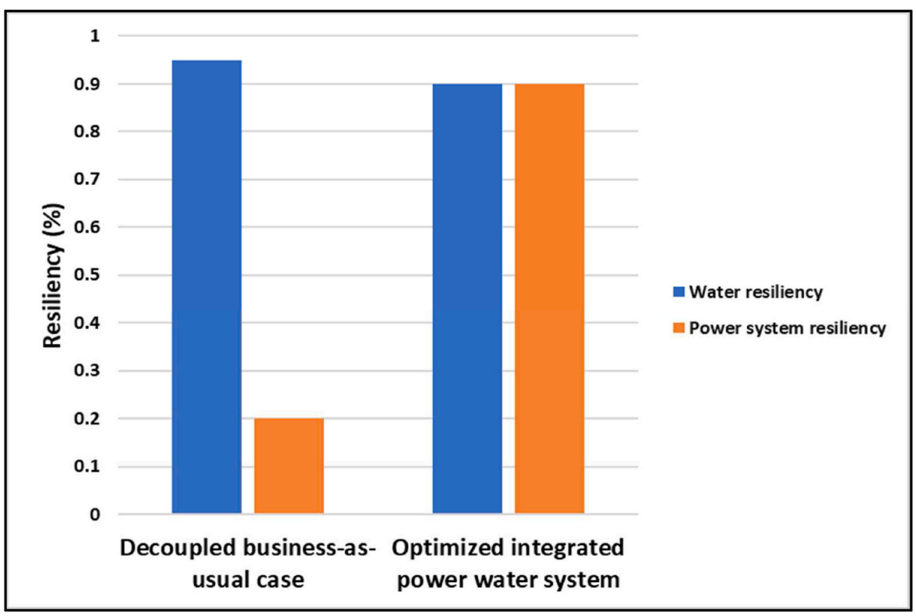

Fig. 5. An example of output from the conceptual framework to assess integrated water-power system resiliency. Achieving higher water resiliency may not resulted in higher power system resiliency. By utilizing conceptual integrated power, it is possible to achieve target resiliency of both power and water system.

disruption is complex and often not coupled, the strategy to achieve power-system resiliency may not be suitable to increased water-system resiliency and vice versa. A bi-objective optimization model is needed to understand how decisions impact integrated water and power resilience and improve both system outcomes.

An integrated bi-objective optimization model will identify a spatial-temporal recovery strategy that enhances both power- and water-system resiliency under various operating constraints of the water-power system. For example, the water-system decision could consist of identifying optimal reservoir operations that decide sequence and volume of water release, optimal pumping policy under disruption state that maximizes resiliency of the integrated water-power system under storage-capacity and flow-limitation constraints. Similarly, a decision in a power system includes optimal dispatching schedule for the power system, optimal sourcing of power, and a grid design under disruption that maximizes the net benefits of the integrated water-power system. It is expected that the conceptual framework to assess this integrated water-power system's resiliency would result in improvement of both power- and water-system resiliency (Fig. 5).

7. Opportunities for improved water and power system resilience

Irrigation systems exhibit the inherent interdependence between the operation of power and water systems. Hence, the proposed conceptual framework creates a great opportunity improve water-power system resiliency. This integrated water-power system resiliency analysis can guide investment in power resources. For example, optimal curtailment of pumps can be determined by understanding the state of soil moisture and plant-growth cycle based on priorities or cost of electricity.

Improved water-power system resilience can be a critical tool for irrigation modernization. The modernization of irrigation districts and inclusion of modern implementations for hydropower generation offer possibilities to enhance the ability of each of these systems to supply their respective demands during normal conditions or after the occurrence of disruptions that affect their operation. Resiliency-enhanced opportunities can be modeled using an integrated water-power resiliency framework. For example, the availability of tanks or reservoirs for water storage (if allowed, according to water rights) provides a mechanism to supply water demand during periods of scarcity. Water can be stored by pumping when power demand is low and electricity is cheaper, and then it can be released to supply water demand during peak hours, reducing costs of electricity consumption. At the same time, stored water can supply water demand in the case of limitations in water availability or operating issues at treatment facilities. Water stored in tanks that is released to supply water demands can also be used for small-scale hydropower generation, including PSH or in-conduit hydropower, by using microturbines installed where the water flows (from reservoirs or in canals). The power generated from these sources can be used to supply pumping-power requirements. This generated power offers another opportunity to enhance the resilience of the interdependent water-power systems; the power can be stored in batteries; in case of disruptions in the main power grid that affect the power continuity for pumping purposes, the generated power can be used to supply power demand in the irrigation district, minimizing the impact of the disruption and also maintaining the operation of the irrigation system.

From this general perspective, the interdependence of these infrastructures not only allows their normal operation, but also leverages the capability of both systems to maintain operational conditions, even in the case of contingencies. This represents enhancements in the robustness of both power and water systems. It is important to keep in mind that additional regulatory challenges are attached to these implementations; these are related to water rights and investment-cost funding.

8. Conclusion

The impact of disruption on interconnected water-power systems can be understood through assessment of the resiliency of integrated water-power systems. This research outlines the relevant factors necessary to understand and advance quantification of integrated water and power systems. It also presents a review of integrated water-power systems resiliency. This research found that primary challenges of computing integrated water power systems are a) different temporal and spatial scales of water and power systems, b) large scale computation to handle stochasticity and variability in parameters, c) the need of integration of different model types for various sectors in the interdependent water-power system, and d) data integration from a wide range of actors with both overlapping and conflicting interests. Based on a literature survey, the authors present quantification and computational steps needed to understand integrated water-power systems resiliency, and a conceptual framework is proposed to quantify system resiliency. The conceptual framework emphasizes the need of a bi-objective optimization method to improve the resiliency of integrated water power system. Finally, this research identifies an opportunity for integrated water-power system resiliency framework to improve the resiliency of interconnected power and water systems in irrigation systems.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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