Heliyon 10 (2024) e32122

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Interdependent water and power infrastructure model (IWPIM): A modeling approach for water and energy resource management in rural communities

Ange-Lionel Toba *, Liam D. Boire, Mohammad Roni

Energy, Environment Science and Technology, Idaho National Laboratory, ID, USA

ARTICLE INFO

Keywords:
Integrated energy systems
Community resilience
Systems modeling
Multi-agent system
Water-energy nexus

ABSTRACT

The importance of the dependencies between water and power systems is more acutely perceived when challenges emerge. As both energy and water supply are limited, efficient use is a must for any sustainable future, especially in rural areas. Although important, a modeling tool that can analyze water-energy systems interdependencies in rural systems, at the architectural level highlighting the physical interconnections and synergies of these systems, is still lacking. We present a multi-agent system model that captures the features of both systems, at the same levels of fidelity and resolution, with coordinated operations and contingency components represented. Unlike other models, ours captures architectural features of both systems and technical constraints of the systems' components, which is critical to capture physical intricacies of the interplay between systems components and shed light on the impacts of disruptions of either system on the other. This model, which includes multiple infrastructure components, shows the importance of a holistic understanding of the systems, for cooperation across systems physical boundaries and enhanced benefits at larger scales. This study looks to investigate water-power resource management in an irrigation system via the analysis of physical links and highlight strengths and vulnerabilities. The effects of water shortage, water re-allocation and load shedding are analyzed through scenarios designed to illustrate the utility of such a model. Results highlights the importance of inter-reservoir relationships for alleviating effects of disruption and unforeseen rise in energy demand. Water storage is also critical, helping to mitigate the impacts of water scarcity, and by extension, to keep the energy system unaffected. It can be a viable part of the solution to compensate for the negative impact of shortage for both resources.

1. Introduction

The concept of the water-energy nexus (WEN) emerges from the relationship between water and energy systems [1–4]. The rising population will predictably add great pressure on the limited resources, including water and energy, presenting communities with trade-offs and potential conflicts among these resources that have complex interactions [5,6]. Resource scarcity and variability, coupled with uncertainties could potentially lead to more vulnerabilities in both energy and water systems [7]. The literature on the WEN is quite unanimous on the point that the analysis of this integration is necessary for decision making [8,9]. However, the ability to

* Corresponding author.
E-mail address: danhoangelionel.toba@inl.gov (A.-L. Toba).

https://doi.org/10.1016/j.heliyon.2024.e32122
Received 8 March 2024; Received in revised form 27 May 2024; Accepted 28 May 2024
Available online 7 June 2024
2405-8440/

deal with challenges due to the links between water and electricity is inhibited by a limited understanding of the nature of those links. It is therefore important for transformative and sustainable solutions to develop a more integrated approach to address the challenges and opportunities of the WEN. Such an approach can support better informed water and energy planning decisions, and further understanding of both systems mechanisms and their linkages. It will ultimately assist policymakers and resource managers in water and energy sustainability [10].

Water and power systems have been traditionally analyzed as two separate and uncoupled infrastructure systems. Strategies for the management of one system are often developed independently of the other, failing to account for the linkages between them. This may result in conflicting strategies and increased competition for the same resources. For this reason, only when viewed through the lens of interdependence can these integrated systems truly be analyzed. Meeting power systems needs requires water for mining, fuel production, hydropower, and power plant cooling [11]. Likewise, water systems require energy for pumping, water treatment, water distribution, and water collection [11]. Many vulnerabilities, which need to be addressed, come with the intricacy of these systems. The availability of water has a profound impact on the availability of energy, while energy production and power generation activities equally affect the availability and quality of water [12]. Water treatment and wastewater treatment plants account for about 3 %–4 % of the total electricity used in the U.S. [13,14], with approximately 80 % of this total electricity consumption employed for pumping and distributing water [15,16].

Most WEN studies focus on production processes, such as electricity production, water treatment, operational flexibility, and dispatch, with very little contribution to the overall system operations. The analyses conducted are still, for the most part, geared toward the performance of one system or the other [17–21] with no holistic view on the system. Some other modeling efforts represent either system in a coarse manner with different levels of fidelity and resolution [22–26]. WEN studies have been performed at multiple scales including household [27,28], community [29], city [30–32], national [33] as well as regional [34,35]. WEN systems in agricultural zones require different management strategies as they present different characteristics. These areas are more sensitive to others as they often lack resources to overcome drop in water supply for instance, which has consequential impacts on agricultural crops. Research at that scale aim to optimize systems design and operations [36–38], costs and operational policy [39–41]. Our purpose is not optimization, rather to understand systems interdependencies and investigate the "two-way" physical interconnections and synergy of water and power systems, when it comes to disturbance effects. The challenge of system interdependency is deepened by the fact that systems operate differently, rely on different combinations of supply, and have different supply and demand profiles. Reducing the possibility of future power and water shortages requires accountability for the mutual dependence of the systems at every level of operation. From the perspective of critical infrastructures, resilience in power and water systems should be associated with the joint capability of these infrastructures to supply their respective power and water demands. The above-described literature suggests a growing need for models and simulations that provide insights into the interactions and feedback structures of power and water systems.

In this paper we present the multi-agent system model, the Interdependent Water-Power Infrastructure Model (IWPIM), which is intended to simulate coordinated water and power systems operations, help demonstrate opportunities and challenges presented by their interdependencies and assess resilience through physical linkages. IWPIM captures the features of both water and power systems, in agricultural zones, at similar levels of fidelity and resolution, with detailed coordinated operations and contingency components represented.

Unlike other models, the one presented here captures architectural features of both systems and technical constraints of the systems' components. The importance of analysis at this level is critical, as it furthers the understanding of the physical intricacies of the interplay between systems components, which would help improve system design if needed, for better management. By architecture, we mean the system structure, its components, the interrelationships between them and how they function together [42]. The approach presented remains at a level of detail adapted to the practical simulation of management of large and complex systems. It captures energy/water management strategic functions like generation, distribution, or regulation, with components responsible for the operations of these functions. In this sense, voltages, phase angles or water pressure for instance, are not taken into account. Water canals (flow rates) or reservoirs (capacity, flow rate), in their capacity of water sources for example, or water regulators/dispatchers in their quality of real-time operation to meet water delivery requirements and coordinate interconnected operations (assess energy requirement with utilities for instance), are accounted for instead. Such level of details offers a sufficient level of fidelity to perform medium-term systems activities and support architectural questions, critical when dealing with physical dependency (functional and structural linkage between components of the water and power systems). This effort seeks to improve rural water-power systems modeling in a manner that overcomes the limitations inherent to modeling approaches that do not incorporate their mutual dependencies, do not incorporate component-level decision-making process and the system regulator function for both systems, and do not analyze both systems on similar fidelity levels and compatible resolution scales. This differentiator proves critical for supporting the design and evaluation of policy options.

This study contributes to the effort to bring transformative change in water and power systems resilience research. That effort breaks down old dichotomies and tradeoffs, utilizing synergies to deliver benefits to both systems, while also enriching and empowering communities and opening opportunities for novel integrated energy technology and water management solutions. This present study looks at integrated system resilience through the lens of interdependencies. We aim to highlight the impacts of couplings between water and power systems on their operations, that is, the extent to which they continue to operate while under disruption. By capturing these relationships, the system resilience can be better understood, and disturbances better prepared for. The paper is structured as follows: section 2 defines the methodology, explaining the notion of resilience and how it is quantified, as well as the modeling approach. Section 3 presents the results. Section 4 provides a conclusion to the work and its limitations.

2. Material and method

2.1. Joint resilience formulation

A system's resilience centers around the system's ability to recognize, adapt to, and absorb disturbances in a timely manner [43, 44]. A resilient system is one that maintains continuity of essential functions and services, at an accepted level of operational normalcy in response to disturbances [45–47]. Such a level would depend on the certainty of the criticality of the services rendered. Addressing resilience issues helps system decision-makers gauge the quantitative impacts of contingencies using measurable and differentiable resilience components.

We seek to better identify the synergy needed to improve the resilience of power and water systems, as opposed to a disconnected or detached view. Improvement of power grid resilience includes integration of distributed energy resources (DER) [48], microgrids [49], and line hardening [50–52]. For the water system, isolation as a mitigation measure was implemented [53]. This measure enables modularity. If one water storing unit closed, the other units can still provide service. Diversification of water sources (surface and ground water), use of reservoir storage, and long-term adaptation planning strategies [54] are other measures to enhance resilience. The coupling of water-power systems means that the resilience of one impact the resilience of the other system. In resilience assessments of such integrated systems, it is beneficial to understand the system's ability to absorb a disruption and recover to a normal state and the required infrastructure and modernization needed to improve resilience. For instance, droughts in California have intensified the pumping of water, which requires a high quantity of electricity, and may eventually dry up the aquifers useable water [55] and hinder farming and agriculture [56]. It is therefore critical to analyze water and power systems as integrated, that is, a composite system whose components can be understood as interdependent subsystems, working together in a concerted manner to form a unified whole.

The resilience of a system can be characterized by its performance when stressed by internal or external interruptions [57]. The "Rs" of resilience, i.e., Recon, Resist, Respond, Recover, and Restore presented by Refs. [58,59] describe the performance of the systems before, during, and after a disruptive event. Our analysis is currently focused on the *recon* and *resist* phase, which describes the immediate consequences of the system from disturbances. In such an uncertain world, disturbances can proliferate across scales and systems in unexpected ways, reducing system performance [60]. Resilience thinking, therefore, emphasizes the need to design, develop and manage systems in a way that resources, and ultimately their function when facing inevitable disturbances, be sustained, be it of short or long duration [61].

In this work, resilience can be understood through the analysis of respective system performance, quantified as the ratio of actual water and power release to the water and power demand during a given time period. By investigating the general effects of disruption of either system on the other, vulnerabilities and strengths can be identified, and resilience issues can be addressed more effectively. Although it is key to understand resilience of power and water systems in an integrated fashion, one should not omit the uniqueness of each system structure and functionality. Any eventual joint metrics which simultaneously consider the performance of both systems would obfuscate information from the individual systems. Therefore, to grasp the origins and impacts of a disruption on a more granular level, the performance of the two systems must be reported in an individual format, though interpreted jointly, with implications for the whole system.

2.2. Modeling approach

We developed a multi-agent-based simulation system, using an object-oriented approach based on the Discrete EVent System specification (DEVS) formalism [62], to capture and evaluate operations taking place both in the power grid and the water systems. DEVS describes the system component behavior using *atomic* models, via state transition functions, and the system structure using *coupled* models, specifying interactions between *atomic* models. An *atomic* model is formally defined as a tuple $S = (T, X, Y, Q, \delta, \lambda)$, where T is the function, determining the lifespan of a given state, X and Y the set of inputs and outputs respectively, capturing messages/interactions between models, Q is the set of states, δ the transition function, internal and external, and λ the output function. See Refs. [63,64] for more details.

This formalism is appropriate for event-driven models, such as systems whose states change anytime an event takes place [63], that is, changing demands or weather variation affecting renewable energy sources for power generation. Discrete Event Simulation (DES) and DEVS have been used to address management issues in both water [65,66] and power [67–69] systems. Each event occurring at a discrete time causes a change in the system, may it be fluctuation of water level in water storage, or power/water demand. This is with the assumption that in each time interval, as small as it may be, the system is in a steady/nonchanging state. This assumption reflects assumptions made in grid system management studies, that consider load change on an hourly basis [70], with no change in between hour or sub-hour time unit. Huang, Scholz [65] in their paper, demonstrated that actions as part of a water management system strategy can be treated as discrete events for simulation models. Water flow, reservoirs and water storage levels which are generally considered as continuous and captured by physically based equations, can be captured and described as a sequence of events, with quantitative values recorded at discrete times. Just like in the power system, we can assume that in each time interval, the system is in a steady state, and fluctuations of water level in canals and demands remain the same.

While DEVS and Agent-Based Modeling (ABM) share some similarities (built around the use of agents), there are distinct differences in terms of paradigm and system representation. DEVS modeling paradigm focuses on discrete events and the state changes of agents that occur as a result of those events. It provides a formal framework for modeling and simulating systems with well-defined discrete events. ABM modeling paradigm focuses on individual agents and their interactions within a system. It simulates the behavior of individual agents and their collective effects on the system, leading to emergent behavior at the system level [71]. Markov process formalisms is also used to model and analyze systems using state transitions [72]. However, although DEVS transitions between states are triggered by discrete events, and the subsequent state changes are explicitly defined, Markov processes are inherently probabilistic, with transitions between states based on probabilities or transition rates. Because we consider changes in demand as events rather than probabilities and the integrated system as a discrete-event dynamic system at discrete times, DEVS is better suited.

2.2.1. Model building implementation and structure

Fig. 1 shows the multi-layer architecture of the integrated water-power systems. The subsystem layer captures the relationships between the different components of each system (water and power). The integrated systems layer captures the relationships between the different systems. Between these layers, a flow of information is exchanged, to allow systems to function collaboratively. Systems components are represented as agents. Table 1 lists the agents, modeled as *atomic*, represented as event-based dynamical systems, interacting with each other, describing the environment [73]. Attributes, objective, and behaviors are also defined. Objectives are the roles they play in the system. Attributes are what differentiate agents from each other. Behaviors are rules determined through internal or external transition functions, defining how a state changes internally or externally (caused by outside interactions), respectively, and through output function, defining how a state generates an output event. Event occurrences cause the states to change, ultimately leading agents to perform the corresponding actions. Each state change leads to changes in the systems, or consequences on the entire system at each time step assuming a steady state. The modeling approach consists of tying state changes triggered by events to agent behavior.

Fig. 2 shows excerpts of DEVS state transition diagrams of the model components. Initially, supply source agents (Fig. 2a) at state *idle*, transition to state *supply*, triggered by an internal transition function. At state *supply*, the agents generate supply quantities (water or power) via *?supply_info*, to regulator agents. In parallel, demand agents (Fig. 2d), having transitioned from state *idle* to *request*, generate demand via *?demand_info* to regulator agents as well. From *request*, the state transitions to *wait*. At this state, demand agents expect messages, *!fulfilled_info*, from regulator agents, indicating the amount of demand met. Once received, the state is changed to *compute*, and the ratio of demand to demand met is calculated. The state transitions again to *request*. Once regulators agents (Fig. 2b) receive both *?supply_info* and *demand_info*, state transitions to either *store* or *request*. This is, depending on the balance supply-demand. If there is an excess of supply, the transition to state *store* occurs. At that point, the agents send *?request_info* to the storage agent, specifying the excess amount of power and water to store, and then transition to state *dispatch*. The message *!dispatch_info* includes what source and how much of this source supply is called upon. The next state transition is triggered, from *dispatch* to *send,* forwarding *!fulfilled_info* messages to demand agents (water pumps, farms, houses, etc.), indicating how much of the demand initially requested can be fulfilled. Subsequently, the state changes to *idle* again, and the cycle repeats. If there is no excess of supply, the transition to state *request* occurs, indicating the deficit in water or power to offset. Similar to the case when there is excess, *?request_info* is sent to the storage agent. However, this time, from *request*, the agent state changes to *wait*, expecting a message from the storage agent to determine how much, if not all, of the requested quantity can be delivered. Once received, via a *!surplus_info* message, the state changes to *dispatch* and follows the same process as in the situation of excess explained above. Storage agents (Fig. 2d) initially in state *idle*, transition to *store* (if supply outweighs demand) or *supply* (if demand outweighs supply). If the agent state changes to *supply*, the agent sends *!surplus_info* to regulator agents, and then changes to state *update*, to update the remaining quantity of power or water. The state finally changes to *idle*, and the cycle repeats. If the agent state changes to *store*, no message is sent, and the state transitions to *update*. These transitions take place in both water and power systems for all agents.

As agents have different role, they have different priorities. That is, certain agents may require information from others to meet their objectives. Fig. 3 shows agent activities prioritization, illustrated by numbers on arrows.

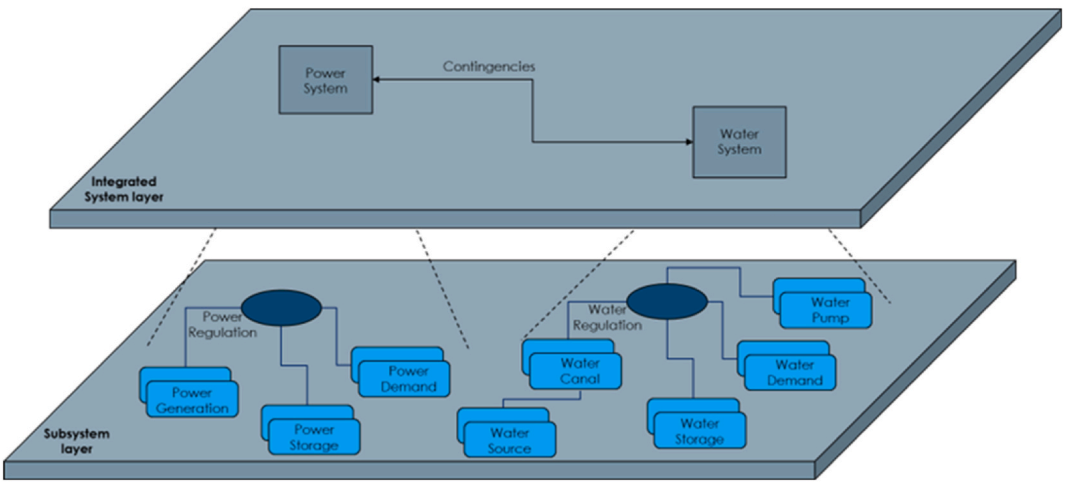

Fig. 1. Hierarchical conceptualization of the integrated water-power systems.

Table 1
Integrated power-water systems components.

Agent: Power and water demand model
Attributes:
• Type of demand: Water or power
• Location: Name of the location it belongs to Objectives: Request power and water, consume power and water
Behaviors:
• Create aggregate load and water demand based on location.
• Compute the amount of demand met
Agent: Power supply model
Attributes:
• Technology: Solar, wind, hydro, gas, nuclear, biomass, etc.
• Location: Name of the location it belongs to
• Operational constraints: Operating capacity, solar irradiation, wind speed, water quantity, etc.
Objectives: Supply power
Behaviors:
• Create supply quantity from power plants.
• Update the power supply based on changing environment
Agent: Water and power regulation model
Attributes:
• Type: Water or power management
Objectives: Balance power and water supply and demand
Behaviors:
• Dispatch power generators or water sources, based on availability.
• Request and store water from storage
Agent: Storage model
Attributes:
• Location: Name of the location it belongs to.
• Type: Water or power
• Operational constraints: Maximum capacity, inflow and outflow rate.
Objectives: Store power and water, supply power and water when requested and if available
Behaviors:
• Create supply quantity.
• Update the capacity after every time unit
Agent: Water source model
Attributes:
• Location: Name of the location it belongs to
•Flow: Flow at which the water is drawn.
Objectives: Supply water
Behaviors:
• Create supply quantity
Agent: Water canal model
Attributes:
• Origin: Location where the canal takes its source
• Destination: Location where the canal serves customers
• Flow: Flow at which the water is drawn
Objectives: Supply water
Behaviors:
• Create supply quantity
Agent: Pump model
Attributes:
• Operational constraints: Energy requirement
• Destination: Location where the water is taken to Objectives: Carry water from one location to another
Behaviors:
• Create power quantity needed

- Arrow 1: Water supply agent send water quantity to the power supply agent (hydro and other sources) while water pump agent sends energy needs information to the power load agent.
- Arrow 2: Power load and supply agents send an output message to the regulator agent with the current power demand and current capacity.
- Arrow 3: Regulator agent aggregates the supply and demand information received, and returns response message to load and supply agents, with the demand met (to load agent) as well as the used supply quantity (to supply agent).
- Arrow 4: In turn, the load can then send the requested energy to the pump agent.
- Arrow 5: At that point, water pump, water load and supply agents send to the regulator agent, the current water demand and current capacity. The message sent by the pump agent helps determine, for areas served using pumps, if and how much water may be delivered.
- Arrow 6: Regulator agent aggregates the supply and demand information received, and sends a request/store message to the water storage agent, either requesting or storing water.
- Arrow 7: Storage agent assesses the request and return a response, specifying available water quantity.

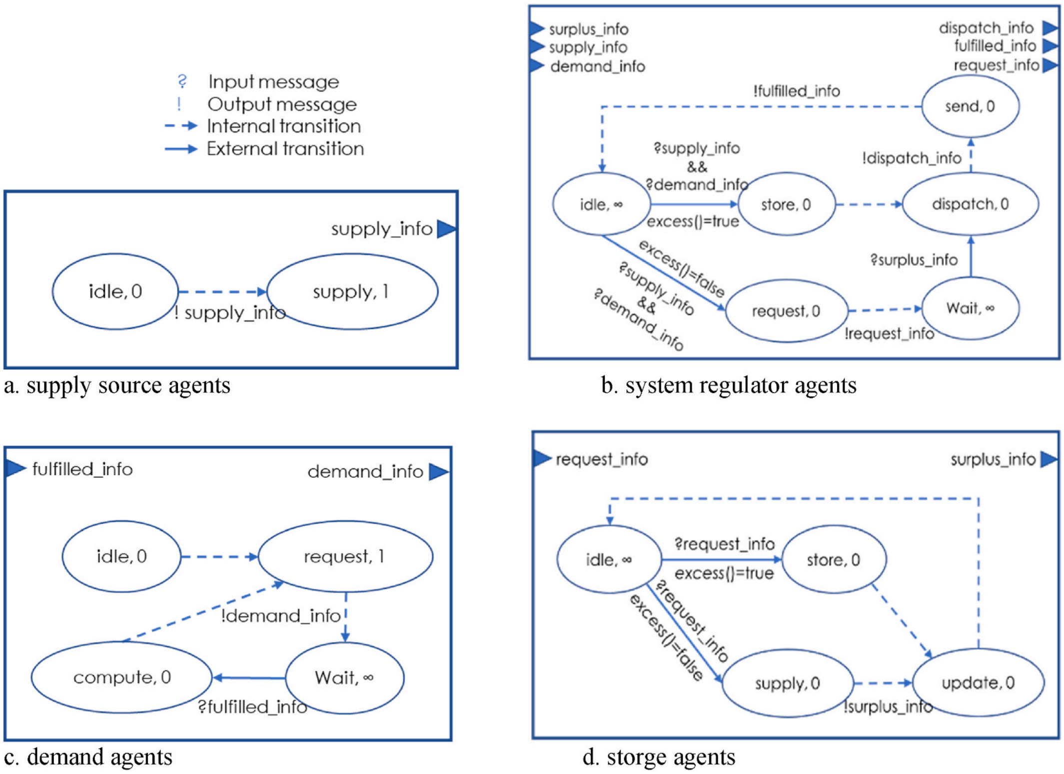

Fig. 2. State transition diagrams for agents in water and power systems.

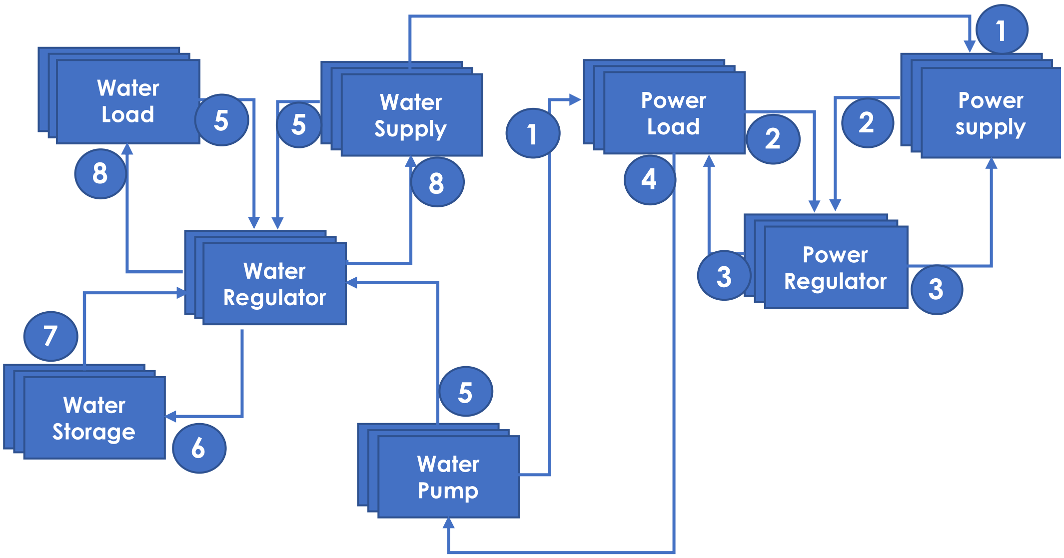

Fig. 3. Agents' prioritization conceptualization.

- Arrow 8: Once a response is received from the storage agent, the regulator agent can finally send messages to load and supply agents, with information regarding water demand met and capacity used.

All these agents' activities occur within the same simulation time. The cycle repeats for the next simulation time.

Table 2 lists all the input data needed to run the simulation model. These are kept in comma-separated value (CSV) files, providing information for all agent attributes, weather data, demand, and supply.

2.2.2. Model spatial and temporal resolution

The objective is for the model to offer enough details to represent the water-power systems interdependencies, and ultimately provide good insight into the systems resilience. The model captures the spatial differences in (water and power) demand as well as sources, across the system considered. For example, in the current implementation, demands are differentiated by areas, capturing various profiles. Water canals are taken from reservoirs, branching into secondary and even tertiary feeder canals, which are characterized by origin, destination, and flow. Water storage is also geographically represented, with different capacity, inflow and outflow. That means, two water storages with either different location, inflow/outflow rate, or else (refer to Table 1 for attributes), will be modeled as 2 different agents. These attributes are what determine how agents interact with each other. For instance, load agents, representing farms or farming zones demand, will only interact with canal agents whose destination location is the same as the farms' location. Storage agents will interact with regulator agents within the same area, unless there is an inter-reservoir relationship with storages in other area, with which they may also interact. The highly discretized structure of the model also allows a more accurate representation of the locational differences and chronological variations in renewable resources (water, wind, solar). Table 3 provides a nomenclature of the model variables (Table 4).

Eq (1) represents output generation *outputGen* for wind sources. We use the Weibull distribution to estimate wind speed *wspeed*, as it is the most common method used to represent wind energy potential at a given location [74–77].

$$\begin{cases} outputGen = 0, wspeed < V_{cutin} \text{ or } wspeed > V_{cutoff} \\ Prated, wspeed \leq V_{cutoff} \text{or } wspeed \geq V_{rated} \\ Prated\left(\frac{wspeed - V_{cutin}}{V_{rated} - V_{cutin}}\right)^2, wspeed > V_{cutin} \text{ or } wspeed < V_{rated} \end{cases} \quad (1)$$

where V_{cutin} is the wind speed at which blades start generating power, V_{cutoff} is the wind speed at which the turbine shuts off to prevent damage, V_{rated} is the wind speed at which the turbine produces its maximum, and P_{rated} is that maximum [78].

Eq (2) represents output generation for hydro sources.

$$outputGen = eff * head\frac{flow}{11.8} \quad (2)$$

where *eff* is the efficiency factor, converting the power of falling water into electric power, head is the distance the water falls, and flow is the amount of water flowing per time unit [79]. Eq (3) represents the output generation for solar sources.

$$outputGen = A * r * H * PR \quad (3)$$

where A is the total solar panel area, r is the solar panel efficiency, H is the solar radiation on the considered area, and PR is the performance ratio, coefficient for losses. In all these equations, solar radiation, water flow and wind speed are recorded hourly. The other power generation sources, because not intermittent, generate the expected amount of electricity. However, these are not modeled individually, rather aggregated per type (gas, biomass, etc.). This approach has shown good increase in computational speed of simulations [80,81] without losing on the accuracy of the results.

The output represents the results of the model, after running some experiments. In our case, we consider the operational performance as main output. Operational performance displays the computed performance of the systems from the simulation, including, ratio of demand met to demand for both systems, energy mix and water storage level, helping to estimate the effects of disturbances in the overall system. Other types of output include water and energy source usage, reservoir capacity and energy requirement. These measures are seen through linkages between the two systems, which, by their nature/constraints, influence systems performance.

2.2.3. Operating constraints

This section describes the mechanisms captured for system operation.

Table 2
Databases used in the model.

Database Input	Definition
Water and power demand database	Data about the water withdrawals/consumptions (plant cooling, agricultural and non-agricultural use, power generation), and power demand (water pumping stations, usual energy needs) per geographical zone and season.
Water and power source database	Data about the water and power sources per geographical zone and type, including, canals, reservoirs, power plants, etc. Data also include physical constraints and factors specific to either source. Hydro generation information, for example, includes data on heads and flows in dams. Heads are change in elevation, between the upper and lower reservoirs. Flow is the speed at which water is flowing. Data also include physical structures and operational limits constraint which limits the volume or timing of the delivery of water.
Water pump database	Data about pumps energy requirement, location, as well as place the water is carried to.
Water flow database	Data about flow of water across water sources.
Solar database	Data about solar irradiance and temperature, locations, and PV (photovoltaic) characteristics
Wind database	Data about wind speed, locations, and wind turbines.

Table 3
Model variables and definitions.

Variables	Definition
wspeed	Wind speed
V_{cutin}	Wind speed at which blades start generating power
V_{cutoff}	Wind speed at which the turbine shuts off to prevent damage
V_{rated}	Wind speed at which the turbine produces its maximum
P_{rated}	Maximum power that can be generated
outputGen	Power generated by hydro
eff	Efficiency factor converting the power of falling water into electric power
head	Distance over which the water comes down
flow	Amount of water flowing per time unit
A	Total solar panel area
r	Solar panel efficiency
H	Solar radiation on the considered area
PR	Performance ratio coefficient for losses
Q_{mw}	Maximum withdrawal discharge
Q_{out}	Authorized discharge
Q_{min}	Minimum operating water volume
Q_t	Water volume at a given time
O_t	Water outflow at a given time
I_t	Water inflow at a given time
C	Capacity of the reservoir

Table 4
Power-water linkages relevant to irrigation systems.

Integrated coupling	Linkage	Examples
Power required for water system	Water transport	Pumping to carry water from one zone to the other
Water required for power system	Power generation	Hydropower

- Reservoir rule curve – Reservoirs have a target rule curve defining the minimum and maximum water volumes. These volumes are usually provided for flood-control purposes. Rule curves guide hydropower operations by balancing competing demands, may it be inflow, water supply, and power generation, for stored water across a period of time [82–84]. Necessary restrictions include water withdrawal, which cannot be higher than the authorized discharge, and water volume, which cannot be lower than operating minimum operating water volume.

$$Q_{mw} \geq Q_{out} \tag{4}$$

$$Q_{min} \leq Q_t t = 1, 2 \ldots n \tag{5}$$

where Q_{out} is the authorized discharge, Q_{mw} is the maximum withdrawal discharge, Q_{min} the minimum operating water volume and Q_t is the water volume at time *t*, *t* is simulation time, incremented to *n*, which is the time over which the simulation is run. Q_{mw} may be constant throughout time or of course, be variable.

- Inter-reservoir relationships – Priorities for different storage reservoir can be defined as operating rule. Inclusion of those relationships within the structure of the system is crucial for proper management of the water resources [85]. Supply can thus be provided by the dispatcher based on the structure of inter-reservoir deployments. In the model, operational decisions are imposed by priority concepts to achieve the supply-demand balance. Storage reservoirs are ranked according to a priority relationship, prioritizing water allocations first by demand quantity and then minimum flow requirements.
- Target measures – Minimum/maximum flow in storage, water flows in canals, flow requirements for hydroelectric plants are specified.

$$Q_t = Q_{t-1} - O_t + I_{t,\&} t = 1, 2, \ldots n \tag{6}$$

where Q_t is the storage volume at time *t*, Q_{t-1} the storage at time *t-1*, O_t the water outflow and I_t the inflow at time *t*. The capacity constraint is used to ensure that storage volumes are less than or equal to the reservoir capacity.

$$Q_t \leq Ct = 1, 2 \ldots n \tag{7}$$

where *C* is the capacity of the reservoir.

Fig. 4 displays the structure of the model at the system component level, capturing the influence of water and power demand on resource usage. Different sources of energy are considered, as well as water sources, constructed to convey water to one or more farms. The thermoelectric sector is the largest withdrawer of freshwater in the nation [86]. The dominant use of water in power plants being cooling, this quantity is captured as water demand. Similarly, energy requirements for pumping are captured as demand. These metrics need to be considered in relation to existing water resources. Water and power consumption values are important indicators for water and power systems management, respectively, helping to gauge impacts of the 2 systems, and vulnerabilities associated with both resources. Water loss is also not taken into account, as well as precipitation. It is also important to mention that the model captures only surface water. Input includes geospatial details (origin and destination) and water flow of canals, weather information for renewable source power generation, dam physical details for hydro generation and operational constraints defined right above. Water/power managers forecast future water/power demand for a more effective use of these resources and ensure balance. The simplest approach of forecasting is to use the product of current per-capita consumption and the expected future population [87,88]. Using forecast data, supply sources are deployed. If said sources do not match current demand, water storage is called upon. In case of the power system, fuel-based supply is used to cover deficit. This operation is executed iteratively until the end of simulation time. The overall model simulation is described below.

1. Data Query: At the beginning of the simulation, input data is queried to collect the necessary information. The data (see Table 2) relate to the characteristics/attributes of the different agent (see Table 1).
2. Process Model Generation: In this step, different classes are created and the necessary number of instances (agents) of canals, pumps, water/power supply sources/demands are created with their necessary initial attributes. An agent is generated when all data tied to its attributes are queried. The behaviors and connections between the simulation entities and the overall layout of the process are created using state transitions, as described in section 2.2.1and Fig. 2.
3. Model Simulation: Once agents are created, they are simulated on the DEVS platform [89]. We use the PythonPDEVS library, a parallel DEVSsimulator written in the interpreted, high-level, object-oriented programming language Python [90].
4. Results: The model collects necessary statistics during the simulation. We use the Matplotlib library [91], data visualization program, also written in Python to display the results.

2.2.4. Model validation

We depict the power and water systems as rule-based water and power resource management systems, with the ultimate objective being to balance supply and demand. The water system is considered as an ensemble of components for the collection, transportation, distribution and use of water. As such, the model represents all the key components performing these activities, including water storage, reservoirs, water canals, water pumps, and water demands. Likewise, the power grid system is considered as an ensemble of components for the generation, transportation, distribution, and use of electricity. The model represents generation sources, distribution, and power demands. In addition, we also capture system regulations, through a regulator component. This component's function is to administer distribution processes in both systems and oversee resource use over time. More importantly, this component

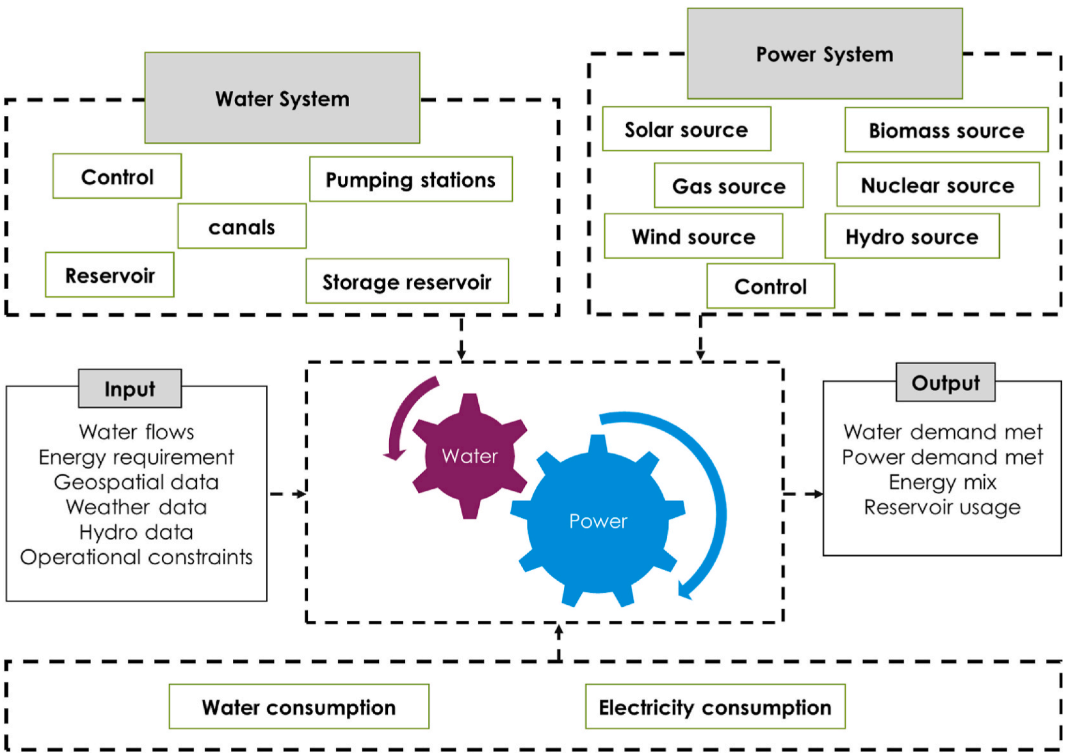

Fig. 4. Structure of the model at the system component level.

ensures contingency components constraints, and requirements are met across systems. For example, energy requirements from water pumps, located in the water system, are recorded by the power system regulator component, which aggregates the overall power demand, including demand from the power system, and accordingly dispatches power generation sources. This problem characterization is in alignment with grid balancing problem, considering the presence of components responsible for resource scheduling and load balancing across the grid [92,93], as well as water management systems, meant to plan and distribute the optimum use of water resources [94], at the functional level. Our conceptualization and model representation of the problem entity and the model's structure, logic, and causal relationships are reasonable for the intended purpose of the model, suggested by the conceptual model validation technique [95–98].

2.3. Case study and data

Southeastern Idaho is home to a variety of water bodies and hydroelectric plants that play important roles in the region's water supply, energy production, and recreational activities. The Snake River flows through southeastern Idaho, providing irrigation water for agriculture. Additionally, several reservoirs, such as American Falls Reservoir, Palisades Reservoir, and Bear Lake, serve multiple purposes including flood control, irrigation, and recreation. Hydroelectric plants harness the power of these water bodies to generate electricity, with notable facilities including the American Falls Dam [99], and Palisades Dam [100]. These hydroelectric plants contribute to the region's renewable energy portfolio and help meet the electricity demand of local communities. This section describes a case study conducted to assess the applicability of the modeling approach. An irrigation district system in Southeastern Idaho (Fig. 5) is used.

The system gets its water from a reservoir upstream of a dam, which provides water for both irrigation and electricity generation. Hydropower from the dam supplies power for both farming and other uses. Water is supplied for irrigation via the canal system and delivered to farms demand using pumps. Power sources come from hydropower plants and the connected grid. The district serves three

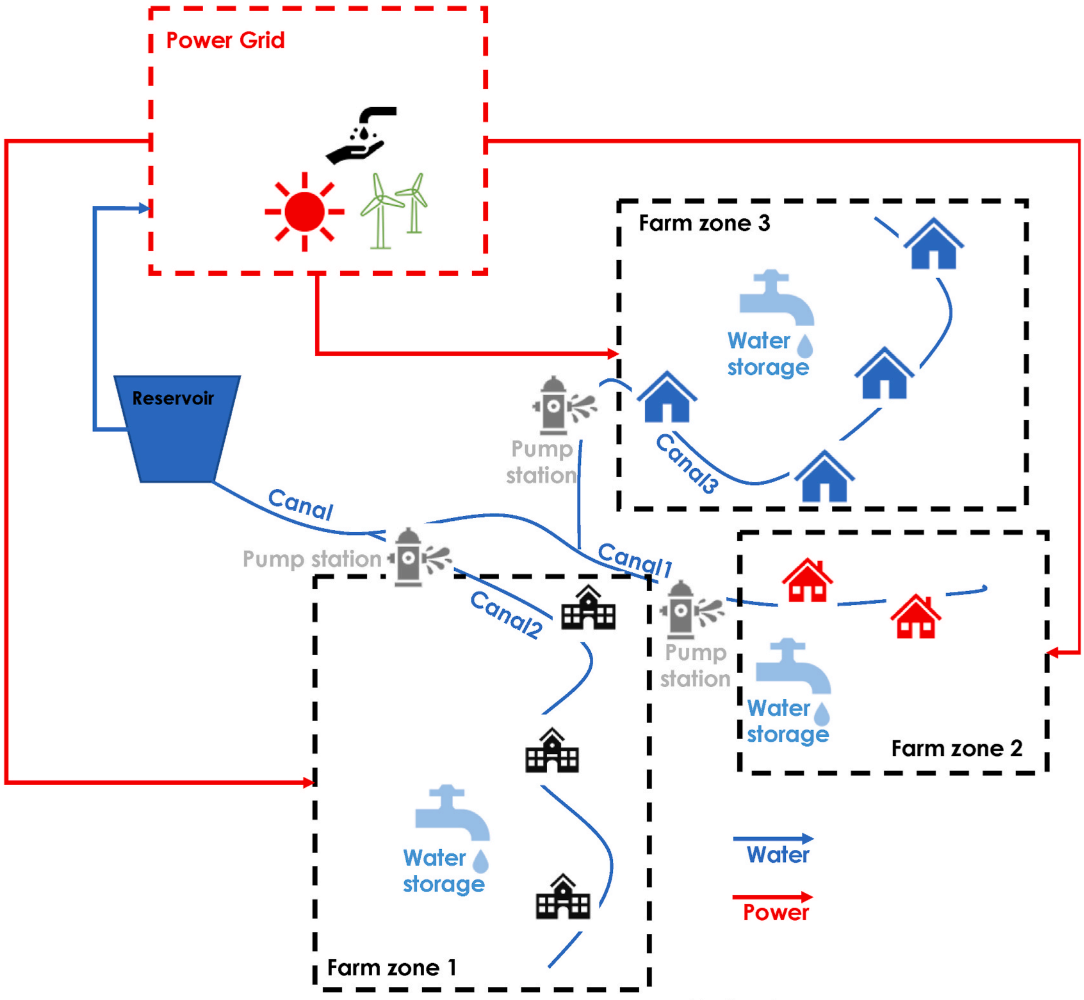

Fig. 5. Conceptualization of irrigation system.

farming regions (group of farms per zone) downstream of the reservoir, located at different places. Irrigation season typically lasts around 26 weeks [101]. We consider one dam, allocating water for power generation, flood control, and irrigation. In addition to water via hydropower, power sources from the grid in Idaho include wind, solar, nuclear, gas, and biomass [102,103]. Their deployment pattern is based on operating costs, as detailed by Ref. [104]. Pressurized irrigation pump stations carry water to farming areas. Water storages (ponds), which store water surplus per farming zone, have a specific capacity. All the elements described are modeled as agents, which are defined in Table 1. As stated earlier, the system performance is quantified as the ratio of actual water and power release and the water and power demand during the specified period. Fig. 5 displays physical aspects of the district system, showing the relationships between components, and serving as a blueprint to build an executable representation. Table 3 summarizes these relationships.

Data used in this analysis are synthetic data, generated using data obtained from the National Water Dashboard [105] (Idaho state) for water demand profile and the Bonneville Power Administration data set [106], for power demand profile and sources. Table 2 shows the list of input and data needed to run the model. Water demand (water consumption) includes water for both irrigation and non-irrigation purposes. Power demand (consumption) includes power for normal usage and water pump operation. Data including all factors used in equations Eq (1), Eq (2), Eq (3), Eq (4), Eq (5), Eq (6) and Eq (7) are assumed from Refs. [107,108].

3. Results & discussion

Using IWPIM, we seek to quantitatively assess how impacts of events propagate between the water and power subsystems, applied on an irrigation system. We developed a set of scenarios that will be used to test the model and also gather, analyze, and interpret information on relevant factors affecting power-water system resilience. The use of scenarios constitutes a valuable approach to inform decision-making, enhance preparedness, and foster a more resilient system. Scenarios help explore and understand the potential impacts of different situations and events on a system. Applied to resilience studies, scenarios selected here help identifying vulnerabilities and highlighting areas of the system that are more susceptible to disruption. Considering scenarios that include low-flow year (drought), water allocation for irrigation or hydropower generation, and load shedding, we are able to see the effects on system performance.

The base case scenario represents the case with no disturbance in the system, with no impediments on water pumps, water and power sources and storage. Irrigation water demand and supply for each farm area match, as well as the supply and demand of power.

3.1. Low flow year scenario

In our first scenario, we assume a low flow year, causing a lower than usual quantity of water throughout the 26-week irrigation period. In April 2022, the Idaho Department of Water Resources (IDWR) declared a drought emergency for Idaho counties south of the Salmon River [109]. In our scenario, such a year would have 20 % less water supply than normal, but with the same flow.

The dynamics of the resilience under this single disturbance event are mostly felt at the water storage level, which we consider at 100 % capacity initially. Over the course of the 26 weeks, water is drawn out of the storage to compensate for the deficit of natural flows. Fig. 6 shows the water storage usage for each farming zone. Because there is enough water in the reservoir storages, the irrigation water demands for all zones are completely met. Even though the system is not operating under optimal conditions, the minimum normalcy conditions are met. There is no irrigation failure in this situation. Reservoir in zone 2 reaches its minimum operating level, assumed at 80 %, illustrated by a straight-line from week 12 on. Reservoir in zone 1 sees a sudden drop at the same time, indicating inter-reservoir relationship, offsetting operating constraint in Zone 2. This redundancy in the system helps maintain

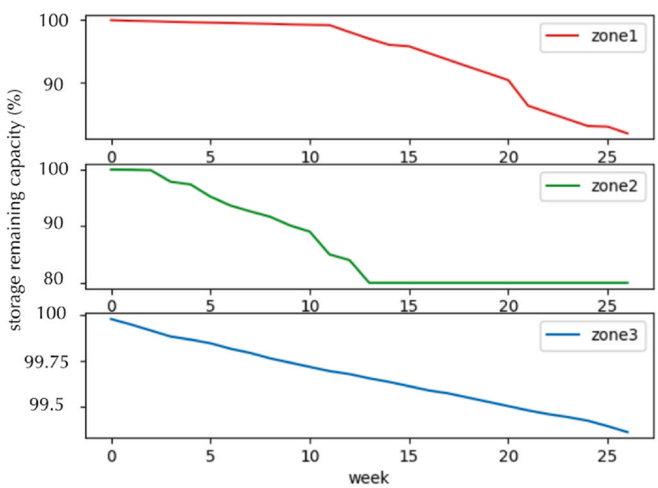

Fig. 6. Water storage utilization under disturbance for all farming zones.

core functionality in the water system, that is, water delivery, and ultimately in the power system. Because the water system has enough water back up, we can assume no impact on the power system, in terms of hydropower reduction for instance. No inter-reservoir relationship is assumed with reservoir 3, which provides water to the attached zone.

The importance of storage systems in the power system is certainly growing. With the increasing penetration of renewable energy and customer demand which inevitably increases the uncertainty in the grid, energy storage systems can help by smoothing out fluctuations and reducing the mismatch between supply and demand [110–112]. Such a role can also be conferred to water storage. In rural water systems, storage is accomplished through retention ponds and other storage mechanisms, in response to water flow changes. Although these changes are not as intermittent as fluctuations of renewable energy in the power system, water storage can certainly help maintain normalcy in the water system during a disruption [113], as shown in our results. Water storage, such as retention ponds where legal and economical, could be a broadly deployable asset for enhancing water system flexibility and increasing resilience. This is even more important now given its linkage to the power system infrastructure. Storage deployment can also be a response to mechanical failures or load shedding.

3.2. Water allocations change scenario

In our second scenario, we look at water allocation between energy and agricultural needs. The need for achieving equitable and sustainable use of water resources to meet those needs is critical, especially in areas with limited resources, or between competing interests [114,115]. We assume a change in water allocation, in the water system for irrigation and electricity generation purposes, with less water assigned for electricity. Fig. 7 displays the energy mix with water from the dam equally distributed (50 % vs 50 %) between power and water systems, while Fig. 8 displays the energy mix with more water allocated to agriculture (60 % vs 40 % for water and power systems, respectively). Energy mix shows the proportion of power generated for each source, on an hourly basis, not the actual generation production. In this sense, proportion fluctuation does not necessarily indicate production fluctuation, rather, reflects demand patterns over time.

Figs. 7 and 8 are shown in hours, for a representative week, to capture the variations of renewable sources. Potential conflict between hydropower and irrigation occurs when the timing of dam release is not coincident with irrigation timing. With worldwide demand for water and energy mounting due to population and industrial growth, it is critical to find efficient ways to meet these demands [116]. With more water set aside for irrigation, other energy sources are called upon (wind, biomass, and solar in this case) (Fig. 7). In a low water year, when the reservoir level is low, both power generation and irrigation flows are limited. It may be more problematic for irrigation districts relying heavily on hydropower to meet electricity demands. With wind and solar not always reliable, such districts may have to turn to non-renewable sources, which also require a considerable amount of water for production [117,118]. Nuclear is also an option, if available. Water use for electricity generation should therefore be considered in relation to changing demands for water from other sectors, and more importantly the increasing threat of drought in certain regions. This could require a re-thinking of the power generation infrastructure system in the future.

3.3. Load shedding scenario

In our third scenario, we assume interruption of power, for a few hours, in two farming areas with no water storage, or with water level under operational limits. This will impact pumps carrying water in those zones (1 and 2). The desired water quantity is not received by these farms, which negatively impact the irrigation needs in those areas. Water availability, in addition to weather conditions have a large impact in agriculture [119]. Fig. 9 displays the proportion of water demand met for all farm areas, with farm zones 1 and 2 noticeably affected.

In the presence of water storage, we observe different results. Water demand is met. Figs. 10 and 11 show how the storage in zones 1 and 2 react to the interruption. In Fig. 10, storages operate in single-reservoir operating mode, with no inter-reservoir relationship. The water levels in both zones' storages drop, providing necessary water quantity to their respective zones, during power interruption. Storage in zone 2 would have to drop below its operational level (80 % of capacity, as assumed earlier) to meet demand. With inter-reservoir relationship between zone 1 and 2 (multi-reservoir operating mode), storage in zone 1 sees it level drop more (Fig. 11). As the

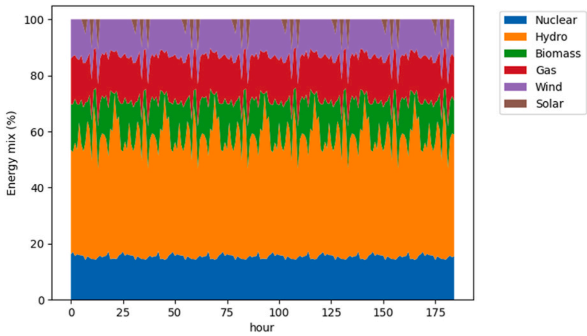

Fig. 7. Energy mix with 50-50 % water allocation for water and power systems, respectively.

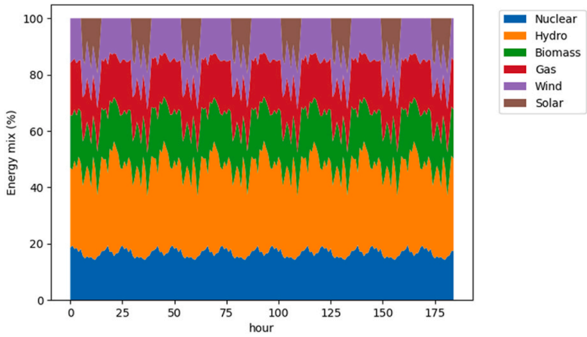

Fig. 8. Energy mix with 60–40 % water allocation for water and power systems, respectively.

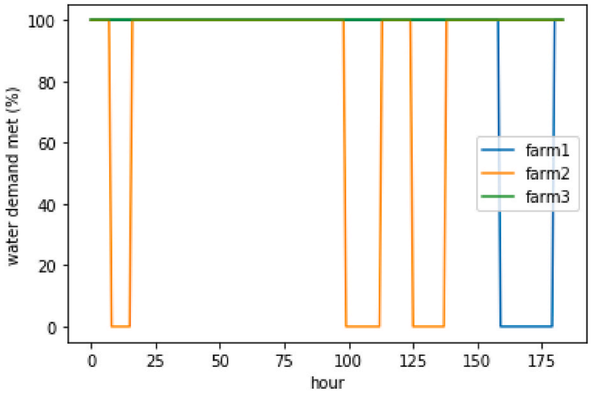

Fig. 9. Proportion of water demand met.

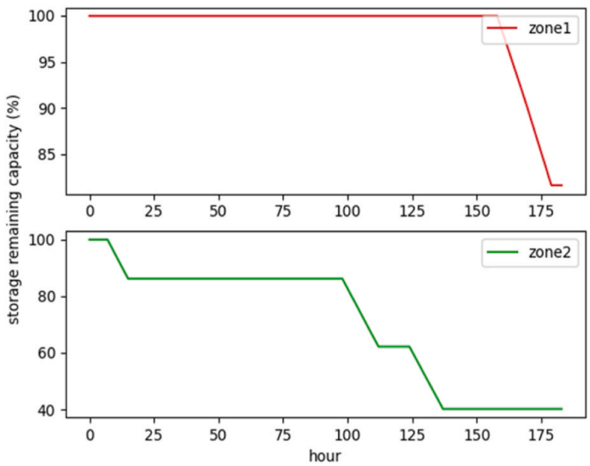

Fig. 10. Water storage level in single-reservoir operating mode.

water level in the reservoir of zone 2 reaches its limit, water stored in the reservoir in zone 1 is released. As these operating rules exist, water can be supplied, and mitigate any deviations from ideal conditions, in a manner that mitigate perceived discomfort to all water users in the system.

As load shedding occur, pumps in the affected area could not transport water to farm areas. Water stress causes reductions in irrigated acres [120], and may impact crop yields. In that sense, the role of micro hydropower or pumped storage hydropower appears critical, as hydropower is deemed the guardian of the grid [121] and can act as a black start resource [122] to provide back-up power. Because it is reliable (able to restart quickly), it can function as an energy storage (pumped-storage hydropower), and is flexible, hydropower can help stabilize the grid and address demand peaks, often responsible for outages [123]. Such an alternative could mean

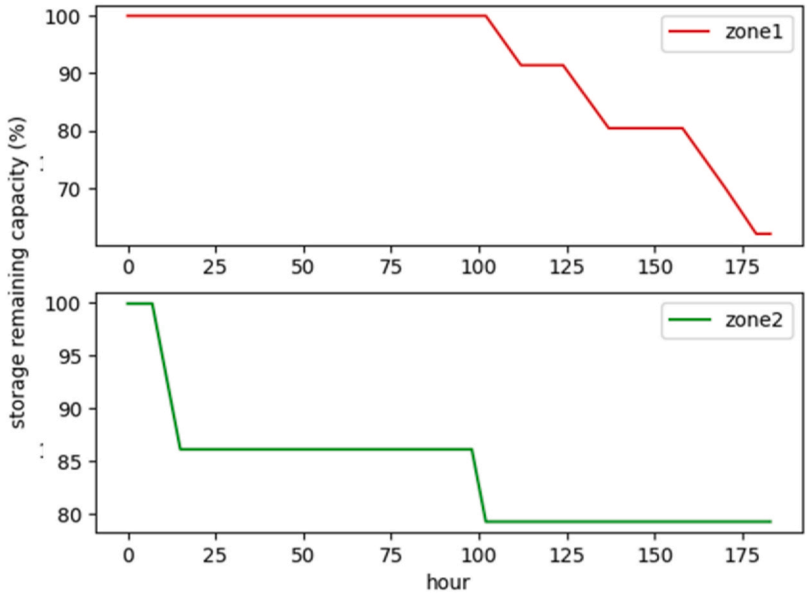

Fig. 11. Water storage level in multi-reservoir operating mode.

more water allocated to the power system, which again highlights the complexity of joint provision for irrigation and electricity. Water therefore could hold the key to this imbroglio, especially in an irrigation district, as could DER near farms. Solar photovoltaic panels, small wind turbines or small modular hydropower could help improve provision of both water and power. DER systems are an effective supply and demand leveling strategy and play a growing role in grid balancing as they add flexibility, resilience, and control to the way in which power is delivered [124–126]. The interdependencies between power and water systems could certainly expand that role in water systems as well, adding that same flexibility and resilience to the way in which water is delivered. According to a research conducted by the Water Research Foundation, DER provide an exciting emerging opportunity for drinking water and wastewater utilities, to offset the increasing energy demand and costs for water services [127]. Since DER are small and dispersed, they can help address specific local challenges in water systems, such as powering pumps and allowing farmers to water their crops, or directly provide water when pumps are out of service due to power outage.

4. Conclusion

We presented IWPIM, a bottom-up event-based dynamic system model that is implementable for water-power systems in rural areas, to demonstrate the potential opportunities of these interdependencies as well as challenges presented. The model captures mutual dependencies, component-level decision-making process and the system regulator function. In addition, both infrastructure systems are modeled at similar fidelity levels and compatible scales, as suggested by Roni, Mosier [128], as a way to address challenges in resilience, and inform decisions that could lead to performance improvements. IWPIM simulates water and power resources management and has proved useful in providing a platform for discussion on water allocation, energy requirement in water pumping, as well as impacts of disturbances of either system to the other. This modeling approach highlights physical feedback between energy and water systems, fostering a comprehensive formulation of management strategies and security measures, in the event of linkage breakdown. Managing water and energy resources as an interconnected system, and eliminating the traditional silo-based planning, would help lead to sustainable development, especially in rural areas.

Results from scenarios shine light on the performance of integrated systems. Our analysis conducted explores the supply vulnerabilities through linkage of water and power resources at the rural level. It helps explore and evaluate different plausible events impacting both systems. By considering those scenarios and their potential consequences, system resilience can be assessed and improved by (1) identifying vulnerabilities, (2) assessing event impacts and (3) providing insights for planning adaptation strategies for both systems. The energy mix in the system we presented, is dominated by water. Results show the need to strengthening the development of water supply system by adjusting the inter-reservoir relationships, to help alleviate disruption and unforeseen rise in energy demand. Water storage in that water supply system appears critical, helping to mitigate water scarcity, and by extension, to keep the energy system unaffected. Water storage is shown to be a viable part of the solution to water conservation, as rigorous conservation practices are needed to compensate for the negative impact of shortage for both resources. In rural areas like the one analyzed here, retention ponds could be a valuable asset for enhancing water system flexibility and increasing resilience. Load shedding or power outage for instance, has a direct impact on water pumps, designed to carry water. Irrigation activities are negatively by energy undersupply, especially those supported by water supplied from lower elevations.

While this work represents an important step forward in water energy nexus analysis in agricultural area, the model and analysis done in this paper address a limited part of resilience. The "Rs" of resilience, i.e., Recon, Resist, Respond, Recover, and Restore presented by Refs. [58,59] describes the performance of the systems before, during, and after a disruptive event. Our modeling capability is currently focused on the *resist* phase, which describes the immediate consequences of the system. The model used could be expanded to inform decision making for *response*, *recovery* and *restoration* by adding components and mechanisms with the ability to sustain supply and balance demand. In terms of operability, the model expansion could include unit commitment issues in the power system, considering forecast demand and scheduling generators and transmission lines back online, specifying the order in which units come back. This model could be coupled with a commitment model to update schedules to reflect recovery from disruption, or the use of water storage as a form of energy storage to overcome the intermittency of renewable energy sources. Beyond these features, the scale of the model could be extended to a larger, or more complex water system, like a municipal system. This would include water treatment components as well as a pipeline network.

Data availability

Code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions. Data included in article/supp. Material/referenced in article.

CRediT authorship contribution statement

Ange-Lionel Toba: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Conceptualization. **Liam D. Boire:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Mohammad Roni:** Writing – review & editing, Validation, Supervision, Formal analysis, Conceptualization.

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.

Acknowledgement

This work is supported by the Water-Power Technologies Office, funded by the U.S. Department of Energy. This manuscript has been authored by Battelle Energy Alliance, LLC under Contract No. DE-AC07-05ID14517 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The views expressed are those of the author only, and do not necessarily represent the views of the DOE or the U.S. Government.

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