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Intersection of Hydrologic Change and Hydropower in the United States: Needs for Future Research and Practice

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ABSTRACT

Hydropower is crucial for electric-grid stability in the context of variable renewables but faces threats from changing hydrology. Here, we summarize the state of the science at the intersection of hydropower operations and planning, hydrologic science, and climate. We focus on the United States, outlining research, development, and training needs. Key knowledge gaps include the risk that intensification of compound extreme events poses to future generation, as well as uncertainties surrounding greenhouse gas emissions from hydropower reservoirs with relevance to hydropower's role in energy decarbonization. Quantifying such impacts and reducing uncertainty are critical where possible, but remaining irreducible or deep uncertainty will require new approaches. Future monitoring and modeling methods must provide a better understanding of the complexity inherent in large watersheds that is critical to managing both hydropower and watersheds in the context of hydrologic change. Yet, research and development will have little impact if they do not inform practice. Standardization and consolidation of platforms are essential for data, modeling, and tool translation to local scales and small operators. An enhanced industry-academia dialog is pivotal for fostering a robust pipeline of hydropower professionals. Collaboration among researchers, policymakers, authorities, and industry stakeholders emerges as a recurring theme, highlighting the imperative for collective efforts.

1 | Introduction

Hydropower is a renewable energy source that harnesses energy inherent in the water cycle. This technology has been used for centuries, beginning with waterwheels to generate mechanical power and later as hydroelectric turbines and generators. Modern hydropower installations take various forms, including those at powered dams on natural waterways, pumped-storage hydropower, and in human-made conduits. Hydropower is predominantly harnessed from natural waterways, often serving as one function in multi-purpose reservoirs. Pumped-storage hydropower uses a second impoundment at a higher elevation

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Summary

- Hydropower is impacted by changing hydrology yet provides grid reliability of value for decarbonization.
- Monitoring and model development are needed but require accelerated investment, use, and training.

that allows water to be pumped and stored uphill at times of low demand for electricity, with water flowing back downhill to generate electricity during peak demand. Conduit hydropower extracts power from human-made waterways (e.g., irrigation canals, water-supply pipelines).

Hydropower is important to the electric grid, providing essential functions such as long-term storage, ramping to accommodate rapid fluctuations in demand, inertia to protect the grid in case of sudden generator malfunctions, and restarting without generators after blackouts (Somani et al. 2021). These capabilities become increasingly important as variable renewable energy sources like wind and solar come online as part of the energy transition (Cohen et al. 2022; Dallison and Patil 2023). However, hydropower availability is threatened by uncertainties from-changes in hydrologic regimes (i.e., hydrologic change) in the context of changes in the broader environment and climate (Kao et al. 2022; Zhou et al. 2023; Broman et al. 2024). For example, extreme, sequential, and compound hydrological events are increasing in frequency (AghaKouchak et al. 2020), which increases risk *to* hydropower facilities and heightens uncertainty in future generation (Hallema et al. 2018). Similarly, changing electricity demands and the process of decarbonization will also have implications for hydropower (Wasti et al. 2022). These have implications for both hydropower operations on shorter time horizons (hours to days) and hydropower planning on longer time horizons (months to decades). There is also uncertainty in the magnitude of greenhouse gas (GHG) emissions *from* hydropower reservoirs which may limit hydropower operations in the future (Song et al. 2018). Incorporating these sources of uncertainty into hydropower operations and planning at watershed, electricity-balancing, or load serving scales requires new methods for decision-making. Yet, despite existing research and development efforts, important knowledge gaps remain regarding how to integrate uncertainties in climate trends and extremes, as well as watersheds' responses and their modulation through water uses and management, to support hydropower long-term planning and operations. Thus, the time is right for innovation in science and technology, with both new research and new application of prior research playing important roles.

The objectives of this literature review are to (1) review topics at the forefront of managing hydropower in the context of climate-induced changes to hydrology and power generation in a developed country like the United States (US), and in that context (2) lay out a vision for research and innovation at the intersection of hydropower, hydrologic science, and climate over the next decade. While we acknowledge the importance of adjacent topics such as aging hydropower infrastructure, population growth, environmental impacts of dams, and water resources concerns beyond hydropower, examining such topics is beyond the scope of the current effort, other than noting their importance at relevant places in the paper. Similarly, this review is primarily conceptual, such that details of hydropower machinery are also out of scope, for example engineering specifications, controls, and software. We focus primarily on conventional powered dams but occasionally discuss pumped storage or conduit hydropower. By focusing geographically on the US, we are focusing on a developed country where conventional hydropower dams are largely built out (Samu et al. 2020), and key investment decisions involve how to maintain or retrofit such dams, and/or whether to decommission them. Yet, our conclusions may have application outside the US, particularly in other parts of the developed world. We further recognize that substantial hydropower dam construction continues elsewhere, particularly in the developing world, where adaptation to hydrologic change will necessarily look different. Our discussion centers on larger-scale interactions of hydrologic change at the watershed scale with electric generation at the grid scale, rather than interactions at individual facilities. In Section 2, we discuss the frontiers of knowledge within key topics at the intersection of hydrologic change and hydropower, including highlighting important knowledge gaps for future research. Broad areas discussed in Section 2 include both direct (hydrologic) and indirect (e.g., via changing grid expectations) impacts of climate change on hydropower, as well as GHG emissions from reservoirs and their possible mitigation. In Section 3, we discuss the current state and needed developments in the methods and tools such as monitoring and modeling used to analyze hydropower in the context of changing hydrology and climate. Finally, in Section 4, we discuss efforts in training the hydropower workforce and disseminating science that will be critical to translating new knowledge and methods into applied success.

2 | Knowledge Areas and Gaps

Managing hydropower systems within the inherently complex hydrologic functioning of watersheds requires knowledge in topics such as hydrology, climate science, water resources engineering, electrical engineering, and systems management, including institutional governance and environmental policy. In recent years, there have been important advances in these technical disciplines, particularly at the intersection of hydrologic change and hydropower. In this section, we discuss areas of research that show particular promise in providing new insight into hydrologic and river system function, and both hydrologic and grid response that may be critical for the management of hydropower generation in the future. Within this context, we are interested in how climate change affects hydropower but also in how hydropower may affect climate through effects on GHG emissions (Figure 1). We note that more complex effects that combine multiple arrows in Figure 1 may exist as well; for example, hydrologic change effects on reservoir operations in turn affecting GHG emissions (e.g., drought decreasing reservoir surface area, with implications for upscaled GHG emissions), but are beyond the scope of this paper.

2.1 | Impacts to Hydropower and Their Mitigation

Hydropower generation is exposed to climate change in terms of risk to hydropower infrastructure and risk to hydropower

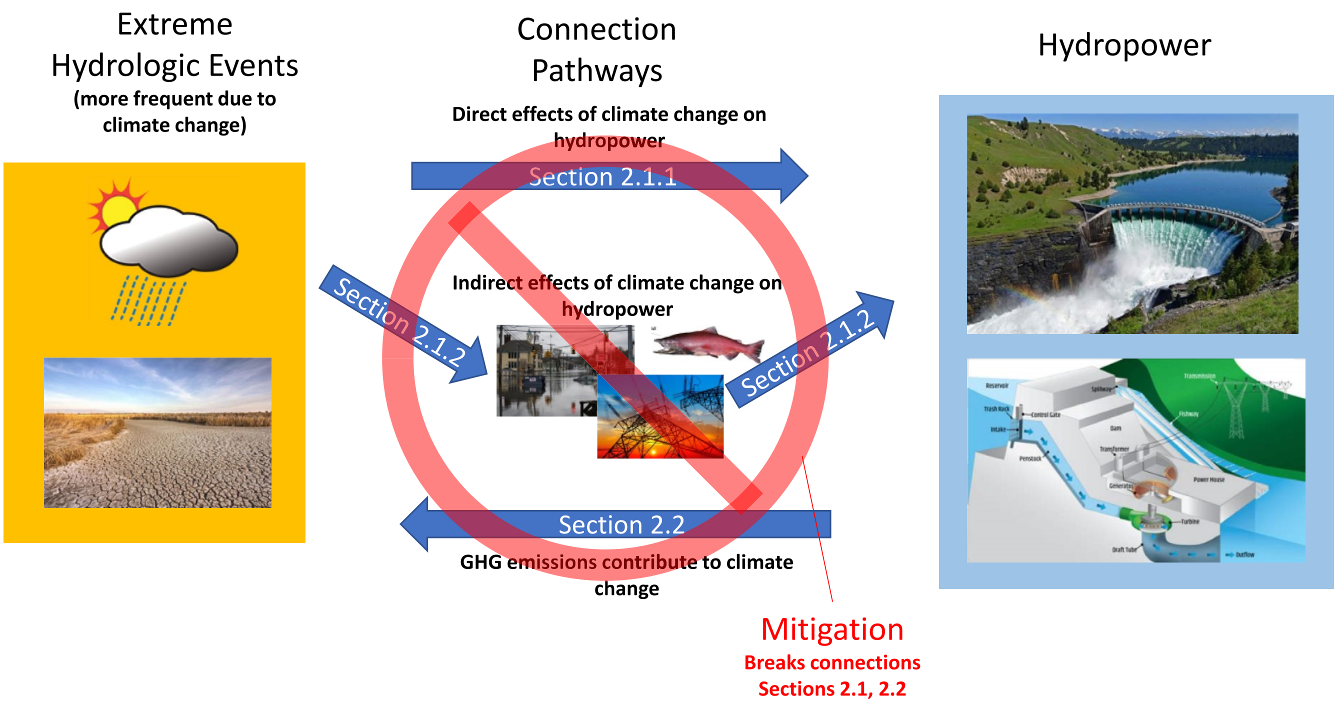

FIGURE 1 | Interaction of hydropower and climate change and relations to sections of this paper. Photo sources: doe.goV, wikipedia.org, noaa.gov, weather.gov. GHG = greenhouse gases.

operations, but here we limit our discussion to impacts to hydropower operations and their longer-term planning. First, climate change will have "direct" effects on operations (Section 2.1.1) via changes to hydrology, which determine the available supply of "fuel" (Kao et al. 2022). Second, it will have multiple "indirect" effects (Section 2.1.2), such as changing electricity demand (Wasti et al. 2022), changing power generation context with the rise of low-carbon power generation sources (e.g., wind, solar), changing demands for other water resource needs such as flood control, and changing hydropower management approaches to address greater hydrologic uncertainty. These effects on hydropower, in turn, will collectively spur new approaches to mitigating such impacts (Section 2.1.3).

2.1.1 | Direct Effects of Extreme, Sequential, and Compounded Hydrologic Events

Under various potential future GHG emission scenarios, defined by representative concentration pathways (RCPs) or shared socioeconomic pathways (SSPs), it is generally projected that many regions will experience increases in long-term average precipitation, leading to more reservoir inflows (Queen et al. 2021; Kao et al. 2022; Qin et al. 2022). While this increase in water availability, where it occurs, can potentially benefit hydropower generation, a challenge arises from the simultaneous intensification of hydrologic events such as floods and droughts (Naz et al. 2018). Existing reservoir and hydropower systems may face constraints in storage capacity and operational flexibility with extreme precipitation, hindering their ability to fully harness the augmented water resources (Zhou et al. 2018; Kao et al. 2022). In addition, runoff and therefore river flows in many regions of the US are expected to increase in winter and decrease in summer due to warming-driven shifts from snow to rain during winter and earlier snowmelt during spring (Huang and Swain 2022). In places with limited multi-season storage capabilities, these changes in seasonal runoff will spur corresponding changes in hydropower generation that may exacerbate seasonal imbalances with power demand in areas that need more water and energy in the summer (Turner et al. 2019; Kao et al. 2022). In this context, the greatest impacts of hydrologic change on hydropower will likely come from extreme, sequential, and compound hydrologic events.

Extreme events are commonly defined as intense weather events such as heavy rainfall, severe storms, or prolonged droughts that have increased in frequency (Katz et al. 2002; Donat et al. 2016; Pendergrass et al. 2017; AghaKouchak et al. 2020; Cook et al. 2020). Extreme rainfall and subsequent flooding can overload reservoirs and dam structures, leading to an increased risk of dam failures and catastrophic downstream flooding (Cox 2023). The types of extreme events can vary geographically, even within the US. One kind of extreme rainfall event that has attracted increased attention is atmospheric rivers (Guan and Waliser 2015; Espinoza et al. 2018), which are defined as long, narrow corridors in the atmosphere that can carry up to 15 times the flow of the Mississippi River. Atmospheric rivers, which in the US are most prevalent along the West Coast, are projected to increase in intensity (Payne et al. 2020; Corringham et al. 2022). Estimates of probable maximum precipitation (PMP), which are used to design large dams and are defined as the largest physically possible rainfall for a given location, were reported to be exceeded in the southeastern US during Hurricane Harvey (Kao et al. 2019). The increasing frequency of extreme events will magnify the effects of land-use change (urbanization, agriculture, and forestry) and river infrastructure (river channelization, diking), which also increase peak flows. Where wildfires are becoming more frequent and extensive, increased storm flow to stream channels can further exacerbate extreme flows (Badía and Martí 2008; Versini et al. 2013; Wu, Baartman, et al. 2021). All of these hydrologic changes will in turn affect sediment movement in river systems, which may affect ongoing sedimentation of reservoirs (Li et al. 2018).

The frequency and severity of droughts are also projected to increase yet vary geographically (Cook et al. 2014; AghaKouchak et al. 2020). Prolonged droughts can reduce water availability and decrease reservoir levels, which in turn affect hydropower-generation capacity, for example in the western US (Bartos and Chester 2015; Turner et al. 2022). The increase in evaporation with warming is expected to be larger in arid relative to humid climates (Kao et al. 2022), further decreasing storage for hydropower (Zhao et al. 2023). Shifts from snow to rain in mountainous regions can exacerbate low flows in summer and fall, for example in California (Huang and Swain 2022). Even with potential increases in total precipitation, more intense rainfall may require increased spill and hence reduced hydropower output as seen internationally (Qin et al. 2020, 2022; Meema et al. 2021). Increasing extremes of both high and low runoff can occur in the same location due to an intensified hydrologic cycle (Kao et al. 2022). Sorting out the dual influences of changes in precipitation and evapotranspiration within watersheds on river flows remains a critical research area (Cook et al. 2014; Wasko et al. 2019; Tabari 2020).

Sequential events refer to the occurrence of multiple, similar extreme events in succession, such as back-to-back storms or extended periods of dryness, exacerbating the impact with more severe consequences. Compound events entail the simultaneous convergence of different types of extreme events; for example, atmospheric rivers cause accumulation of heat, which in turn encourages the formation of heat waves and enhances spring snowmelt (Mo et al. 2022). Both sequential and compound events have the potential to intensify the risks of flooding and drought and disrupt ecosystems, damage infrastructure, and jeopardize human lives (AghaKouchak et al. 2018, 2020). Sequential and compound events also make it harder for hydropower systems to recover between consecutive events, affecting their long-term reliability and economic viability. A key need is better understanding the relationships between individual and compound or sequential events and related cascading hazards such as flooding (AghaKouchak et al. 2020). Compound flood-heat wave events also merit further study; for example, where extreme heat amplifies a rain-on-snow event or enhances thunderstorm or hurricane activity (Gu et al. 2022). All of these hydrologic events in turn have implications for the volume and timing of water availability for hydropower generation.

2.1.2 | Indirect Effects via Changing Power Grid Expectations, Intersecting Water Resources Concerns, and Heightened Uncertainty

Simultaneously with changes to hydrology, there will be shifts in the expectations for hydropower within the electric grid, given the new roles hydropower could provide under evolving load profiles and fleet of generators. Hydropower can play a vital role in grid integration during the renewable-energy transition, offering a stable and flexible source of electricity to complement intermittent renewables like solar and wind (Dallison and Patil 2023). Further, hydropower's ability to provide flexible ramping and store energy could help balance the variability of solar and wind generation (USDOE 2022). However, to implement a sustainable energy future, both the grid and hydropower systems will require adaptations. Grid infrastructure needs to be upgraded to accommodate a higher share of renewables, with expanded transmission networks to connect hydropower facilities, renewable generation sites, and major industrial or municipal power loads (Dallison and Patil 2023). We hypothesize that increased hydrologic variability (e.g., atmospheric rivers, rain on snow events) may create situations where hydropower plants need to generate at maximum capacity and thus provide less of the flexibility needed to integrate renewables. Geographic variation in the prevalence of this situation now and into the future bears further investigation. A key need for improving optimization of hydropower in future grid settings is continued improvements in modeling and data collection (Kincic et al. 2022; Oikonomou et al. 2022; Ploussard et al. 2022; Helseth et al. 2023) as discussed in Section 3.

The impacts of hydrologic change on hydropower and efforts to mitigate such impacts do not occur in isolation, but instead exist together with the impacts on other human and ecological needs of water resource systems and their respective mitigation efforts. For example, as rainfall events intensify and flood risk increases (Elliott and Wang 2023), maintaining existing levels of flood control risk protection provided by reservoirs will require operational changes or even structural changes to provide more storage through enlarged dams and/or spillways (Watts et al. 2011). A transition from snow to rain in mountainous areas will shift flood peaks earlier in the year and require altered schedules to balance flood control and reservoir refill (Lee et al. 2009). Similarly, maintaining the reliability of the water supply for agricultural, industrial, and municipal uses in the face of more intense storms and/or droughts will require larger storage facilities, altered operational strategies, and increased water-use efficiency (Gohari et al. 2014). Yet, water supply demands may simultaneously increase with climate change (Wang et al. 2016). A key distinction is that managing flood risk is centered on addressing changes in large storms, while managing water supply will focus on mean or total annual flows (Quinn et al. 2018). Other water uses such as recreation, transportation, ecological flows, and groundwater recharge may also need to adapt (Sadoff et al. 2013). At the same time, climate change will directly affect ecosystems and their needs (Justice et al. 2017; NOAA 2020).

Ultimately, hydrolo change will affect both the demand for and ability to provide a range of water resource needs. Because of the interconnected nature of watersheds, these different effects all act on a single system, thereby affecting hydropower. For example, increased vulnerability of fish migration as a result of climate change may require altered spill, spillways, or turbines at hydropower dams or even dam decommissioning that will in turn directly affect hydropower (NOAA 2022). These tradeoffs indicate the benefit of seeking win-win scenarios where multiple water resource needs benefit or at least simultaneously minimize loss. One approach to achieve multiple benefits includes creating outlets lower in dams for more flexible reservoir operation, together with improved long-term forecasts and forecast-informed reservoir operations (Hamlet et al. 2002; Cox 2023). Revising operational strategies can better optimize competing demands in the face of climate change (Watts et al. 2011; Rafique et al. 2020). Incorporating societal values through stakeholder or political processes is critical in this context. For example, hydropower generation is often a lower priority than other functions of reservoirs in the US (Kao et al. 2022). We note that practical considerations raised here in a US context, where dam buildout is largely complete, may not apply elsewhere in situations where substantial dam building continues (Liu et al. 2018; Hecht et al. 2019).

Shifts in hydrology, power-grid expectations, and other water resource needs all bring uncertainty that affects decision-making for hydropower on both shorter-term operational (minutes to days) and longer-term planning (months to decades) timescales. For example, hydrologic uncertainty has increased, with implications for both short-term river forecasting and long-term planning involving hydrologic statistics (Milly et al. 2008). A key part of longer-term uncertainty stems from uncertainty in future precipitation, which results from uncertainty in future human actions/emissions themselves and the effect of current and future emissions. But there are other sources of hydrologic uncertainty as well, such as spatially and temporally variable glacier melt as seen internationally (Nie et al. 2021). Quantifying such deep uncertainties (Reed et al. 2022) requires comparing multiple complex models with many options and methodological decisions (Kao et al. 2022) to account for uncertainties in model structure, input data, and other factors (Herman et al. 2020; Srikrishnan et al. 2022). Regardless of the source(s), hydrologic uncertainty represents a financial risk to hydropower owners, operators, and users (Hamilton et al. 2020, 2022). Uncertainty associated with future build-out trajectories and geographies of renewable energy sources such as wind and solar, and hence grid expectations of hydropower, would heighten this risk, as would uncertainties of trajectories of other water resource needs and their priorities relative to hydropower.

With increased uncertainty in multipurpose water resource systems, decision-making may benefit from metrics of reliability, resilience, and vulnerability (Rafique et al. 2020). In addition, the information content of such metrics may change with non-stationarity, requiring updating or evolution of the metrics themselves. Short-term operational decisions can be improved by increasing the range of information used in algorithms associated with decision-making and through emulation modeling that can efficiently isolate decision-critical processes (Giuliani et al. 2021). As policy pushes toward a renewables-heavy future grid, analyzing hydropower's role in supplying power for planning will require linking hydrologic, hydropower, and grid simulations while understanding and partitioning the uncertainties of each simulation (Zhou et al. 2023). Successful future management of hydropower requires accounting for these simulation uncertainties, the climate uncertainties discussed earlier, and socioeconomic uncertainties (not discussed here), which combined are known as deep uncertainty (Quinn et al. 2018).

Decision-making under deep uncertainty (DMDU) is an approach that can address these uncertainties and has recently been applied to water resources (Babovic et al. 2018; Miro et al. 2021; Smith et al. 2022; Webber and Samaras 2022). DMDU provides a framework to make management decisions when probabilities cannot be calculated for future events, for example, non-stationarity associated with hydrologic change. While deep uncertainty has been considered in hydropower modeling (Ren et al. 2019; Hurford et al. 2020), these studies did not include power system modeling. Conversely, uncertainty has been considered in integrated hydropower and power-system modeling (Hill et al. 2021; Wessel et al. 2022), but not specifically deep uncertainty. Thus, applying DMDU to hydropower operations and planning by integrating hydropower and power-system modeling is ripe for future research, given the deep uncertainties associated with climate-change impacts on river flow and power needs. All of this points to a need for more sophisticated modeling and prediction, as discussed in Section 3.

2.1.3 | Novel Strategies for Mitigating Hydrologic-Change Impacts to Hydropower

In a broad sense, mitigation for hydrologic change impacts to hydropower generation could include any actions that add new hydropower generation capacity, for example recent efforts to power non-power dams, integrate pumped-storage into existing powered dams, and deploy small and micro-hydropower. However, here we limit our discussion to approaches that more directly mitigate the hydrologic impacts to hydropower operations and their longer-term planning as discussed above, i.e., approaches that counter the effects of extreme hydrologic events such as increasing peak flows and decreasing low flows. This includes mitigation of changes to storm/annual hydrographs, as well as impacts to sediment, temperature, and water quality, if they have an impact on hydropower. Most of these approaches involve enhancing hydrologic or electrical storage or connectivity. Below, we discuss example techniques, such as river restoration, grid interconnections, and agricultural water supply practices.

The increased peak flows and decreased low flows of hydrologic change can be mitigated by enhancing storage in the upstream watershed. A conventional approach to enhancing such storage is through adding additional reservoirs (Qin et al. 2022). However, a lack of remaining good places to site such facilities, together with concerns over their environmental impacts, has encouraged the growth of nature-based alternatives. An important example is river floodplain restoration, which can enhance hydrologic storage by increasing the exchange of water between river channels and adjacent riparian zones and floodplains (Hammersmark et al. 2008; Sholtes and Doyle 2011; Ohara et al. 2014; Hunt et al. 2018; Powers et al. 2019; Federman et al. 2023). However, restoration efforts and associated models are mostly focused on small headwater catchments, such that the magnitude of their impacts on larger rivers where most hydropower reservoirs are located is unknown. Thus, future research could extend this analysis to larger river network/watershed scales (Hawley et al. 2023). Additionally, the relative effects of hydrologic storage versus hydrologic losses such as evapotranspiration are not well understood.

Increasing hydrologic extremes can also be mitigated through enhanced grid connectivity, where grid interconnections and enhanced transmission capacity can better balance load and generation across regions. For example, not all hydropower plants within a given power grid are necessarily impacted by drought at the same time. Regional coordination is already helping to mitigate the negative impacts of drought on hydropower by allowing areas with hydrologic droughts in different seasons or years to mutually compensate (Voisin et al. 2019). Interconnections and coordination among adjacent regions with differing climates can buffer some of these extremes, increasing overall reliability (Voisin et al. 2020). Grid interconnections also enable achieving broader resilience goals by integrating other renewable-energy sources, such as solar and wind, that have geographic patterns of variation that are different from hydropower (Martin et al. 2015). A knowledge gap is whether solar and wind "droughts" (Bracken et al. 2024) will generally co-occur with hydrologic droughts either temporally or geographically.

Finally, agricultural practices that reduce irrigation water use can help mitigate decreasing low flows and/or drought, benefiting water supply for humans (McMahon and Smith 2013; Varzi and Grigg 2019), aquatic organisms (Pierce et al. 2022), and hydropower generation. These practices include precision irrigation techniques, improved water-management strategies, payments for fallow land, and buying out farmer water rights. For human water supplies, the primary benefit of reduced irrigation water use is increased flow that provides more total available water for diversion or storage in reservoirs downstream. By contrast, the benefit to both aquatic organisms and hydropower would primarily be from increasing low flows. For hydropower, this would reduce the overall variability of flows available for generation and reduce the chance of curtailment at low flows. However, the social impacts of these approaches, for example, community effects of reducing agricultural activities in rural settings, can be contentious (James and Hing 2021; AP 2022) and bear further attention.

2.2 | GHG Emissions From Reservoirs and Their Mitigation

In addition to climate change impacting hydropower, hydropower operations may impact emission of GHGs from reservoirs (Figure 1). Here, we examine the latter effect, where study is only beginning, such that the net effect of hydropower generation on GHG emissions from reservoirs remains highly uncertain. We note that in this section our US focus necessarily widens, in that discussing GHG emissions at times requires a global perspective. For example, multiple studies have estimated GHG emissions from reservoirs globally, and these values have ranged by almost an order of magnitude (Harrison et al. 2021). For methane (CH_4) emissions specifically, a global modeling study estimated that reservoirs (both with and without hydropower) may contribute ~6% (range: 3.7% to 17.4%) of global anthropogenic CH_4 emissions (Harrison et al. 2021). According to one estimate, approximately 20% of dams globally have hydropower as a primary use (Zhang and Gu 2023). By multiplying the global anthropogenic CH_4 reservoir emission estimates by the estimated percentage of dams worldwide that have hydropower, this suggests that CH_4 emissions from hydropower reservoirs may contribute ~1.2% (range: 0.7% to 3.5%) to global anthropogenic CH_4 emissions. However, attributing GHG emissions to hydropower operations specifically versus to other reservoir purposes, especially given that many reservoirs are multipurpose (i.e., used for flood control, hydropower generation, recreation, etc.), is difficult and further complicates this issue. Nevertheless, recent progress includes a conceptual model to describe impacts of water-level fluctuations associated with hydropower operations on GHG emissions (Jager et al. 2023), empirical studies that examine how water-level fluctuations affect GHG emissions (e.g., Harrison et al. 2017; Beaulieu et al. 2018; Prairie et al. 2021), and recent additions to the G-res model that coarsely allocate a GHG footprint to different reservoir uses (Prairie et al. 2021).

A key challenge is that GHGs are emitted not just from reservoirs, but rather all natural and human-made waterbodies, and are part of larger inland water systems that cycle and transport carbon toward the oceans (Regnier et al. 2022). In reservoirs, GHG emissions primarily take the form of carbon dioxide (CO_2) and methane (CH_4), with lesser amounts of nitrous oxide (N_2O) (Gruca-Rokosz 2018, 2020). These GHGs are generated from the bacterial decomposition of allochthonous organic matter submerged during reservoir formation and input from the surrounding watershed, and autochthonous organic matter generated in the reservoir (phytoplankton, algae, macrophytes). The decomposition of these organic materials releases CO_2, and in anoxic areas, CH_4 can be produced through anaerobic processes such as methanogenesis (Rosa et al. 2004). Most estimates of GHG emissions from reservoirs are reported as 'gross emissions', which include all CO_2 and CH_4 emissions measured post-impoundment (Prairie et al. 2018). However, to estimate how the creation of a reservoir alters GHG emissions, it is necessary to account for pre-impoundment emissions in any post-impoundment GHG assessment (i.e., "net emissions") (Prairie et al. 2018). Specifically, to what extent are new GHGs produced and emitted with the creation of a reservoir compared to natural emissions that would have occurred if the reservoir was not created? Addressing this question is very difficult in practice due to the dearth of GHG emission measurements in general, and especially a lack of GHG emissions estimates made prior to impoundment, although some studies have been conducted in reservoirs in Canada and China (Bastien et al. 2011; Teodoru et al. 2012). One approach to estimate net emissions is to assume that all new GHG emissions are attributed to the reservoir (Prairie et al. 2018). These new emissions include all CH_4 emissions and CO_2 emissions only from the decomposition of soil organic matter that was submerged when the reservoir was formed (Prairie et al. 2018). Emissions of CO_2 due to the decomposition of terrestrially derived organic matter that enters the reservoir from the surrounding watershed are not included, as these emissions would have occurred in the absence of the reservoir (albeit likely further downstream in the riverine network or in the coastal ocean) (Prairie et al. 2018). For the purposes of this paper, we focus on providing a high-level overview on the state of the science on understanding net GHG emissions from reservoirs, and for brevity, clarity, and applicability to understanding the net effects of reservoirs, we focus on CH_4 emissions. For a comprehensive discussion on an approach to estimate net GHG emissions from reservoirs, including the consideration of CO_2 emissions from flooded soils and sequestration from carbon burial, the reader is directed to the paper by Prairie et al. (2018).

Estimating CH_4 emissions from reservoirs is challenging, in part due to high spatiotemporal variation in the multiple processes and pathways by which CH_4 is produced and emitted from a reservoir (Harrison et al. 2021). There are three primary pathways by which CH_4 can be emitted to the atmosphere: diffusion, ebullition (bubbling), and degassing (dissolved CH_4 passing through turbines and released downstream). In some reservoirs, the predominant CH_4-emission pathway is ebullition (DelSontro et al. 2011; Gruca-Rokosz et al. 2011; Venkiteswaran et al. 2013; Fernández et al. 2020). Ebullition of CH_4-rich bubbles most often occurs in shallower water (~< 10 m; Beaulieu et al. 2016; DelSontro et al. 2016), so reservoirs with a larger proportion of total surface area as shallow water may have higher CH_4 ebullitive emissions (Beaulieu et al. 2020; Jager et al. 2023). However, ebullition is a temporally and spatially variable process, and ebullition rates can vary multiple orders of magnitude when measured in different locations within a single reservoir (e.g., Beaulieu et al. 2016; Pilla et al. 2024), making it a challenging emission pathway to accurately quantify. Dissolved CH_4 that passes through turbines can also contribute to emissions via the 'degassing' pathway (Roehm and Tremblay 2006; Kemenes et al. 2016; Zhou et al. 2024). Degassing can be the predominant CH_4 emissions pathway in some reservoirs, especially those that stratify and that have deep-water intakes, which together can result in deep water with high CH_4 concentrations being pulled through turbines and then emitted downstream (Guerin et al. 2006; Soued and Prairie 2022).

In addition to the multiple pathways by which CH_4 can be emitted from reservoirs, there are also a myriad of inter-related factors that influence CH_4 emissions, including climate, reservoir, and watershed physical and biological conditions (e.g., reservoir age, temperature, water level fluctuations, bathymetry, carbon inputs from the surrounding watershed, and trophic status) (Barros et al. 2011; Ai et al. 2022; Delwiche et al. 2022; Hansen et al. 2025). Temporally, factors such as seasonality in algal photosynthesis and senescence, and thermal stratification can affect the production and emission of CH_4 (Beaulieu et al. 2014; Ollivier et al. 2019; Waldo et al. 2021; Montes-Perez et al. 2022). In areas where reservoirs ice over in the winter, CH_4 can be trapped in ice or below the ice and is then released once ice thaws in spring (Karlsson et al. 2013; Sepulveda-Jauregui et al. 2015). Decreases in water levels during drawdown can reduce hydrostatic pressure and increase CH_4 ebullition (Harrison et al. 2017; Jager et al. 2023), and wetting and drying cycles can also increase CH_4 emissions (Kosten et al. 2018). Spatially, studies have been conducted in tropical, subtropical, temperate, and boreal, also semi-arid, Mediterranean, and humid settings (Huttunen et al. 2002; Rosa et al. 2004; Guerin et al. 2006; Bastien et al. 2011; Venkiteswaran et al. 2013; Gruca-Rokosz and Tomaszek 2015; Kemenes et al. 2016; Rodriguez and Casper 2018; Ollivier et al. 2019; Montes-Perez et al. 2022). A global modeling study found that CH_4 degassing and ebullition rates were higher in tropical and subtropical regions than in colder regions, and overall, CH_4 emissions via degassing and ebullition were much higher than via the diffusion pathway (Harrison et al. 2021). Most existing measurements have been at individual reservoirs, leaving the need for a systematic typology and inventory to allow extrapolation to watershed scales (Jager et al. 2022) with recent efforts to create archetypes based on reservoir morphology and climate (Hansen et al. 2023) and analyze multiple reservoirs in sequence (Shi et al. 2023). While progress has been made (Ai et al. 2022; Wang et al. 2024), additional empirical and modeling studies are needed to strengthen the understanding of the relative importance of different CH_4 emission pathways and their drivers in time (diel, seasonal, interannual cycles) and space (within and across reservoirs, and up- and downstream). A related need is standardizing measurements and modeling techniques (Beaulieu et al. 2020). These advances are needed before rigorous guidance for mitigation can be developed.

More specifically for hydropower, it will be important to delineate CH_4 contributions from hydropower versus other functions of reservoirs such as flood control, water supply, transportation, or even tourism. Optimal reservoir operation is often different for these different objectives. For example, maximizing flood control may entail maximizing drawdown before storms or high flow seasons, while optimizing hydropower output may require increasing release rates during times of day or year with high electricity demand. Key research needs in this area include how CH_4 emissions vary with reservoir water levels and release rates (Amorim et al. 2019; Jager et al. 2023).

Nevertheless, some concepts for mitigation are already being suggested. For example, the design of a dam can affect CH_4 emissions. Shallow water intakes (or variable-depth intakes) that do not pull CH_4-rich, deep water (especially during stratification when CH_4 can build up in deep waters) can result in lower CH_4 degassing emissions (Beaulieu et al. 2014; Soued and Prairie 2020). Altering reservoir conditions and managing the surrounding watershed may also impact emissions. For example, reducing nutrient inputs may have cascading effects by decreasing eutrophication-induced CH_4 emissions (Beaulieu et al. 2019). Finally, for hydropower aspects of reservoirs in particular, the operation mode may affect GHG emissions. For example, in pumped-storage facilities, CH_4 ebullition was less for continuous, diurnal pumped storage operation than for longer-duration pumped storage cycles (Fernández et al. 2020). Nevertheless, the efficacy of these mitigation measures and how they vary in space and time remains limited, and is a key area for future research.

3 | Methods/Tools and Needs

Managing hydropower systems in the face of heightened uncertainty due to climate change requires a suite of tools that can accurately analyze and predict system performance under a range of conditions, including various climates and mitigation strategies. This requires developing and utilizing the next generation of analytical and sensing methods and facilitating their adoption in practice. In this context, there are parallel developments happening in allied hydrologic fields that can be harnessed by, extended to, and tailored for hydropower analysis. Such broader hydrologic efforts have recently focused on challenges associated with the wide range of relevant spatial scales and multiple, interacting, nonlinear processes (Hickmon et al. 2022). To improve prediction and decision-making for both shorter-term operational and longer-term planning levels, there is a need for hydropower operations and constraints analyses of high spatial and temporal resolution across a range of temporal horizons

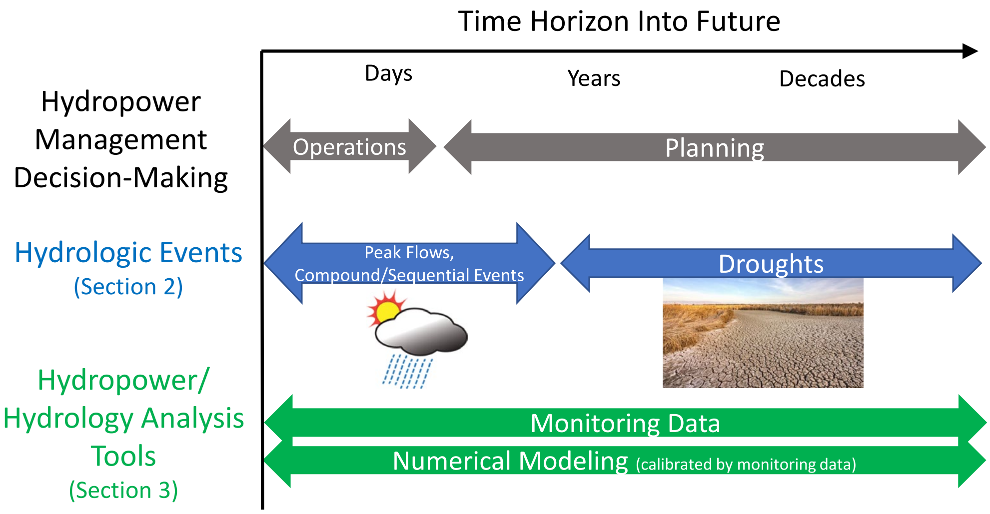

FIGURE 2 | Approximate temporal horizons of hydropower management decision-making, hydrologic events, and hydropower/hydrology analysis tools. Photo source: noaa.gov.

(Figure 2). This would be supported by autonomous, integrated, field-sensing systems, data access/consolidation/curation, and numerical modeling.

3.1 | Monitoring Data

Increased uncertainty in hydrologic change necessarily increases the value of monitoring (AghaKouchak et al. 2018; Nie et al. 2021). In particular, the increasing likelihood of future hydrologic events outside the range of historical norms elevates the need for improved monitoring techniques to (1) enhance understanding of emerging hydrologic events in near real time for short-term hydropower operations and (2) continually improve long-term predictions necessary for planning and infrastructure upgrades.

3.1.1 | In Situ and Remote Sensing Measurements

There is a need for further deployment of automated and integrated sensing systems that can continuously monitor key parameters such as water flow, reservoir levels, sedimentation, turbine efficiency, and environmental conditions (e.g., water temperature, dissolved oxygen) to improve management efficiency in balancing power generation, maintenance needs, and environmental concerns. Hydropower monitoring benefits from developments in the broader field of hydrology (Reif and Theel 2017). The main recent developments in hydrologic monitoring are within the field of remote sensing, which greatly improves data coverage in regions where in situ data are scarce.

Satellite-based remote sensing of inundation extent paired with numerical modeling can fill important data gaps in river flows and reservoir inflows, storage, and outflows in river systems with multiple dams (Brakenridge et al. 2012; Klein et al. 2021; Bellucci et al. 2023). Similarly, snowpack extent and snow water equivalent quantify seasonal storage and therefore drive seasonal inflow forecasting for hydropower facilities in complex mountainous terrain (Zhang et al. 2021) as well as reservoir ice thickness and extent (Siles and Leconte 2023). The gravity recovery and climate experiment (GRACE) satellite can detect groundwater levels (Tapley et al. 2004; Rodell et al. 2009), which may be useful for large-scale (e.g., regional) water budgets and modeling. These remote-sensing approaches still have limited application to run-of-river facilities (Du et al. 2022) and would benefit from continued development of processing algorithms (Whittaker and Leconte 2022) and ground truthing (Vachon et al. 2010). Radar altimetry is particularly good for water-surface elevations (Yan et al. 2021) but would benefit from extension to smaller water bodies that are currently infeasible (Park et al. 2020). By contrast, synthetic aperture radar can handle smaller water bodies (Park et al. 2020). However, there are still several weaknesses of satellite-based approaches; for example, limited temporal resolution (which is affected by the frequency of satellite bypasses) and limited application to short-term (e.g., diel) analysis and management of hydropower generation. Other weaknesses include detection abilities (e.g., discriminating snow vs. cloud) and attribution (e.g., ground vs. atmospheric water in GRACE). In addition, the life expectancy of satellites for scientific data collection is often less than 10 years (Bellucci et al. 2023), limiting the observation of low-frequency processes such as decadal atmosphere–ocean interactions and multi-year droughts. Efforts to merge satellite products with river gages will help enhance in situ datasets (Jiang et al. 2012).

Closer to the ground, light detection and ranging (LiDAR) is best for measuring snow under a forest canopy (Broxton and van Leeuwen 2020), but would benefit from improvements in estimating snow density to improve estimates of snow water equivalent. Promising approaches include artificial neural network (ANN)-generated density maps (Broxton et al. 2019) or passive microwave remote sensing (Han et al. 2019). Uncrewed aerial vehicles (UAVs) with photogrammetry can enhance monitoring of reservoir inundation extent during hydropeaking, including for pumped-storage hydropower (Jurevicius et al. 2023). Lagrangian measurements can be achieved using sensors that float passively, can measure a wide range of both flow (e.g., velocity) and water-quality parameters, and that are relatively inexpensive (Tinka et al. 2016; Fuentes-Perez et al. 2022), but would benefit from enhancing their spatial coverage and coordination. Ultimately, integrating different remote-sensing technologies, such as satellite imagery and LiDAR, can offer valuable insights that cannot be achieved independently (Reif and Theel 2017). Developments are also needed in making datasets and data-processing tools more available and turnkey (Section 3.1.2) to allow easier integration with modeling tools (Section 3.2).

3.1.2 | Data Curation, Integration, and Access

There is a growing push to make hydrologic data broadly available and interoperable. A big driver in the U.S. has been data availability requirements of the Foundations for Evidence-Based Policymaking Act of 2018 (www.congress.gov/bill/115th-congress/house-bill/4174). This prompted many federal agencies and federally funded research entities to generate or further develop repositories. Example federally funded repositories relevant to hydrology, climate science, and hydropower include U.S. Geological Survey (USGS, waterdata.usgs.gov/nwis), U.S. Federal Emergency Management Agency (FEMA, www.fema.gov/about/openfema/data-sets), U.S. Environmental Protection Agency (EPA, www.epa.gov/data), U.S. Department of Energy (DOE, e.g., ess-dive.lbl.gov), U.S. Bureau of Reclamation (USBR, data.usbr.gov), National Oceanic and Atmospheric Administration (NOAA, data.noaa.gov), Critical Zone Observatories (CZOs, discover.criticalzone.org), Long-Term Ecological Research centers (LTERs, lternet.edu/using-lter-data/), and the National Ecological Observatory Network (NEON, data.neonscience.org).

However, because each agency and project is funded independently, these repositories are similarly independent. The development of centralized, publicly open databases and data repositories specifically designed for hydrologic data is important to facilitate easier access, sharing, and integration of information (Klein et al. 2021). This would involve the creation of user-friendly interfaces and data portals that allow researchers, authorities, policymakers, and stakeholders to explore and retrieve relevant hydrologic data. Such centralized approaches could also establish standardized protocols for data collection, quality control, and metadata documentation to ensure consistency and interoperability across different hydrologic data sources (Teng et al. 2016; Merks et al. 2022). The development of open data initiatives and collaborative platforms can foster data sharing and collaboration among institutions, encouraging the collective effort to address water resource management challenges. This is important for all water resources agencies and users, but would benefit hydropower as well. Example attempts include data.gov, DataOne (www.dataone.org), Environmental Data Initiative (EDI, portal.edirepository.org), Hydroshare and HIS by the Consortium of Universities Allied for Hydrologic Science Inc. (CUAHSI, www.cuahsi.org), Multisector Dynamics Living Intuitive Value-adding Environment (MSD-LIVE, msdlive.org), and Integrated Hydro-Terrestrial Modeling (IHTM) (Community Coordinating Group on Integrated Hydro-Terrestrial Modeling 2020). Attempts to consolidate hydropower resources include HydroSource (hydrosource.ornl.gov) with datasets related to stream flows, hydropower opportunities, and existing operating licenses. However, each of the sites on this list points to only a subset of potentially relevant data, yet are also mutually overlapping. As a result, continued improvement and integration is necessary (Pang et al. 2020) to form a truly centralized repository.

Additional steps are needed to extend this work. For example, providing data with reasonable refresh time is important for public decision-making and scientific research alike (Stadler et al. 2011). Data access improvements are particularly important for transboundary basins (Kibler et al. 2014; Klug and Kmoch 2014).

3.2 | Numerical Modeling

The field of hydrologic modeling is undergoing significant advances to improve hydrological forecasting. This involves incorporating advanced data assimilation methods, numerical techniques such as machine learning (ML) algorithms, and high spatial resolution and multi-scale modeling approaches. Such advancements have allowed the development of global-scale models that integrate a wide range of hydrologic domains and processes (e.g., E3SM, e3sm.org). Furthermore, system-of-systems models developed in other fields are starting to link hydrologic models to models of climate, social, and economic systems (Amaya et al. 2022; Abdolabadi et al. 2023). Finally, the integration of remote-sensing data and real-time monitoring networks (Section 3.1) can improve model calibration and validation. Increased application of these developments to hydropower systems will improve hydropower forecasting, planning, and decision-making.

When simulating hydroclimate impacts on hydropower, the choice of climate models and/or emission scenarios often outweighs the influence of hydrologic or hydropower models (Kao et al. 2022). Where data are scarce, modeling hydropower at scales ranging from individual power plants to watersheds can be facilitated by remote sensing and global gridded datasets (Nasir et al. 2022; Chowdhury et al. 2024). Highly spatially resolved hydrologic models are sometimes needed to adequately predict the environmental effects of hydrologic or operational changes. Using hydrologic and temperature modeling as an example, the ability to simulate a large river network including thousands of small tributaries and dozens of reservoirs in multiple dimensions are emerging in the southeastern US (Cheng et al. 2020). However, their application remains limited in regions like the Columbia River due to the complexity of representing snowmelt processes (Wigmosta et al. 2022). Accurate simulation of large-scale hydrologic phenomena such as atmospheric rivers is also important (Guan and Waliser 2015) and requires both high spatial and temporal resolution and/or extent (Lesschen et al. 2009). In addition, ensemble techniques (running multiple models) are recommended for modeling hydrologic extremes due to the poorer accuracy of statistical analyses such as generalized extreme value distributions (van der Wiel et al. 2019). All of this points to the critical need for increased computational power.

Recent advances in both hydrologic data availability (Section 3.1) and ML algorithms to train models on those data hold great promise for improving hydrologic model accuracy, while reducing model construction and run times (Ardabili et al. 2019; Mariethoz and Gomez-Hernandez 2021; Shen et al. 2021; Di Salvo 2022). Recent examples of ML-enabled hydrologic predictions include projections of reservoir outflows, snow-water equivalents, and reservoir inflows (Zhang et al. 2021; Garcia-Feal et al. 2022; Gangrade et al. 2023). Yet, challenges remain; for example, most hydrologic ML applications have used relatively small datasets applied to single response variables, whereas larger datasets allow testing of parameter interactions (Shen et al. 2021). Other ML efforts have sought to infer reservoir operating rules and their parameterizations in models (Chen et al. 2022; Steyaert et al. 2022). While there are ML-based reservoir release models (e.g., Li et al. 2024), ML-based models to predict daily hydropower ultimately require different training datasets than planning analyses for long-term reservoir storage, specifically day-ahead and month-ahead electricity prices as well as details on hourly operations most often not publicly available. Addressing the challenge of training complex hydrologic models with small datasets is an important area for future efforts, with examples of proposed approaches including data augmentation (Chen et al. 2019), physics-informed ML (Pateras et al. 2023), and crowdsourcing (Dasgupta et al. 2022). Regardless, interpreting ML output can be challenging to hydrologists (Rozos et al. 2022), underscoring the value of broad efforts within the earth science community to support integration of AI/ML in hydrologic studies (Hickmon et al. 2022), as well as direct collaboration with ML experts (Karpatne et al. 2019).

Whether the increased accuracy of ML-enabled hydrologic predictions translates into increased accuracy of hydropower models depends on the magnitude of hydropower-system constraints (e.g., minimum reservoir elevations or outflow rates) which can prevent weather forecasts from informing reservoir operations (Doering et al. 2021). The increasing complexity and scale of linked hydrologic and hydropower models will enable broader analyses of the interactions of hydrology, hydropower, and grid reliability over time (Turner and Voisin 2022). Cascading reservoirs need to be simulated in tandem to understand how system constraints impact hydropower and water-supply functionality (Bakken et al. 2016; Zhang et al. 2023). The linking of models is also context and stakeholder-dependent, varying among countries (Helseth et al. 2023). In the U.S., the U.S. Army Corps of Engineers, together with other federal and state agencies, is developing the forecast-informed reservoir operation approach to use recent advances in the accuracy of long-range weather forecasts to relax those constraints and better optimize reservoir outflow management. In this context, continued development of multi-objective optimization (Giuliani et al. 2021) will be useful.

Ultimately, hydrologic and hydropower models will need to be linked with a broader suite of social and economic models to understand how value delivered to a range of stakeholders will shift with climate and socioeconomic drivers. System-of-systems (SoS) frameworks have recently increased in use because of their facility for capturing multiple interacting drivers and feedbacks among multiple models and systems (Little et al. 2016; Zhang et al. 2018; Kreibich and Sairam 2022; Abdolabadi et al. 2023). An example is linking water, energy, and food-system models, including the underlying economic interactions (Wu, Elshorbagy, et al. 2021). SoS approaches are also useful for successfully bridging discrepancies in temporal and spatial scales among component models. More specific to hydropower, SoS approaches can mediate multi-scale hydrologic modeling (Boldrini et al. 2022), incorporate groundwater withdrawals and management in addition to reservoir operation and hydropower generation (Eldardiry et al. 2022), link environmental and economic concerns (Singh et al. 2024), link to economic models for hydropower marketing and contracting (Lu et al. 2017), and simulate multi-sector dynamics (Gonzalez et al. 2023). Hydrologic variability of rivers could be linked to production cost models at continental scales, to enhance their value in assessing the interaction of hydropower with renewables and other energy sources at power-balancing scales (Voisin et al. 2018; Dyreson et al. 2022; Magee et al. 2022; Yates et al. 2024). Yet, hydropower SoS use cases are thus far uncommon, indicating considerable scope for future research and application, for example incorporating biological models such as lifecycle models of migratory salmon (NOAA 2020) or reservoir GHG emissions (e.g., G-res, g-res.hydropower.org, Prairie et al. 2021).

4 | Translation and Training

While new knowledge and tools are important, their applied value is diluted unless translation and training keep pace. Key obstacles to successful adaptation to climate change are present even in the most well-funded and science-driven hydropower systems such as those in the Columbia River Basin of North America. Examples of recent obstacles from this particular system include the assumption of hydrologic stationarity and short planning horizons, fractured jurisdictional authority, loss of technical expertise after the dam building era, and rigid operating rules (Hamlet 2011). Yet, translation issues are generally greatest at local scales, particularly for small operators and utility districts with comparatively few resources. In most cases, issues of climate change and hydropower are superimposed on a wider range of adjustments, including changing societal values, aging infrastructure, environmental and ecosystem concerns, and changes to the power grid. In particular, the longer design lives of water resource infrastructure (e.g., dams) relative to power infrastructure (e.g., generators) create an inherent disconnect.

To effectively disseminate developments in data, models, and planning with small hydropower operators, a multi-faceted approach is recommended. Establishing user-friendly platforms or online portals that provide accessible and up-to-date information on relevant data, models, and planning resources are helpful (Ahmad and Hossain 2019). These platforms should offer user-friendly interfaces, clear documentation, and tutorials to assist operators in understanding and implementing the latest developments (Hui et al. 2020). Collaborative partnerships between national and regional research institutions and government agencies on the one hand and industry associations representing small operators on the other hand can facilitate the sharing of information, case studies, and best practices. For example, the US Global Change Research Program (USGCRP) coordinates research that helps better understand the effects of global change on water resources through interagency collaboration. The Integrated Hydro-Terrestrial Modeling (IHTM) initiative brings together US federal and non-federal researchers as well as water managers.

Recent efforts have been made to address these obstacles and provide platforms to facilitate the translation of solutions to multi-faceted climate impacts to hydropower. For example, the Electric Power Research Institute's (EPRI's) Resilience and Adaptation Initiative (READi, www.epri.com/research/sectors/readi) aims to identify and disseminate state-of-the-art climate adaptation and resilience approaches, while the Center of Energy Advances through Technology Innovation (CEATI) promotes industry-led information exchanges on best practices and support (www.ceati.com/a/what-climate-change-means-for-electric-utilities). Yet, translation challenges can be difficult to generalize across power plants and utilities, with risks of certain needs falling through the cracks. Remaining needs for development mirror some needs in Sections 2 and 3, including access to consistent climate, flow, and sectoral water demand data, which can be generalized. Where most translational frameworks are challenged includes understanding institutional compliance requirements and how governance influences hydropower planning and scheduling across regions. Ongoing research focuses on regional coordination in managing water and energy resources and understanding deep uncertainty and risk for stranded assets, given longer hydropower plant life cycles relative to typical energy planning horizons. However, we need to extend the research to understanding financial systems to complement the engineering-environmental assessment with financial stability (Denaro et al. 2022) including the evolution of energy markets and the valuation of services that hydropower can provide (Haugen et al. 2024).

On the training side, there is a growing recognition for the need to enhance the pipeline of hydropower professionals given the increased value of hydropower in the current renewable energy transition. In addition, the US hydropower industry in particular is experiencing increased retirement of engineers and the associated loss of engineering culture at

TABLE 1 | Example knowledge gaps and methodological needs.

Categories	Example knowledge gaps and methodological needs
Knowledge areas (Section 2)	
Impacts to hydropower operations and planning	
Direct effects of extreme, sequential, and compound hydrologic events	• Relationships between extreme hydrologic events (individual, compound, sequential) and risk to hydropower, and related cascading hazards such as flooding • Variation in relative influence of changes to precipitation and evapotranspiration within watersheds on river flows
Indirect effects via changing power grid expectations, intersecting water resources concerns, and heightened uncertainty	• Continued development of system-of-systems and machine learning assisted approaches to objectively choose among an otherwise intractable range of possible options • Applying decision-making under deep uncertain to hydropower operations by integrating hydropower and power-system modeling • Geographic variation in prevalence of increased hydrologic variability causing hydropower to be run at maximum capacity thus reducing flexibility to integrate renewables
Novel strategies for mitigating impacts to hydropower	• Effect of river restoration on channel flows throughout river networks • Understanding whether solar and wind "droughts" co-occur with hydrologic droughts either temporally or geographically • Community effects of reducing irrigated agricultural activities in rural settings to increase channel flows
Greenhouse gas (GHG) emissions from reservoirs and possible mitigation	• Separating hydropower from other functions of reservoirs in attribution of net GHG emissions • Better understanding of relative importance of GHG emission pathways from reservoirs and their drivers across locations, types of reservoirs, reservoir water levels and release rates, and times of year • Systematic measurements/modeling of reservoir emissions across time (diel, seasonal, interannual cycles) and space (within and across reservoirs, and up- and downstream)
Methods/tools (Section 3)	
Monitoring data	• Refinement of remote sensing approaches, including increased temporal resolution (for application to daily hydropower management), application to run-of-river facilities, improved attribution/detection, and extended satellite longevity • Standardized GHG emission pathway measurement techniques • Creation of centralized, consolidated, publicly available databases and data repositories
Numerical modeling	• Standardizing GHG emission pathway modeling techniques • Ability to simulate water temperature throughout large river networks at high spatial resolution necessary to simulate effects on individual aquatic organisms • Further development of multi-objective optimization, machine learning, and system of systems approaches to hydropower simulation

the same time as an increase in required adaptation to new technologies (Daw et al. 2022). Most U.S. universities do not have hydropower-specific programs and many do not have even hydropower-specific classes. Hydropower content in civil and environmental engineering departments is often scattered in small pieces among water resources, geotechnical, and structural programs. Critical content is also found in electrical and mechanical engineering departments, among others. Hydropower careers, like civil engineering more generally, may not pay as well as other areas of engineering such as biomedical, robotics, or artificial intelligence (Kroman 2023). Yet, career opportunities in hydropower are much broader and include other engineering disciplines (e.g., environmental engineers, mechanical, electrical), atmospheric scientists, ecologists, and lawyers. Increased dialog between the industry and academia is needed to convey the importance, breadth, and excitement of hydropower careers to faculty and most importantly, to the next generation of students.

5 | Conclusions

There is significant potential for hydropower to contribute to the green energy transition, but its configuration and roles may differ significantly from those of the past in response to hydrologic change and changing expectations of grid services (e.g., balancing wind and solar power) and water resources management (e.g., facilitating ecosystem recovery). Research and development are needed (e.g., Table 1) to understand the multiple interacting pathways between climate change and hydropower operation and planning (Section 2, Figure 1), develop monitoring and modeling approaches to analyze hydropower and its role in the environmental and energy systems (Section 3, Figure 2), and enhance translation and training to improve incorporation into management (Section 4). Common needs running through these topics include developing ways to cope with both (1) the complexity of multiple interacting systems at watershed scales and (2) the deep uncertainty associated with climate trajectories. We use these themes to organize our conceptualization of the challenges ahead, while recognizing that the two are related; for example, more complex systems are inherently harder to simulate, leading to greater uncertainty.

Watersheds are inherently complex. Comprehending this complexity is critical to understanding the interaction of hydropower with surrounding watersheds in the context of climate change. For example, better understanding is needed of the relative significance of changes to precipitation and evapotranspiration on watersheds flows, interactions of both processes in complex compound events, and the cascading effects on hydropower operations. Similarly, better understanding is needed of indirect effects of hydrologic change via other systems such as aquatic ecosystems, agriculture, and flood control. Other indirect effects of climate change occur through the energy system, such as effect of hydropower via the transmission grid. A key element of complexity is that the interaction between climate and hydropower operations can run both directions, including the controls on net GHG emissions (and CH_4 emissions in particular) from reservoirs, whose diversity and variation in space and time are poorly understood. Adequately addressing such complexity requires continued improvements to monitoring and modeling. System-of-system models hold promise to link hydrologic models and those of climate, social, and economic systems, and to capture interacting drivers and feedbacks in multi-sector dynamics. Multi-scale modeling may address the spatial complexity of watershed processes to holistically simulate large river networks with sufficient spatial resolution at critical locations. And ML can better integrate large datasets for calibration or validation to improve hydrologic model accuracy, and reduce model construction and run times—yet requires specialized expertise.

Reducing uncertainty of future climate realities for hydropower operations and planning is critical where possible, for example, better understanding effects of extreme, sequential, and compound hydrologic events on river flow and hence hydropower. Conversely, our understanding of how hydropower affects GHG emissions is rudimentary. Both require improved analytical and sensing methods to better understand hydrologic events in real time for short-term hydropower operations but also improve long-term prediction for planning. Remote sensing is promising, particularly in data-poor regions, but requires continued refinement of temporal resolution, longevity, detection, attribution, and processing algorithms. This must be paired with improved model calibration and validation, for example, forecast-informed reservoir operation. Nevertheless, at the core of climate uncertainty is the unknowability of future human emissions trajectories, which are the underpinning of all future climate predictions, where further development of DMDU applications may help.

Research and development have little impact on the future if they do not inform practice. Yet, such translation to local scales and small operators is often hindered by insufficient coordination and resources. There is a need for continued consolidation and standardization of platforms to facilitate the translation of data, modeling, and tools to these communities of practice. Areas of particular need include access to data, coordinating across regions, managing deep uncertainty, financial planning, and understanding evolving hydropower valuation. Finally, all efforts described above require a sufficient supply of professionals trained in relevant subjects and skills. Here there is a need to enhance the pipeline of hydropower professionals given the increase in retirement during a period of great change. Increased dialog between industry and academia can help improve recognition of hydropower careers and the creation of relevant curriculum paths in subjects such as engineering, hydrology, geology, ecology, and law.

Some roadmaps for relevant research and development have been published, such as U.S. DOE's HydroWIRES Initiative Research Roadmap (USDOE 2022). Yet, this example only addresses a portion of the needs described here, creating broader opportunities for researchers, policymakers, and industry to collaborate.

Author Contributions

Natalie A. Griffiths: conceptualization (supporting); writing – original draft preparation (supporting); writing – review and editing (supporting). **Erich T. Hester:** conceptualization (lead); writing – original draft preparation (lead); writing – review and editing (lead). **Shih-Chieh**

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

This manuscript documents a literature review process, which did not generate any data, shared or otherwise.

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