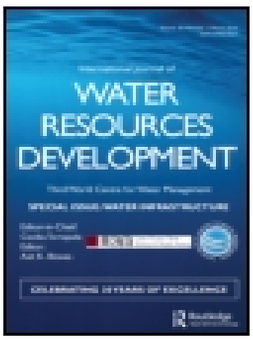

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Approaching obsolescence? A multi-criteria analysis of high-risk dams in the United States Pacific Northwest

Alexander C. Nagel and Thomas Ptak

Department of Geography & Geological Sciences, University of Idaho, Moscow, ID, USA

ABSTRACT

This research uses a multi-criteria analysis tool and field site observation to critically analyse a network of dams across a single watershed in the US Pacific Northwest. The analysis offers a template to better understand some nuances and complexities involved in decision-making leading to relicensing, retrofitting or decommissioning of both powered and non-powered structures. The study focuses on 13 dams in Oregon's Willamette River Basin Reservoir System, where the average age of structures is 62 years, exceeding a national mean of 57 years. Research outcomes can inform stakeholders who make decisions regarding America's high-risk dam network as it rapidly approaches obsolescence.

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High-risk dam network; multi-criteria analysis; hydropower; renewable energy; Pacific Northwest

Introduction

In February 2017, an aged and neglected spillway failed during a high-water event at California's Oroville Dam, the nation's highest impoundment structure. The resulting emergency forced an evacuation of 200,000 people downstream (Megerian, 2017). While infrastructural failure occurs primarily for older dams, breaches in younger structures – such as the case of Idaho's Teton Dam catastrophe in 1976 – are also manifest (Solava & Delatte, 2003). According to the National Inventory of Dams (NID) database, of the 91,468 dams across the United States, 75% are classified as high-hazard potential, suggesting the Oroville failure, which resulted in USD1.1 billion of repairs (Vartabedian, 2018) may not be an isolated incident (NID, 2020; Nuccitelli, 2017). Developed between 1941 and 1969, 13 dams located in Oregon's Willamette River Watershed form the Willamette River Basin Reservoir System (WRBRS). The installations, commissioned by the United States Army Corps of Engineers (USACE), are tasked with generating hydropower, and facilitating flood control, irrigation and recreational opportunities (USACE: Portland District, 2019). The average age of WRBRS structures is 62 years, which exceeds the national mean of 57 years (NID, 2020; Uría-Martínez et al., 2018). Correspondingly, unprecedented numbers of hydroelectric dams (WRBRS structures included) will face Federal Energy Regulatory Commission (FERC) relicensing in the near future, presenting a crucial juncture for stakeholders who will need to make decisions ranging from removal to recommissioning (Chaffin & Gosnell, 2017; Fostvedt et al., 2020). Furthermore, as extreme weather events are expected to increase under

CONTACT Alexander C. Nagel nagel@uidaho.edu

anthropogenic climate change scenarios, decisions regarding the most appropriate course of action for the WRBRS and America's fleet of ageing dams require urgent investigation.

Decommissioning of low-performing dams is increasingly common, as an array of impacts to riparian habitats transpire, and often exacerbate over time (Branco et al., 2014). Notwithstanding, entities such as the United States Department of Energy (USDOE) and National Hydropower Association (NHA) are engaged in promoting dams as a critical component of the future electricity landscape. Specifically, they advocate the retrofitting of existing structures as a viable strategy to expand generation portfolios (USDOE, 2018). A notable example of this programme is evidenced through a retrofitting of the WRBRS Dorena Dam, which saw two hydroelectric turbines installed within the previously unpowered structure (Wihtol, 2014). The project reflected an effort by the USACE to create technological lock-in for recommissioning through significant capital investment (Mcmanamay et al., 2019; Vu & Mayer, 2018). However, the retrofit became mired by budget overruns, delays, substandard construction, workplace injuries as well as lawsuits between investors and developers. An original project budget of USD20 million ballooned to a final cost of USD38 million (Douglas & Tong, 2012; Pracheil et al., 2019; Wihtol, 2014). This research will reveal how the retrofitting only marginally improved the performance of the dam, and even with substantial investment Dorena Dam still lacks safety release valves and a fish ladder, posing high structural risk while generating adverse biophysical impacts (Jerome, 2019). The consideration here of several critical services and disservices seeks to convey the multidimensional nature of dams, further detailed through field observations and a literature review that seek to identify whether core performance is driving decision-making. This process elucidates how performance is merely a singular factor in processes which shape the landscape of dams.

Deleterious outcomes resulting from the Dorena retrofitting and multiple dam failures across the United States sharpen the need for multidimensional research that evaluates a range of complexities to advance discourse beyond the decommissioning versus retrofitting binary. Consequently, this study analyses the WRBRS through a mixed-methods and multidimensional framework to holistically evaluate multiple dams in a single watershed. The research develops critical understandings that may not be evident in singular dam studies and illuminates future considerations facing the multifarious network of ageing dams across the United States. In order to offer fresh insights, this research interrogates the following questions:

- Based on a multi-criteria analysis tool and field site observations, how do current levels of services and disservices for the 13 WRBRS dams help shape decisions about their future use?
- How do outcomes gleaned from the study help inform broader debates about the future of ageing dam structures across the United States?

Background

A growing body of research is questioning the increasing costs of dams weighed against diminishing returns, particularly as key age thresholds are surpassed (Beck et al., 2012). However, dams continue to occupy a central position in current policies and discourse surrounding future scenarios for river management and energy landscapes, complicated

by emerging disruptions induced by climate change (Siciliano et al., 2015). Despite a nascent global transition away from fossil fuels in favour of renewable energy, dams inhabit a nebulous middle ground (Tortajada, 2015). Mainstream news articles commonly discuss solar and wind deployment, yet often overlook substantial contributions to electrical grids from hydropower and its role in national, regional and local development strategies (Biswas & Tortajada, 2001). Because dams have reflected an integral component of America's energy apparatus for decades, they are often uncritically accepted and thus endure in a manner best described as 'hidden in plain sight'.

At the start of the new millennium, hydroelectricity supplied approximately 98% of 'renewable' (this categorization is contested) energy in the United States (FWEE, 2017). Also, in 2015, hydropower was responsible for more than 85% of global renewable generation (IFPRI, 2017). However, while hydropower remains the largest source of non-fossil energy, the past decade has seen a proliferation of wind and solar installations that are transforming the energy landscape as these markets become cost competitive. In fact, the Bonneville Power Administration (BPA), which controls transmission from WRBRS structures, regularly forces the curtailment of wind energy, as contracts with utility companies mandate prioritization of hydroelectricity, resulting in challenges for non-hydro-renewable entities (Flatt, 2017). BPA's monopoly on long-distance transmission lines fuels tensions between non-hydro-renewable generators (primarily wind and solar), regulators, communities and an increasingly sceptical civil society (Liebenthal, 2019). Often, hydropower now costs more per kilowatt-hour on average than solar and wind (based on the 2017-levelized cost estimated by the International Monetary Fund – IMF). However, a strong argument often presented by dam proponents is that the infrastructure is already in place, providing renewable baseload energy to regional grids. These complex dynamics thereby clearly raise questions about the role of hydropower in future energy landscapes, notably in the Pacific Northwest where the wind market is among the fastest growing in the world (Bogmans, 2019; Sovacool & Walter, 2019).

Despite selective removals, it is evident that dams will continue to play an important role in electricity markets for the foreseeable future, in addition to providing services such as irrigation, flood control and recreation that bolster their utility. Currently, the landscape for new dam construction has predominantly shifted to the Global South, where they are viewed by many countries as necessary components of national and regional economic development models (Kirchherr et al., 2017; Obour et al., 2016; Ptak, 2019; Tortajada, 2000). Their omnipresence, however, is increasingly viewed as superfluous by a growing community of scientists aware of a shifting energy economy (Nikiforuk, 2016; Kirchherr & Charles, 2016). Further, a history mired by procedural failures, uneven development and increasing environmental consequences is calling into question whether the benefits of dams offset or justify concurrent and common impactful outcomes (Rapp, 2015).

In the United States, dams are not only physically embedded in formerly free-flowing rivers but also imbued with symbolism of ingenuity and nationalism (Klingensmith, 2008). By the 1970s, when environmental movements begun to manifest, more than 80,000 dams of 15 m or higher had been constructed along more than 66% of the nation's waterways (Rosenberg et al., 2000). These architectural advancements, although institutionalized and responsible for lucrative economic activities, began to be characterized through adverse biophysical outcomes by scientific and environmental communities

(Wilkinson, 1992). However, the momentum of dam-building continued with little impediment until optimal sites for structures had been exhausted (Nikiforuk, 2016). By the end of the century, a robust network of regulatory and administrative bodies, along with associated stakeholders, had developed. Consequently, attempts to remove dams have consistently been met with factious disagreement and bureaucratic roadblocks. An apropos example is the pending removal of four structures along the Klamath River in California. Conflict amongst stakeholders (notably water-user associations and local Native American Tribes) has stymied decommissioning for two decades and represents a common dynamic that emerges as removal projects proceed (Saulters, 2014). Sections 401 and 404 of the United States Clean Water Act (CWA), which include the most specific national legislation on criteria for dam removal, are underdeveloped through case law and lack regulatory teeth (Environmental Protection Agency (EPA), 2016). Resulting from this scenario is that removal proponents are overwhelmed by strong lobbying from often long-established pro-dam groups (Ciocci, 2008). Therefore, outcomes thus far are commonly based more on political dynamics than scientific analysis.

Meanwhile, however, geomorphic and hydrologically focused research has developed a strong body of evidence detailing how dam structures pose direct impacts to the biological, chemical and physical properties of rivers and riparian ecosystems (e.g. American Rivers, 2010; Blachly & Uchida, 2017; Branco et al., 2014; Cui et al., 2014; Kuby et al., 2005; Magilligan et al., 2016; Pejchar & Warner, 2001; Quiñones et al., 2015; Shaffer et al., 2018; Tomsic et al., 2007; Wilcox et al., 2014; Zheng & Hobbs, 2013). Furthermore, a growing literature is interrogating social outcomes on proximate communities (e.g. Borgias & Braun, 2017; Fearnside, 2016; Kirchherr & Charles, 2016; Magilligan et al., 2017; Ptak, 2014; Saulters, 2014; Siciliano et al., 2015; Tilt et al., 2008; Wang et al., 2013). However, there endures a research gap synergizing quantitative and qualitative data to produce comprehensive and robust understandings of multidimensional issues. Therefore, instead of offering yet another study investigating exclusively biophysical or social impacts, this research adopts a mixed methods approach that analyses both biophysical and social dimensions of dams. Doing so helps to unearth nuance and complexity, and thus advance platforms for dialogue amongst stakeholders, rather than further entrench positions already strongly divided along ideological lines (Sovacool & Walter, 2019).

Study area

A total of 250 hydroelectric installations across the Pacific Northwest region of the United States comprise 40% of the national hydroelectric portfolio (Scherer & Pfister, 2016). Physical characteristics of the region provide optimal landscapes for hydropower generation, as large rivers with headwaters often above 8000 feet lose elevation rapidly over short distances (Figure 1). The resulting steep gradients facilitate conditions for flow regimes to charge large hydroelectric turbines (Wilkinson, 1992). Oregon's Willamette River is amongst the most voluminous waterways in the western United States. As the second largest sub-basin of the Columbia River Watershed in terms of discharge (averaging 33,000 cubic feet/second at its confluence with the Columbia just north of Portland, Oregon), its network of tributaries converges along the floor of the Willamette Valley, which hosts the waterway's mainstem (Willamette Basin Watershed Councils (WBWC),

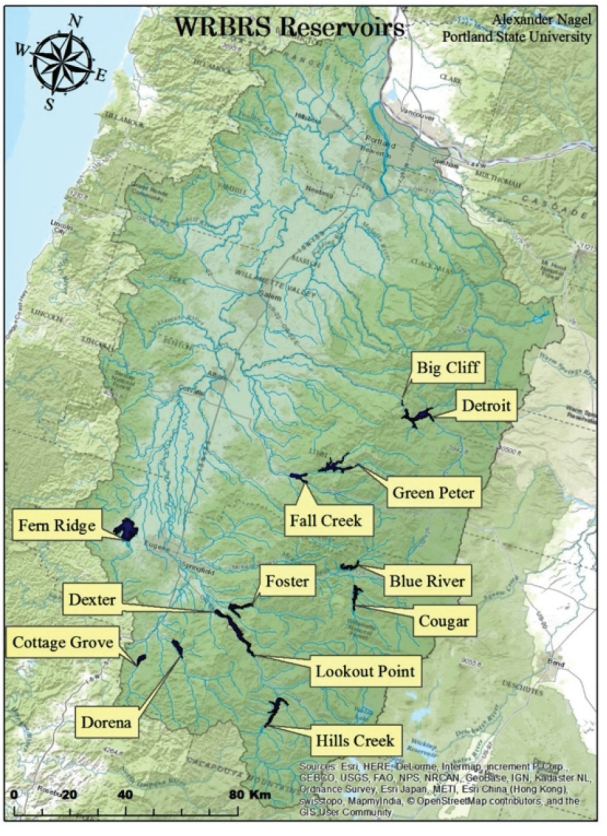

Figure 1. Map of dams in the Willamette River Basin Reservoir System (WRBRS).

2015). Rich and diverse soils produce a fertile corridor, attracting settlement and agricultural activities since western expansion (Sinclair, 2005). The maritime-influenced climate is conducive to a diversity of crops, including hops, wine grapes and berries reliant on a positive moisture index (Thornthwaite & Mather, 1955). The Willamette Watershed's geographical setting, however, leads to high fluctuations in seasonal runoff, which historically jeopardized harvests and restricted settlement as peak flows inundated flood plains during spring snow melts (Rapp, 2015).

Despite challenges shaped by the natural environment, population centres throughout the Willamette Valley have grown steadily since the early 19th century, facilitated by infrastructure projects that improved transportation and standards of living (Reisner, 1986). The United States reclamation era, stimulating projects such as the Boulder Canyon (Hoover Dam) and Columbia Basin (Bonneville and Grand Coulee Dams), spearheaded the transition to dam-based watershed management for water rights holders and regulatory bodies in the Willamette Valley (Robbins, 2017). Perceptions evolved that the watershed's hydrology could be profitable if managed accordingly (Wilkinson, 1992). Lack of environmental regulation and congressional mandate by three federal flood control acts in 1936, 1944 and 1960 opened the floodgates for development of the WRBRS (United States Congress, 1960). The 13 structures that now occupy the Willamette Watershed produced a dramatic transformation from a series of energetic and variable

tributaries to a chain of lakes tamed by flood and hydropower focused flow regimes (Magilligan et al., 2016). Table 1 provides a general orientation of the functions and characteristics of the structures to be analysed.

Following completion, the WRBRS succeeded in providing specific services designated for each dam in the system. Beyond flood control and generation of hydroelectricity, the reservoirs have developed into popular recreational areas. Agriculture benefited from reliable irrigation sources and municipalities were allocated water for public utility supply (USACE, 2019). Meanwhile, alongside these favourable outcomes, adverse impacts on riparian habitats emerged. A notable example is the greater than 55% reduction in anadromous fish runs throughout the watershed (Wilkinson, 1992). Furthermore, habitat fragmentation caused by dam induced bifurcation of rivers has resulted in higher downstream temperatures (United States Geological Survey (USGS), 2020). Increased thermal impacts have proven harmful to aquatic biota. During the early 1980s, a backlash from environmental groups compelled the USACE to adapt its policies for aquatic habitat protection (Oregon Department of Fish and Wildlife (ODFW), 2007). This included partial management delegation to the ODFW (USACE, 2015). Moreover, the Endangered Species Act (ESA) and CWA required the USACE implement programmes such as temperature regulation, fish relocation and collaboration with local conservation organizations (WBWC, 2015). Such efforts helped to safeguard against potential decommissioning, as each dam creates financial benefits for the USACE and federal government (Sharpe, 2013). Mitigation programmes have curtailed the intensity of habitat impact, yet are incapable of restoring conditions to pre-dam levels (Rapp, 2015). Currently, the USACE remains steadfast in maintaining long-term management strategies for each of the WRBRS structures (USACE, 2019).

Safety inspections in 2010 determined several spillway gates were at risk of malfunctioning as high water levels placed considerable pressure on the gates (Grasso, 2015). Therefore, the USACE has been pursuing long-term gate rehabilitation in the WRBRS

Table 1. Characteristics of the dams in the Willamette River Basin Reservoir System (WRBRS).

Dam	Primary function[a]	Reservoir capacity (acre-feet)[a]	Host river[a]	Coordinates[a]	Elevation (masl)[a]
Big Cliff	Hydropower	6450	North Fork Santiam	44.75°N, 122.28°W	369
Blue River	Flood regulation	89,500	Blue (McKenzie)	44.17°N, 122.33°W	415
Cottage Grove	Flood regulation	32,900	Coast Fork Willamette	43.72°N, 123.05°W	246
Cougar	Hydropower	219,000	South Fork McKenzie	44.13°N, 122.24°W	518
Detroit	Hydropower	455,100	North Fork Santiam	44.72°N, 122.25°W	482
Dexter	Hydropower	29,900	Middle Fork Willamette	43.92°N, 122.81°W	214
Dorena	Flood regulation	77,600	Row	43.79°N, 122.96°W	264
Fall Creek	Flood regulation	125,000	Fall Creek	43.94°N, 122.76°W	256
Fern Ridge	Flood regulation	116,800	Long Tom	44.12°N, 123.30°W	116
Foster	Hydropower	60,700	South Fork Santiam	4.41°N, 122.67°W	214
Green Peter	Flood regulation	249,900	South Fork Santiam	4.45°N, 122.55°W	279
Hills Creek	Flood regulation	355,500	Middle Fork Willamette & Hills Creek	43.71°N, 122.45°W	472
Lookout Point	Flood regulation	455,800	Middle Fork Willamette	43.92°N, 122.75°W	287

Sources: [a]Data are from the Oregon Department of Water Resources (ODWR) (1998); National Inventory of Dams (NID) (2020); and United States Army Corps of Engineers (USACE) (2005, 2019).

(USACE, 2019). However, such conditions are likely to experience increased vulnerability as climate change impacts manifest, due to variable and volatile precipitation patterns (Jung & Chang, 2012; Kunkel et al., 2013). In fact, the winter of 2019 saw the most significant flooding in the Willamette Valley over the past 50 years, despite ongoing efforts to mitigate inundation with adaptive fill and release programmes of all 13 structures (Williams, 2019).

Even though the WRBRS structures are ageing, they are firmly embedded within local/regional social, economic and political systems. The structures generate a nexus of associated infrastructure, for example, roads, transmission lines, lakeside homes, businesses and recreational facilities such as boat launches and information kiosks. Such development reinforces the embedded nature of dams, as path dependencies shape complex interactions between human and environmental systems (Araújo, 2014; Bridge et al., 2013). Holistically analysing dams thereby necessitates a robust understanding of their role in shaping both positive and negative outcomes, particularly how decisions regarding their future will inevitably involve trade-offs.

The next section will assess each WRBRS structure by evaluating its services and disservices. A specific focus is centred on primary functions as defined by the NID database. Disservices were established through an extensive literature review of the principal impacts generated by the 13 structures. These metrics provide a template for analysis regarding the balance between decision-making based on ideological or scientific positions.

Services and disservices (criteria)

Criterion 1: Flood regulation

A foundational precedent for the WRBRS was the Flood Control Act of 1938. The legislation was created to reduce damage on infrastructure during peak flow events, support reliable water supply and encourage development along fertile corridors of waterways (Rivers and Harbors Act of 1960) (United States Congress, 1960). With high seasonal discharge fluctuation, the USACE was instructed by the United States Bureau of Reclamation (USBR) to achieve satisfactory control of the Willamette network to minimize potential of catastrophic events (Sinclair, 2005). This operational latitude gave the USACE authority to build dams on each major tributary of the mainstem Willamette River over a span of three decades (ODWR, 1998). Flow regulation structures have succeeded in preventing major channel breaches by regulating releases, in addition to dramatically modifying the riverbank and fluvial topography of the waterways (East et al., 2015).

One caveat to the USACE success in administering flood reduction, however, is revealed though geomorphological analyses measuring diminished capabilities of dam-influenced channels to adjust their bed and sediment storage (Cui et al., 2014). These alterations, coupled with side channel elimination, concentrate discharges and diminish the complexity of aquatic habitats (Avery, 2014). While floods have been suppressed, anomalous events leading to an overflow of storage capacities can result in severe destruction downstream. In analysing flood mitigation, the USACE provides data approximating cumulative savings secured by each dam's presence (USACE, 2019). Cumulative averages are bolstered by drawdown priority, determined by a range of factors, including

reservoir capacity, discharge and historic records highlighting areas of vulnerability (ODWR, 1998).

Criterion 2: Hydropower capacity

Nine structures in the WRBRS generate hydroelectricity. The 408 MW capacity can provide electricity to supply approximately 300,000 dwellings. By comparison, Bonneville Dam on the Columbia River east of Portland, Oregon, has a capacity of 1242 MW (USACE, 2019). While this calls into question the need for hydropower from the WRBRS, electricity is more effective when transmitted shorter distances, and the USACE posits the logic of hydroelectric generation in the Willamette Watershed for meeting local demand (Kruzic & Taylor, 2008). As three WRBRS structures (Detroit, Green Peter and Lookout Point) reflect between 70% and 75% of the network's total capacity, the utility of lower capacity dams is questionable, despite what the USACE and hydropower developers argue (USACE, 2019).

Criterion 3: Recreation

Recreation is not classified as a critical service, such as flood control or electricity generation. Nonetheless, the social benefits associated with impounding rivers to create reservoirs have been among the most visible outcomes in the Willamette River Watershed. Activities include boating, angling, camping, bird watching and hiking, while annual visitation days throughout the WRBRS have a range of 3–4 million (USACE, 2015, 2015). Field observations illuminated the social benefits of recreation, particularly at Fern Ridge Reservoir. During the summer, Fern Ridge plays host to significant numbers of residents from the two neighbouring urban areas of Eugene and Springfield. Infrastructure such as lake-front homes, a marina and a yacht club characterize the watershed's most visited reservoir (Connolly et al., 1991). This waterfront infrastructure demonstrates a high level of social embeddedness, and similarly to structures containing hydroelectric facilities, efforts to decommission such dams would likely be met with significant opposition. Field observations highlight how socio-political dimensions such as embeddedness and inertia are critical when assessing the utility and future of America's ageing dam network, regardless of factors such as risk or economic feasibility.

As the USACE focused resources on flood control and hydropower generation during the early stages of WRBRS development, the ecological health of reservoirs has suffered (Sinclair, 2005). Since the reservoirs are imbued with social value, recreational use is an important criterion to consider, because it can be seen as corresponding with approval of, and interaction with, the WRBRS. It is beyond the scope of this study to detail the complex arrangements of financial benefits and costs produced by the reservoirs, as each location plays host to a web of organizations that generate revenue from reservoir operations or receive funding allocated for management activities (Linn County Parks and Recreation (LCPR), 2011). However, data that informed the quantitative analysis of recreation focus on visitation days, intended to calibrate the importance of each dam in the regional community (Connolly et al., 1991).

The USACE actively promotes recreation at each WRBRS reservoir, thus making it the most visible service, because the reservoirs host substantial public infrastructure to host these activities (USACE, 2019). Management bodies promote these activities because they

stimulate local economies and facilitate positive sentiments for the structures by local populations. Certainly, path embeddedness is present through recreation because surrounding economies are dependent on the reservoirs for tourism and employment. Therefore, despite the increasing impacts caused by these ageing structures, their roles in the sociocultural landscape of the areas they inhabit endure.

Criterion 4: Fish mortality

One of the most substantial impacts of dams is upstream habitat obstruction, leading to impacts on aquatic species. Barriers from anadromous fish spawning grounds have been severe in the north-west United States due to dam construction. Abundant fish runs were suddenly confronted with one of the most extensive impoundment networks in the world (Reisner, 1986). Fish mortality levels increased, resulting in the designation of two species of salmon and steelhead as endangered in 1999 (Northwest Power and Conservation Council (NPCC), 2019; USACE, 2011). Biologists estimate that even structures hosting adequate fish ladders for passage precipitate species losses of between 5% and 13% (Branco et al., 2014; Wilkinson, 1992). Not a single WRBRS structure hosts a fish ladder, although Cougar and Detroit Reservoirs have recently imitated fish transportation systems via trucks (Keefer et al., 2012; USACE: Portland District, 2018). In the most severe cases, an absence of fish ladders has resulted in 85% declines for anadromous fish runs throughout the Willamette and its major influents (Angilletta et al., 2008; Lundin et al., 2019).

Although most of the Willamette's tributaries are obstructed by multiple dams, notable studies have concluded that rehabilitative effects can occur with a single decommissioning (Branco et al., 2014). Habitat normalization and fewer barriers accommodate less precarious journeys to spawning grounds, and correspond with higher survival rates (Quiñones et al., 2015). The historic salmon returns on each WRBRS channel varies, but all host anadromous runs that have been impacted (Evans et al., 2016). Increasing awareness on the severity of declines has spurred a backlash against the USACE, responding with hatchery programmes, fish relocation and surveying for fish passage retrofitting (Associated Press, 2013; USACE, 2013). Release schedules have been modified to maintain minimum flows suitable for fish habitats (USACE, 2019). However, populations have not recovered sufficiently to appease environmental groups, who maintain that the USACE continues to prioritize revenue over restoration (WBWC, 2015). Barring removal, the USACE will maintain a delicate balance between dam operation and response to ecological impacts of WRBRS structures (Tomsic et al., 2007).

Criterion 5: Water temperature imbalance

When a previously free-flowing river plays host to a dam, the channel is bisected and a formerly cohesive habitat develops fragmented characteristics. Riparian habitat succession manifests through several outcomes, including the 'destruction of fisheries, and overall loss of the ecosystem services on which the human economy depends' (Postel, 1998). Concurrently, the change in magnitude and timing of flows to optimize hydropower or flood control alters the amount of time a reservoir is at full pool (Kruzic & Taylor, 2008). Drawdown regimes focused primarily on flood control or hydropower lead to

shallow summer fills, allowing solar radiation to have a significant impact on water temperatures.

Large drawdowns leave summer fills shallow and resultant solar penetration heats surface water and causes higher temperatures upon release. The USACE has mitigated these issues through adapted management schemes, including maintaining flow levels to comply with EPA standards for fish health (EPA, 2017). The Cougar Dam temperature regulation represents a technical response to exacerbated conditions, but is the only WRBRS reservoir with this infrastructure (USACE, 2005). The lone temperature control tower cost USD52 million to construct (USACE, 2018). While the tower has ameliorated water temperature conditions within and below the reservoir (Cougar had zero days over 18.0°C between 2014 and 2019), the WRBRS functions as a collaborative network. Consequently, the total number of days above the hazardous threshold (18.0°C as defined by the EPA) throughout the system is increasing (USGS, 2020). In order to generate basin-wide improvements, the USACE would need to instal towers in several WRBRS reservoirs. Such an initiative would necessitate significant capital inputs and result in a range of logistical/technical challenges.

The USACE has employed adapted fill-and-release schedules intended to align more closely with natural flow regimes, yet it maintains an adherence to flood control and hydropower generation, limiting the potential for improvement. Furthermore, these techniques have limited capacity for success because reservoirs by their nature disrupt flow and temperature to some extent, regardless of how aggressive the management practices to mitigate impacts (Connolly et al., 1991). For example, Cougar Reservoir, which yields the second highest overall score and is touted by the USACE as a symbol for best practices, has experienced anadromous fish run decline from approximately 4000 to 250–525 (USACE, 2013, 2018). These declines have transpired despite the implementation of both the temperature control tower and a fish transportation programme (USACE, 2019). Despite annual and seasonal climate variability, increasing temperatures and lower alpine snowpack has impacted the timing and quantity of water that fills the WRBRS reservoirs (Rounds, 2010; USACE, 2005). Therefore, the USACE faces a twofold challenge in maintaining healthy water temperatures, as full pool levels are decreasing and summer temperatures increasingly hover into levels considered harmful for aquatic species and the overall health of riparian habitats (EPA, 2017; USGS, 2020).

Criterion 6: Structural risk

Fifteen-year seismic studies on Oregon's dams have recently exposed high-risk levels for each WRBRS structure (NID, 2020). In the event of an earthquake along the Cascadia Subduction Zone, hazards stemming from structural failure would be significant (Associated Press, 2013). These precarious conditions have compelled the USACE to invest in more thorough seismic and safety inspections to comply with current codes and standards (Grasso, 2015). However, ongoing evaluations by private consulting firm the Battelle Memorial Institute, in consultation with federal and state entities such as the USGS and Oregon Department of Transportation (as well as by the USACE internally), suggest the WRBRS dams are vulnerable even without a major seismic event (Associated Press, 2013; Battelle Memorial Institute, 2018). High water periods, the root of failure for Oroville and other structures, may lead to similar malfunctions throughout the country

(USACE, 2011). Modelled impacts of anthropogenic climate change project increasingly variable seasonal precipitation events, compounding the likelihood of dam breaches (Jung & Chang, 2012).

Repairs to critical components of several dams, such as the 2010 spillway restoration at Blue River, demonstrate that the USACE is focused on long-term structural rehabilitation (Grasso, 2015). However, as the average age of the WRBRS dams is 62 years, evidence suggests that structural issues will continue to increase and eventually reach a tipping point (Larrauri & Lall, 2020). The ability of federal dam managers to confront structural entropy may rely on federal congressional support, yet the disposition towards a major infrastructural overhaul has been debated for decades with little resolution (Chaffin & Gosnell, 2017; Wilkinson, 1992). Nonetheless, numerous tools have been developed to model and analyse dam risk. The FERC and USACE collaborate to manage the NID, which provides structural hazard assessment data for large dams across the United States (NID, 2020). Informed decision-making will rely on collaboration between a complex web of dam operators, scientific organizations, and state and federal entities, thus requiring a commitment to cooperation that has been elusive in many American watersheds.

Methodology

This research adds to a limited literature considering future pathways for managing watersheds playing host to ageing dam networks, particularly studies evaluating multiple structures within one river basin (e.g. Branco et al., 2014; Kuby et al., 2005; Null et al., 2014; Pejchar & Warner, 2001; Quiñones et al., 2015; Tomsic et al., 2007). These studies analyse coordinated systems with a single watershed by evaluating services and disservices of individual structures based on performance. Each dam is then ranked or prioritized for potential removal within the broader river network. Branco et al. (2014) modelled habilitation suitability loss incurred by channel fragmentation to create a prioritized dam removal simulation. Their methodology can be applied to other watersheds to evaluate the performance of individual structures. Quiñones et al. (2015) employed a multi-criteria analysis tool (MCAT) similar to that used in this study to assess California's dams' impacts on anadromous fish species. This research evaluated habitat suitability under current conditions, contrasted against outcomes supported by simulated removals. Although these studies contribute to a novel framework for multi-structure dam analysis, results are limited one specific element (i.e. fish habitat, hydropower, etc.) of what are commonly multidimensional issues. A notable exception is Kuby et al. (2005), who incorporated multiple objectives to conclude that 12 removals in the Willamette Basin could achieve 52% reconnection of fish spawning habitat. However, this study solely incorporates quantitative analysis and does not analyse socio-political dimensions. Overall, these studies offer valuable templates for understanding complex relationships coupling dams and riparian health. However, orthodox approaches are advanced here by evaluating multiple criteria to develop a robust framework for synthesizing both the services and impacts generated by dams within a single watershed. This represents a novel approach through the development of an MCAT which is used to inform and validate observations ascertained through field visits.

Initial quantitative data analysis is supplemented by field observations undertaken through site visits to each structure. First, the MCAT is used to rank the 13 dams through an assessment of their services and disservices. The tool developed for this study was developed specifically for the project, and individualized for the WRBRS, as dams are situated and operate within

unique biophysical, socioeconomic, environmental and political circumstances (Poff & Hart, 2002). The selection of three services (flood control, hydropower capacity and recreation) to be measured was chosen based on the primary official purposes, as categorized but the NID (2020) and USACE: Portland District (2017). Disservices (fish mortality, water temperature imbalance and structural risk) were selected based on the most commonly reported adverse implication resulting from the dams, as detailed in a range of academic articles ($N = 21$). Services are scored between 0 and 3, with disservices between 0 and −3, respectively (Oregon Emergency Management Division (OEMD), 2016).

Evaluations for each dam were developed by averaging scores, calibrated by a percentage of the highest scoring dam. For example, Lookout Point Dam hydroelectric capacity is the greatest among the WRBRS structures at 120 MW, thereby receiving a score of 3.00. Green Peter Dam has a capacity of 80 MW, therefore scoring 2.00. Green Peter's score was calculated by the formula: $(80/120) \times 3 = 2.00$. All other structures with hydroelectric capacity were scored using the same formula, and unpowered structures receive a score of zero. Alongside the MCAT, field observations provide site-specific context that is valuable, but not possible through purely quantitative analysis. For example, field observations facilitated understandings of the infrastructure built around the reservoirs, reading USACE information boards at reservoir visitor areas, visually assessing the potential for fish ladder constructions and other mechanisms to contextualize the quantitative information being gathered. Field observation is a useful tool for such studies because data can be elucidated through physical interaction with the study area.

Flood regulation is scored through two criteria: drawdown priority and estimated savings from flood avoidance. First, drawdown priority scores are generated based on eight priority levels (1–8), assigned by the USACE in the Willamette Basin Reservoir Study (ODWR, 1998). Scores were calculated using the following formula: $(9 - \text{priority level})/8) \times 3.00$. For example, the number 2 priority dam received a score of $(9–2)/8) \times 3.00 = 2.63$. Dams without drawdown priorities assigned by the USACE were scored zero.

Second, scores for flood avoidance savings were calculated using the following formula: (US dollars saved through each respective dam/USD5.3 billion) × 3.00. The figure of USD5.3 billion reflects the highest estimated US dollars saved through flood avoidance at Lookout Point Reservoir, which is the highest for any WRBRS dam.

Finally, the MCAT score is determined by averaging scores of the two variables. For example, Detroit Dam was assigned a drawdown priority of 6, generating a score of 1.13. Estimated savings through flood avoidance was USD3.7 billion, generating a score of 2.10. The final service score was calculated through the following formula: $(1.12 + 2.10)/2 = 1.62$. Each additional service and disservice was scored using the same formula, yet the remaining criteria with the exception of structural risk incorporate one, rather than two, metrics.

Expanding on the quantitative methodology, correspondence with dam managers and site visits substantiated this criterion. The USACE estimates the 13 structures have saved USD18.9 billion in cumulative damage for downstream communities (USACE, 2019). While the WRBRS dams have reduced the consistency of flood impacts, inundation events have not been completely mitigated. Recent flooding during the winter of 2019 supports this claim (Hill, 2019). Furthermore, while dams can hold significant capacity to regulate flows, the accumulation of water in a concentrated location conversely increases potential for major downstream inundation (Marcus et al., 2001; Thakkar, 2007). Since the structural risk of each WRBRS dam is categorized as 'high' in the NID database, in addition to the location of the watershed along

the Cascadia Subduction Zone, a seismic event may compromise their stability and result in downstream catastrophe of much higher intensity than naturally flowing waterways (Megerian, 2017). Furthermore, hydrological studies have begun to understand and convey how the topographies of dam altered rivers shifts, yet may increase the susceptibility of flooding in certain areas of the watershed (Degu et al., 2011). Field observations were critical to discern how the locations of particular dams shape their potential for flooding related impacts. WRBRS structures such as Lookout Point and Detroit Dam are situated directly upstream from the population centres of Eugene and Salem, respectively. Fern Ridge, meanwhile, is removed from major infrastructure, thus flooding would filter directly into the mainstem Willamette, reducing potential for impacts on human settlements.

Observational assessment across the entire WRBRS illuminated how the physical geography of most sites preclude options for fish passage. The combination of concrete buttress and earth-filled arch dams are located predominantly in narrow canyons, ideal for harnessing electricity, yet challenging for retrofitting to accommodate fish ladders. Currently, no evidence suggests plans for the installation of ladders, and the WRBRS continues to obstruct anadromous fish passage. Several information kiosks proximate to the reservoirs discuss fish mitigation efforts: the only meaningful efforts involve fish transport in trucks, which yields low rates of success (Keefer et al., 2013). Consequently, the USACE is poised to face challenges as the WRBRS operates in a contemporary landscape where the public understands the importance of healthy fish runs, and the vital role that these aquatic species have in the ecological balance of riparian habitats (Gavrilles, 2012). Observation of the reservoirs in both the spring and fall of 2017 and 2018 revealed substantially low water levels throughout the watershed, indicating mounting pressure on species and habitats along with potential for hydroelectric generation. USGS gauging station data reflect a clear trend of increasing temperatures throughout the basin as most structures had several days above the 18.0°C threshold in both 2018 and 2019 (USGS, 2020).

Importantly, the evaluation of structural risk must be spatially situated for proximity to human settlements and other infrastructure to be adequately understood. While modelling plays as a key role in informing these metrics, field observation is an additional, and essential tool for obtaining landscape-specific data and determining the consequences of a structural failure. For example, Fern Ridge Dam is among the oldest, but it is situated in an area of level topography. Structural failure would predominately result in water reaching the mainstem of the Willamette River, minimizing the risk of infrastructural damage and catastrophic impacts to human populations. Meanwhile, Detroit, Green Peter and Lookout Point hold the greatest reservoir capacity and are situated directly upstream from large urban areas such as Eugene and Springfield. They are classified as high risk, and Detroit and Lookout Point are both 66 years old. The USACE has implemented emergency action plans, and while these structures are not the oldest in the WRBRS, failure remains a distinct possibility (NID, 2020). Mixed-method approaches incorporating field observations, therefore, facilitate a more holistic means for assessing the risk level of each dam as they age. Table 2 outlines this mixed methodology.

Results

Upon calculating the MCAT scores, the results convey the overall service and disservice levels. Cumulative scores were calculated by summing and averaging each service and disservice to

Table 2. Decision-based support system outline based on multi-criteria analysis tool (MCAT) and field observations.

Progression of analysis	Step 1	Step 2	Step 3
Criteria selection	Data collection for Willamette River Basin Reservoir System (WRBRS) variables (services and disservices)	Evaluation of criteria performance based on field observations conducted at each study site	Expansion or reduction of criteria based on results analysis and further research priorities
Evaluation method	Equal output scoring (i.e. 0 to ±3) or ranking based (i.e. numbers 1–13)	Comparison of multi-criteria analysis tool (MCAT) scores alongside observation-based assessment of structural characteristics	Corroboration with dam managers (Oregon Department of Fish & Wildlife, Federal Energy Regulatory Commission (FERC), US Army Corps of Engineers – USACE) to compare results with current operation schemes

form overall respective metrics, then subtracting the disservice score from the service score. For example: Detroit Dam scores 1.62 (flood control) + 2.49 (hydropower capacity) + 2.87 (recreation) = 6.98 cumulative service score. This is subtracted by the cumulative disservice score, which is −2.47 (fish mortality) −0.00 (temperature imbalance) + −2.36 (structural risk) = −4.83 cumulative disservice score. Finally, the overall score is calculated by (6.98) + (−4.83) = 2.15. Therefore, Detroit has a positive cumulative performance score. Charts comprising each service and disservice calculation are included in the following section.

The MCAT scores detail six structures with positive scores, while seven were negative. Despite steep declines in several anadromous fish species and substantial structural vulnerabilities, several structures are performing as intended by the USACE. However, structures exhibiting the lowest scores generate substantial disservices, leading to an average basin-wide score of −0.40 (calculated from the sum of cumulative scores divided by 13). The negative overall score suggests disservices incurred by the dams outweigh ongoing services and have less capacity for growth. Meanwhile, two of the three largest dams (Detroit and Green Peter) score positively, while Lookout Point is essentially flat, indicating that despite significant disservice levels, the highest hydropower yielding structures function as the core of the WRBRS.

An initial assessment of dam performance can be derived from the scores. As seven of the 13 dams have sub-zero scores, suggesting that the USACE has been unsuccessful at adjusting flows to facilitate healthy aquatic habitats, mitigating temperature imbalances and upgrading structures to reduce their risk of failure (USACE, 2019). These outcomes suggest the USACE should consider alternative pathways for increasing the utility of the structures by mitigating disservices that currently impact riparian ecosystems around dams. For example, field observations illuminated that the physical conditions at Dorena Dam were suitable for a fish ladder; however, as noted above there are no indications of future plans for fish ladders at any of the WRBRS sites.

The negative overall MCAT score for the WRBRS figure suggests the coordinated system faces serious management challenges and possible policy decisions in the near future. Removal of four structures (Big Cliff, Cottage Grove, Dorena and Fern Ridge) would shift the overall score for the system to a positive figure, notably eliminating structures with high fish mortality, compounded by summer temperatures above 18.0°C. Only three (Dexter, Big Cliff and Dorena) of the five low-scoring structures generate hydropower, and none is among the high-priority flood regulators. Tables 3 and 4show the scores for each

Table 3. Results for services.

Dam	Drawdown priority[a]	Score	USD saved in damages[a]	Score	Rank (high–low)	Criteria 1 score (0–3)	Hydropower capacity (MW)[a]	Rank 1–13 (high–low service)	Criteria 2 score (0–3)	Annual number of recreation visitation days (10-year average)[a]	Rank 1–13 (high–low service)	Criteria 3 score (0–3)
Big Cliff	n.a.	0	615 million	0.35	13	0.17	18	7	0.45	50,000	13	0.20
Blue River	3rd priority	2.25	375 million	0.21	7	1.23	No hydropower	= 11	0.00	66,000	11	0.26
Cottage Grove	5th priority	1.50	1.2 billion	0.68	8	1.09	No hydropower	= 9	0.00	417,000	4	1.63
Cougar	2nd priority	2.63	452 million	0.26	6	1.45	25	5	0.63	64,000	12	0.25
Detroit	6th priority	1.13	3.7 billion	2.10	4	1.62	100	2	2.49	735,000	2	2.87
Dexter	n.a.	0	5.3 billion	3.00	5	1.50	15	8	0.38	321,000	6	1.25
Dorena	5th priority	1.50	3.4 billion	1.92	3	1.71	7.5	= 9	0.18	343,000	5	1.34
Fall Creek	5th priority	1.50	900 million	0.51	9	1.01	No hydropower	= 11	0.00	269,000	7	1.05
Fern Ridge	8th priority	0.38	415 million	0.23	12	0.31	No hydropower	= 11	0.00	768,000	1	3.00
Foster	7th priority	0.75	1.9 billion	1.08	= 10	0.92	20	6	0.51	590,000	3	2.30
Green Peter	5th priority	1.50	600 million	0.34	= 10	0.92	80	3	2.00	230,000	8	0.90
Hills Creek	4th priority	1.88	3.2 billion	1.81	2	1.85	30	4	0.75	109,000	9	0.43
Lookout Point	1st priority	3.0	5.3 billion	3.00	1	3.00	120	1	3.00	97,000	10	0.38

Sources: [a]Data (criterion 1) are from Atlas of Oregon Lakes (2017); ODWR (1998); Sinclair (2015); USACE (2017); are USGS (2020). Data (criterion 2) are from Scherer and Pfister (2016); and USACE (2016, 2019). Data (criterion 3) are from Connolly et al. (1991); Johnson et al. (1985); Linn County Parks and Recreation (LCPR) (2011); Oregon Parks and Recreation Department (OPRD) (2019); Reinhardt (2017); USACE (2005, 2009, 2015, 2019); and United States Forest Service (USFS) (2009).

Table 4. Results for disservices and overall scores.

Dam	% Below dam wild anadromous fish mortality[a]	Rank 1–13 (low–high disservice)	Criteria 4 score (0 to −3)	Average number of days with a mean temperature > 18.0°C, 2015–19[a]	Rank 1–13 (low–high disservice)	Criteria 5 score (0 to −3)	Dam age (years)[a]	Structural risk (seismic studies)[a]	Hazard potential (based on urban proximity and estimated breach damage)	Rank (high–low)	Criteria 6 score (0 to −3)	Cumulative score	Ranking (1–13)
Big Cliff	73%	= 9	−2.47	0	= 1	0.00	67	High	Low	= 8	−0.85	−2.50	10
Blue River	28%	2	−0.11	6	= 1	−0.15	51	High	Low	1	0.00	1.23	3
Cottage Grove	69%	7	−2.26	58	= 11	−1.49	78	High	Medium	= 12	−1.95	−2.98	11
Cougar	32%	3	−0.31	0	= 1	0.00	56	High	Low	5	−0.27	1.75	2
Detroit	73%	= 9	−2.47	0	= 1	0.00	67	High	Extreme	= 8	−2.36	2.15	1
Dexter	26%	1	0.00	47	= 1	−1.21	66	High	Extreme	7	−2.30	−0.38	9
Dorena	81%	12	−2.89	39	=11	−1.00	71	High	Extreme	11	−2.57	−3.23	12
Fall Creek	36%	4	−0.52	0	= 1	0.00	54	High	Medium	4	−0.66	0.88	5
Fern Ridge	70%	8	−2.31	117	13	−3.00	79	High	Low	= 12	−1.50	−3.50	13
Foster	57%	6	−1.63	0	= 1	0.00	52	High	High	2	−1.05	1.05	4
Green Peter	83%	13	−3.00	0	= 1	0.00	53	High	Low	3	−0.11	0.71	6
Hills Creek	53%	5	−1.42	0	= 1	0.00	59	High	Extreme	6	−1.93	−0.32	8
Lookout Point	80%	11	−2.84	47	= 1	−1.21	67	High	Extreme	= 8	−2.36	−0.03	7

Sources: [a]Data (criterion 4) are from Connolly et al. (1991); Inc (2013); National Oceanic and Atmospheric Administration (NOAA) (2017); ODFW (2007); Sharpe (2013); USACE (2011, 2013, 2019); United States Forest Service (USFS) (2009); and Willamette Basin Watershed Councils (WBWC) (2015). Data (criterion 5) are from United States Geological Survey (USGS) (2020). Data (criterion 6) are from National Inventory of Dams (NID) (2020).

individual service and disservice, alongside the ranking of each structure and final cumulative scores and rankings.

Discussion

The USACE faces increasing dam management challenges as the WRBRS structures age and disservices continue to rise. A key discovery through the MCAT reveals the most pronounced overall disservice scores are fish mortality and structural risk, and these issues are shared amongst most of the reservoirs, suggesting they have manifested into basin-wide threats. Although the USACE has introduced programmes responsive to these by-products, unless greater investment and innovation take place, these conditions will continue to deteriorate (Quiñones et al., 2015). The level distribution of service levels stands to benefit from amelioration of disservices, as soundly built structures can regulate floods effectively, and healthy fish populations contribute to recreation and riparian habitat health in general (Gavrilles, 2012).

Clearly, financial logic drives management and policy decisions regarding dam development and maintenance. Yet, when habitat or species conservation is considered in assessments following removal, the case for decommissioning may quickly outweigh arguments for retrofitting or relicensing a dam (Quiñones et al., 2015). Tributaries obstructed by only one dam, such as the Row (Dorena) and Long Tom (Fern Ridge), could experience substantial restorative success upon removal. Watershed-scale studies estimate optimized removal strategies of only a few structures are capable of reviving between 35.0% and 37.2% of basin-wide channel connectivity (Branco et al., 2014; Null et al., 2014). The present analysis aligns with these estimations, because selective removals of low-performing structures substantially improve disservice scores by opening up fish passage to tributaries, mitigating thermal impacts and reducing hazard potential.

While every dam and watershed is unique, local conditions are vital in gaining a comprehensive understanding of outcomes. Key phenomena occurring throughout the WRBRS are shared amongst any river influenced by flow modifications and physical obstructions. Therefore, the priorities of federal organizations such as the USACE and the USDOE, which hold significant authority over the management of the national dam network, must be critically analysed and contextualized. Dams function in a reflexive manner because their locations are based on specific landscape characteristics, yet they disrupt and shape sociospatial patterns in corresponding areas (Connolly et al., 1991). For example, dams at Fern Ridge, Dorena and Cottage Grove are responsible for substantial ecological damage. However, the removal of these structures would likely be resisted, and shape intended and unintended consequences throughout their proximate communities. Specifically, Fern Ridge has the most pronounced local community surrounding the reservoir, as well as substantial visitation from people around the region (USACE, 2015). Dorena also receives many visitors, is amongst the most important flood-control regulators, and the recent hydropower retrofit suggests the USACE is intent on many more years of commissioning (ODWR, 1998; Wihtol, 2014). Quantitative analysis shaped through the MCAT tool was valuable for holistically evaluating dam performance and can play a major role in evaluating watersheds hosting dams in the future.

A lack of multidimensional studies has facilitated an urgency to re-evaluate ageing structures. The importance of mixed-methods evaluation in this process is evident

because empirical studies have played a key role in many dam-removal projects across the United States, particularly larger scale decommissioning such as the Elwha Dam in Washington (East et al., 2015; Rapp, 2015). Major decommissioning relies on both pre- and post-removal analyses to advance the project efficiently and minimize riparian impacts, while developing evaluation methods and data sets for future studies (Tomsic et al., 2007). A more holistic understanding surrounding post-removal riparian habitat successions is growing as more than 1500 dam decommissioning projects in the United States are documented and analysed (American Rivers, 2010). Importantly, there does not seem to be a direct link between structural risk and the level of success in decommissioning. However, this research clearly shows a correlation between age and performance, and suggests the significant potential for rehabilitative success upon prioritized removal scenarios (Magilligan et al., 2016).

Conclusions

Three main discoveries can be located as a result of this research: (1) a clear relationship exists between dam age and diminishing returns of services/increasing levels of disservices; (2) the MCAT is a valuable tool for generating a general and balanced understanding of dam performance based on comparisons with other structures in a shared watershed; and (3) incorporating field observation data and understanding 'realpolitik', as this study illustrates how social embeddedness and socio-political factors can override scientific data in decision-making and the greater dam landscape.

Responding to the first research question (based on an MCAT and field site observations: How do current levels of services and disservices for the 13 WRBRS dams help shape decisions about their future use?), the following conclusions are drawn.

Although quantitative scores derived from the MCAT clearly reveal low performance in several structures, field observations revealed the complex roles low-scoring structures play in their proximate environments and communities. For example, the lowest scoring dams are amongst the most significant sites of recreation and support local economies. Therefore, mixed-method studies such as this allow researchers to understand and illustrate nuance inherent in advance of purely statistical measurements and analysis. This suggests a need for more mixed-method and multidimensional research as it provides fresh insights to help inform decisions regarding the future of ageing dams across the United States and beyond.

Field observation across the WRBRS illuminated how the USACE is aware of, and attempting to mitigate, increasing disservices, specifically fish survival and temperature control, while also maintaining core services such as flood control, hydropower and recreation. Despite mitigation efforts, however, current challenges surrounding fish mortality, water temperature hazards and structural risk are increasing, while service levels remain steady. Through field observations this study illustrated that while Fern Ridge, Dorena, Cottage Grove and Big Cliff scored distinctly low, they were among the most visited for recreation. Consequently, these four dams support local economies and shape corresponding social and political dynamics. Therefore, statistics must be complemented by stakeholder and community outreach so that different perspectives are understood and pathways for removal or recommissioning reflect transparent processes.

Responding to the second research question (How do outcomes gleaned from the study help inform broader debates about the future of ageing dam structures across the United States?), the following conclusion are drawn.

Data analysis from this study supports the concept of diminishing returns. The overall negative score for the WRBRS was significantly shaped by unfavourable conditions of older dams, namely Cottage Grove, Dorena and Fern Ridge. The USACE has certain autonomy in managing the WRBRS and is responsive to environmental conditions as their institutional mandate states. However, the results of this study suggest select decommissioning or intensive restoration to reduce the magnitude of disservice has a greater capacity to benefit a system than marginally increasing service levels through retrofitting (Branco et al., 2014).

This study provides a critical illustration of the relationship between ageing infrastructure and diminishing returns through the retrofitting of Dorena Dam. Dorena yielded the second lowest overall score of any dam in the WRBRS, suggesting further evaluation to determine viability for removal. However, it is the only WRBRS dam to be retrofitted, undergoing and subsequently passing FERC assessment and relicensing in 2008 (National Oceanic and Atmospheric Administration (NOAA), 2017). The results of the present study and data obtained through the retrofit can be used to inform similar projects in the United States and elsewhere. Many of Dorena's disservices are evident across dam-managed watersheds in the United States. According to the results, a narrow evaluation of dams is concluded through a single metric (such as the USDOE economic analysis) is at best limiting and at worst highly problematic. This research highlights the value and utility in holistic research as it is able to illuminate contradictions and vulnerabilities not evident through singular, narrow considerations.

On 19–20 May 2020, the Sanford and Edenville Dams on Michigan's Tittabawassee River failed, resulting in the evacuation of 10,000 people and causing USD175 million in initial damage (Einhorn, 2020). According to a report commissioned by the Columbia Water Centre, a significant amount of critical infrastructure such as other dams, roads, bridges, power stations and water treatment plants are located downstream of existing, high-risk dams (Larrauri & Lall, 2020). The Association of State Dam Safety Officials estimates the cost to rehabilitate high-hazard potential dams in the United States at USD22 billion (Riley, 2019). What is not understood, however, is the costs that will be incurred if requisite rehabilitation projects are not carried out. When considering the repairs to Oroville Dam cost USD1.1 billion, they are likely to be much higher after failures occur. As a period defined by human-induced climate change is navigated, the role and risks associated with America's network of ageing dams, especially as failures are projected to increase, must be continually questioned.

Despite the omnipresence of dams, their lifespans are finite. As structures deteriorate, maintenance costs increase while functions diminish. Decisions regarding their short- and long-term futures will be determined by a range of stakeholders who are often informed by narrow data and analysis. Such challenges are uniquely magnified across the United States, where thousands of dams, semi-centennial or older, are approaching obsolescence in unprecedented numbers.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Alexander C. Nagel http://orcid.org/0000-0001-6543-9389
Thomas Ptak http://orcid.org/0000-0002-4124-0129

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