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REVIEW

Closing the gap between science and management of cold-water refuges in rivers and streams

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Abstract

Human activities and climate change threaten coldwater organisms in freshwater ecosystems by causing rivers and streams to warm, increasing the intensity and frequency of warm temperature events, and reducing thermal heterogeneity. Cold-water refuges are discrete patches of relatively cool water that are used by coldwater organisms for thermal relief and short-term survival. Globally, cohesive management approaches are needed that consider interlinked physical, biological, and social factors of cold-water refuges. We review current understanding of cold-water refuges, identify gaps between science and management, and evaluate policies aimed at protecting thermally sensitive species. Existing policies include designating cold-water habitats, restricting fishing during warm periods, and implementing threshold temperature standards or guidelines. However, these policies are rare and uncoordinated across spatial scales and often do not consider input from Indigenous peoples. We propose that cold-water refuges be managed as distinct operational landscape units, which provide a social and ecological context that is relevant at the watershed scale. These operational landscape units provide the foundation for an integrated framework that links science and management by (1) mapping and characterizing cold-water refuges to prioritize management and conservation actions, (2) leveraging existing and new policies, (3) improving coordination across jurisdictions, and (4) implementing adaptive management practices across scales. Our findings show that while there are many opportunities for scientific advancement, the current state of the sciences is sufficient to inform policy and management. Our proposed framework provides a path forward for managing and protecting cold-water refuges using existing and new policies to protect coldwater organisms in the face of global change.

Francine H. Mejia and Valerie Ouellet contributed equally to this research and are considered joint first authors.

KEYWORDS
behavioral thermoregulation, climate change adaptation, lotic ecosystem management, refugia, salmonids, temperature, thermal heterogeneity, thermal refuges

1 | INTRODUCTION

Human activities and climate change disproportionately affect freshwater ecosystems relative to terrestrial and marine ecosystems (Birnie-Gauvin et al., 2023; Reid et al., 2019; van Rees et al., 2022; Woodward et al., 2010). Rivers and streams are warming, experiencing more frequent and extreme warm temperature events, and becoming more thermally homogeneous (Arora et al., 2016; Hannah & Garner, 2015; Isaak & Rieman, 2013). These changes put organisms that are physiologically restricted to cold and cool water (termed "coldwater organisms") at risk. Many coldwater organisms are ecologically, economically, and culturally significant and are particularly vulnerable to climate change because increasing temperatures exceed their thermal limits (Barbarossa et al., 2021; Begon et al., 2006; Pinsky et al., 2019). Homogeneous thermal conditions also make coldwater organisms vulnerable to losing access to cool water to avoid thermal stress and to warm water to optimize growth. Thus, homogenous water temperatures may inhibit adaptations that can have a negative population-level response such as a decrease in survival and productivity that, in turn, decreases coldwater organisms' resilience (Amat-Trigo et al., 2023; Armstrong et al., 2013, 2021; Pinsky et al., 2019; Whitney et al., 2016). To overcome higher temperatures, organisms may move to cold areas during periods of thermal stress (Armstrong & Schindler, 2013; Brewitt et al., 2017; Hahlbeck et al., 2022; Wilbur et al., 2020). These areas of water that are cooler than the surrounding ambient water are referred as cold-water patches (CWPs). When coldwater organisms use discrete CWPs within rivers for thermal relief, the CWPs are considered cold-water refuges (CWRs; Figure 1).

Cold-water refuges protect coldwater organisms from high water temperatures and prevent or reduce potentially life-threatening metabolic consequences of thermal stress (Breau et al., 2011; Keefer et al., 2009). Use of CWRs by organisms also improves biotic interactions and stabilizes population dynamics (Berryman & Hawkins, 2006; Reside et al., 2019), particularly for individuals existing on the edge of their preferred geographic ranges (Cordoleani et al., 2021). Cold-water refuges also are increasingly important for sustaining native coldwater species in the context of invading non-native species. For example, warmwater fish and nonnative salmonid species often expand their ranges in a warming climate (Rahel & Olden, 2008; Rubenson & Olden, 2017) and this contracts native coldwater species' ranges as warmer conditions decrease their ability to compete for more suitable thermal habitat. (Hitt et al., 2017; Ramberg-Pihl, 2020).

Scientists and resource managers increasingly recognize the importance of CWRs for the short-term survival of coldwater organisms experiencing thermal stress during the warm season (Keppel et al., 2012; Morelli et al., 2016; Reside et al., 2019; Snyder et al., 2022; Sullivan et al., 2021). Cold-water refuges are spatiotemporally dynamic and thermally heterogeneous. They compose shifting mosaics of warm- and cool-water habitats that are the result of a lack of rapid thermal and hydrodynamic mixing with the main river channel flow and groundwater (Sullivan et al., 2021) and multidimensional connections to the adjacent landscape (Torgersen et al., 2022). This complexity makes their identification, measurement, protection, and management a challenge. However, progress has been made in understanding both the physical processes that create and maintain CWRs as well as their biological importance.

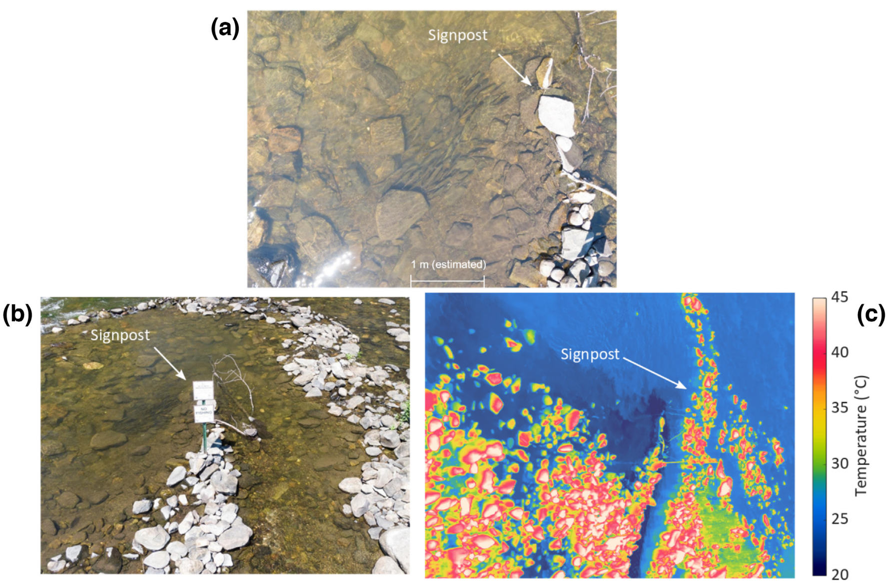

FIGURE 1 Brown trout (*Salmo trutta*) observed behaviorally thermoregulating in a cold-water refuge (CWR) to avoid high water temperatures in the Upper Housatonic River in Connecticut, USA (a). Designated areas are closed to anglers and delineated by signs posted (b). Thermal infrared (TIR) image of the surface water temperature of the cold-water plume entering the river (c). Images courtesy of Christopher Sullivan and Nancy Marek, University of Connecticut, USA.

Previous reviews have focused on identifying CWRs and determining their hydrological and ecological context to protect, manage, and restore them (Ebersole et al., 2020; Morelli et al., 2016; Torgersen et al., 2012). However, the links between CWR science and policy have not been clearly defined in the context of aquatic conservation; therefore, there is a need to evaluate the effectiveness of policies aimed at conserving the physical processes that create and maintain CWRs, the connectivity among CWRs, and thermal heterogeneity in general (Ebersole et al., 2020). Efforts to develop a framework to integrate science, policy, and management of CWR also have been limited (Ebersole et al., 2020) but are needed to address impacts and potential social conflicts arising from incompatible human activities and uses.

Here, we present the outcomes of an international workshop convened in 2021 to better understand and address science-policy gaps in CWR management. This is the first time an international group of scientists, environmental regulators, and resource managers have come together to address the need to integrate science, indigenous knowledge, policy, and management of CWRs and the species that rely on them. To inform policies and management related to CWRs, we (1) synthesize the state of the biological, physical, and social science, (2) identify policy and management-related research and policy gaps, (3) compare policy and management across continents using five case studies, and (4) propose a management and conservation framework targeted towards scientists, environmental regulators, and resource managers. The first three sections focus on the state of CWR science and management and identify gaps in research and management. The final section integrates science and management and provides a framework for supporting conservation and management actions and improving outcomes for coldwater organisms and the people who depend on them. We use "interested groups" instead of "stakeholders" throughout the review. The former term is more inclusive with respect to rights holders such as Indigenous peoples and more reflective of a participatory process (Reed & Rudman, 2022). Because of the emphasis on fish in the literature, the proposed framework uses coldwater fishes as proxies for all mobile coldwater organisms present in global freshwaters (Figure S1).

2 | STATE OF THE SCIENCE

In this section, we synthesize the state of the physical, biological, social sciences, and recent advances in monitoring and modeling tools available to inform ecological research and management of CWRs. We also identify critical research gaps and opportunities to address research and management challenges. Because inconsistent terminology can interfere with clear communication among interdisciplinary research and management teams and can delay the adoption of science into management and policy, we highlight differences between terms: "refuge" and "refugium/refugia," and "cold-water refuges," and "cold water patches" (CWPs).

Definitions of the terms "refuge" and "refugium/refugia" have been discussed extensively in aquatic ecosystems (Keppel et al., 2012; Morelli et al., 2016; Reside et al., 2019), with numerous studies focused on thermal refuges in both freshwater and marine systems (Bongaerts et al., 2010; Frade et al., 2018; MacDonald et al., 2018; Sullivan et al., 2021; Torgersen et al., 2012). The most important distinction is that "refugium/refugia" refers to conditions sufficient to ensure long-term species persistence, whereas "refuge" refers to a habitat unit capable of aiding the short-term survival of individuals (Ebersole et al., 2020; Sullivan et al., 2021). Cold-water patches are areas of water that are cooler than the surrounding ambient water, distributed longitudinally, laterally, and vertically in the water column, and variable in size and location over time (Wawrzyniak et al., 2016). When coldwater organisms use discrete CWPs within rivers for thermal relief, CWPs are considered cold-water refuges (e.g., shaded areas, tributaries, deep pools, groundwater upwelling zones; Dugdale, 2016; Ebersole et al., 2003a; Torgersen et al., 1999). Recognizing the interaction between "refuge" and "refugia," we adopt the terminology used in Sullivan et al. (2021), where CWRs are subsets of discrete CWPs known to be used by fish or other cold-water adapted organisms during the warm season. When discussing physical properties, we use the terminology CWP, whereas when we focus on their use by biota, we use CWR.

2.1 | Hydrology and geomorphology

The scientific understanding of the processes that create and maintain CWPs in the landscape are well described. These physical (geologic and landscape features), hydrological, and atmospheric processes operate at multiple scales from the reach to the watershed (Dugdale et al., 2015; Ebersole et al., 2003b; Mejia et al., 2020; Monk et al., 2013; Torgersen et al., 2012). Cold-water patches have longitudinal (upstream-downstream), lateral (in-stream and floodplain), vertical (hyporheic zone and groundwater), and temporal connections to the adjacent landscape (Torgersen et al., 2022). Thus, the spatiotemporal variability of hydrological connectivity, climate, land use, and geological setting affects CWP characteristics (Dugdale et al., 2015). These characteristics include their size, geometry, temporal persistence, spatial distribution along the river network, and type of thermal response (Arrigoni et al., 2008; Dugdale et al., 2013, 2015; Dzara et al., 2019; Fullerton et al., 2018; Wawrzyniak et al., 2013). Cold-water patch thermal responses can be described in relation to differences in the mean, amplitude, and phase between the diel temperature cycle of the CWP and ambient water. A "cooled" response indicates a difference in means, a "buffered" response is a difference in amplitude, and a "lagged" response is a difference in phase between respective water temperature signals (Arrigoni et al., 2008). Cold-water patches in rivers and streams are associated with tributary confluences or plumes, lateral seeps, springbrooks, side channels, alcoves, hyporheic upwelling, and wall-based channels and pools (for a thorough description of these features, see Dugdale et al., 2013; Ebersole et al., 2003a; Torgersen et al., 2012).

Studies have suggested that under climate change, CWPs may decrease in size and number and may become fragmented (Daigle et al., 2015; Fullerton et al., 2018). These changes affect thermal heterogeneity in reaches with historically abundant cold-water habitats (Fullerton et al., 2018; Kuhn et al., 2021) and may increase the distance between CWPs, thereby limiting accessibility (Fullerton et al., 2018).

Also, the capacity of CWPs to provide effective refuge in the future may be limited by a long-term decline in groundwater storage due to excessive withdrawals for other human uses. Groundwater discharge generates streamflow and influences stream thermal regimes because groundwater is generally cooler than surface water during the warm season and warmer in the cooler season (Bierkens & Wada, 2019). Lateral seeps and springbrooks sourced by shallow groundwater may exhibit more variable and higher temperatures over time due to climate change (Hare et al., 2021; KarisAllen et al., 2022). Perennial streams also can become intermittent during extended dry periods (Costigan et al., 2015; Gendaszek et al., 2020; Price et al., 2021), thereby disconnecting CWPs from warm stream reaches in headwater systems (Briggs et al., 2022). Cold-water patches fully mix with ambient water at high streamflow in rivers draining large stratified natural lakes that show abrupt wind-driven drops in river temperature, leading to the loss of discrete CWPs (Lisi & Schindler, 2015) and a reduction in CWRs. Armored and clogged streambed sediment (i.e., the erosion-resistant layer of relatively large particles that is established on the surface of the streambed through the removal of finer particles by stream flow) can also impact CWPs by limiting water exchange with groundwater (Wawrzyniak et al., 2016) and reducing groundwater discharge points that can dry out when the water table level lowers as a result of channel incision from mining, logging, grazing, channel straightening, and sediment starvation (Marteau et al., 2022).

2.2 | Biology and ecology

Thermal requirements of coldwater fishes and their responses to temperature heterogeneity have been reviewed extensively (Amat-Trigo et al., 2023; Kefford et al., 2022; Morash et al., 2021; Richter & Kolmes, 2005). Here, we focus on recent advances in thermal biology relating to stress, heat tolerance, and CWR use. We also emphasize that various CWPs can serve as CWRs, but their refuge function for thermally stressed organisms can be difficult to assess (Barrett & Armstrong, 2022). In the context of fish thermal requirements, research has focused on thermal performance curves and thermal tolerances. Performance curves or thermal niches relate to performance or fitness as a function of body temperature, whereas thermal tolerances apply to temperature thresholds at which survival or performance changes abruptly (Kingsolver & Buckley, 2017). Prior thermal history, time scale, and thermal heterogeneity affect how coldwater organisms respond to temperature (Kefford et al., 2022; Kingsolver & Buckley, 2017; Morash et al., 2021).

Physiological processes, including energy assimilation, growth, and gonad development, are impaired at temperatures considerably higher or lower than an organism's range of thermal tolerance (Beer & Steel, 2018; Devine et al., 2021; Elliott & Elliott, 2010; McCullough et al., 2009). Most organisms require diverse thermal habitats to grow and reproduce (Armstrong et al., 2021; Hahlbeck et al., 2022), and their thermal tolerances change throughout their life cycle (Dahlke et al., 2020). Thus, recent studies have recommended that river management consider thermal heterogeneity and thermal niche requirements to protect coldwater fish populations (Armstrong et al., 2021; Ebersole et al., 2020; Snyder et al., 2022; Steel et al., 2017). This is particularly crucial for species at the latitudinal or altitudinal limits of their range if they also must maintain their resilience to other human activities such as land-use change, hydropower generation, and water abstraction.

To cope with thermal stress, juvenile and adult coldwater fishes may either resist warm conditions by moving long distances to tributaries or short distances to behaviorally thermoregulate in CWRs, or they may remain in river mainstems and tolerate warm conditions (Barrett & Armstrong, 2022). Thermoregulation involves moving between ambient water temperature and CWRs to maintain narrow temperature ranges consistent with physiologically optimal temperatures (Amat-Trigo et al., 2023; Brewitt & Danner, 2014; Frechette et al., 2018; Gutowsky et al., 2017). Cold-water refuges thus support species' persistence by enabling individuals to exploit fine-scale thermal heterogeneity in systems where ambient thermal conditions would be lethal (Armstrong et al., 2021; Brewitt & Danner, 2014; Corey et al., 2017). However, there are trade-offs to using CWRs because the spatial aggregation of fish may cause food resources to be locally depleted (Armstrong & Griffiths, 2001) which, in turn, increases exploitative competition between individuals (Brewitt et al., 2017). Therefore, individuals may need to move in and out of the refuge to forage, digest, and avoid competition (Armstrong & Schindler, 2013; Brewitt et al., 2017; Hitt et al., 2017). Additionally, fish density and health can influence the spread and severity of parasites and infectious diseases (Beldomenico & Begon, 2010; Krkošek, 2017). Cold-water refuges may decrease the spread of disease because most parasites and bacteria grow and reproduce more rapidly at higher temperatures than those observed in CWRs but proximity can potentially increase the spread of the diseases (Benda et al., 2015; Chiaramonte et al., 2016). Density dependent thresholds influencing disease spread are still poorly understood (Chiaramonte et al., 2016). Finally, CWRs can delay movement during warm periods by causing fish to remain in cool waters where they may be subject to increased predation or angling pressure. These behavioral changes, while enabling individuals to escape lethal temperatures, can lower the likelihood of reaching spawning grounds or decrease the fitness of offspring (Fitzgerald et al., 2021; Guillen, 2003; Keefer et al., 2009), thus affecting long-term population persistence.

2.3 | Human dimensions

Understanding how human activities can impact CWRs is critical for resource planning (e.g., mapping and prioritization), better management decision-making, and policy development (Ebersole et al., 2020). Limited recognition of CWRs in environmental policy and management may lead to degradation of CWRs. Social conflicts may also occur when incompatible interests overlap and CWRs become limited. Thus, integrating human dimensions into CWR research and management is critical for their effective management. However, CWRs and water temperature heterogeneity more broadly are not common topics in the social science literature (although this is beginning to change; Hirsch, 2020; Wöelfle-Hazard, 2022). This section focuses on three major human dimensions' topics that can influence CWR management: historic context for the use of the term "cold-water refuge," potential ways humans can impact CWRs, and social conflicts that may arise from implementing CWR conservation measures.

Indigenous and non-Indigenous peoples have long been aware of the importance of the hydrological features that create CWRs and the biota that use them, and they have depended on CWRs for millennia as sources of local food and cultural identity (Aboriginal Affaires, 2021; Allen, 2005; Atlas et al., 2021; Griebler & Avramov, 2015; Hirsch, 2020; Svanberg & Locker, 2020). However, recognition of CWR as an integrated concept in the social sciences and regulatory realm has been limited. Early use of these cold-water areas by humans for cultural, subsistence, and recreational purposes has been documented worldwide, with examples from Sweden (Bergman & Ramqvist, 2018) and the Americas (Yu, 2015). The earliest known use of the thermal refuge concept in print was Walton (1653), who observed fish in ponds using cold-water areas in the summer and warm-water areas in the winter to avoid thermal stress. The first known mention of CWRs in the peer-reviewed literature was Huntsman (1942), who reported observations of Atlantic salmon (*Salmo salar*) and brook trout (*Salvelinus fontinalis*) in Nova Scotia, Canada behaviorally thermoregulating in cooler side channels. The use of the term "cold-water refuge" in aquatic ecology is relatively recent (Kaya et al., 1977; Torgersen et al., 2012), but the concept has emerged as an important conservation consideration for freshwater fish populations (Ebersole et al., 2020), even though policy development has not kept pace with scientific advances in CWR understanding.

The slow assimilation of CWR concepts into policy and limited recognition in environmental policy and management makes it difficult to manage and regulate the impact of competing activities that affect CWR quantity and quality including (1) surface and groundwater withdrawals for drinking water or irrigation; (Dzara et al., 2019); (2) dam-related flow and temperature alterations from epilimnetic and hypolimnetic releases (Ernst et al., 2015); (3) point source discharges such as thermal effluent from power generation, wastewater, and stormwater (Caldwell et al., 2019; Chen et al., 2021); (4) alterations to in-stream habitat that affect hydraulic mixing and the surrounding land use (e.g., deforestation), which in turn impacts hydrologic exchanges or shading (Bense et al., 2008; Kurylyk et al., 2015); (5) human activities such as angling, damming, and river recreation that directly stress or disrupt the use of CWRs by fishes (Reid, 2007); and (6) stocking of non-native species that limit native species' use of refuges (Ramberg-Pihl, 2020) (Figure 2). Climate change exacerbates these human disturbances, thereby escalating competing demands for global water resources by ecosystems and humans (van Vliet et al., 2013).

Competing activities affecting CWRs may create social conflicts that complicate management (Figure 2). Here, we illustrate competing activities and their impact on CWRs. For example, in times of thermal stress, fisheries are often closed to reduce the impact of recreational fishing, specifically in rivers with existing regulations for CWRs (DFO, 2012). Conflicts between anglers and fish conservation have occurred in Montana (USA), where increasingly frequent temperature and drought-related fishery closures ($n = 74$ imposed from 2015 to 2017 [Montana Fish, Wildlife and Parks, 2022]) are already leading to a shift in angler behavior and in the angling economy away from impacted waters and toward drought-resistant, colder rivers (Cline et al., 2022). The Indian and Hudson rivers in New York, USA provide another example of conflicts between recreational activities and fisheries management. In the summer, periodic reservoir releases support rafting when water temperatures frequently exceed thermal thresholds for trout survival (Ernst et al., 2015). These surface water releases decrease the size and number of CWRs, thereby reducing small-scale thermal heterogeneity while mean river water temperatures are unaffected. Also, when resources are perceived as limited, there is an increased risk of conflict between humans and wildlife that seek to use similar resources (van Rees et al., 2019; e.g., predatory birds feeding on fish aggregation sites that are close to fishing activities; Figure 1). Water withdrawals, reservoir storage management, and thermopeaking (i.e., sharp intermittent alterations of stream temperature associated with hydropeaking releases from storage hydropower plants [Zolezzi et al., 2011]) affect thermal and flow regimes and, ultimately, the quantity and quality of CWRs. In urban rivers supporting high population centers and industrial development opportunities, thermal heterogeneity and the quantity and quality of CWRs are reduced by flood protection (e.g., impervious channels that transfer heat and limit surface-groundwater interactions), water extraction (Carlson et al., 2020), and wastewater discharge (Abdi et al., 2020; Arora et al., 2018).

2.4 | Monitoring and modeling

Managing CWRs requires robust monitoring networks for water temperature and occupancy by organisms (Table 1, Figure 2). Strategic monitoring is also necessary to evaluate management outcomes and adjust approaches as needed. Modeling, in combination with monitoring, can help predict or explain CWR dynamics where data are either unavailable or insufficient. Modeling also can be used to examine large-scale patterns, predict effects of global changes, and assess management scenarios (Table 2; Jackson et al., 2017; Ouellet et al., 2020). We expand on recent water temperature monitoring and modeling reviews by Benyahya et al. (2007), Dugdale et al. (2017), and Ouellet et al. (2020), which did not focus on CWRs, and we summarize the tools specifically available for CWR monitoring and modeling (Tables 1 and 2). We describe the spatiotemporal domain, applications, logistical and data requirements, and limitations to help guide future work on CWRs.

Identifying the distribution of CWPs is the first step towards monitoring them and can be facilitated through a combination of the methods outlined below, alongside local and traditional

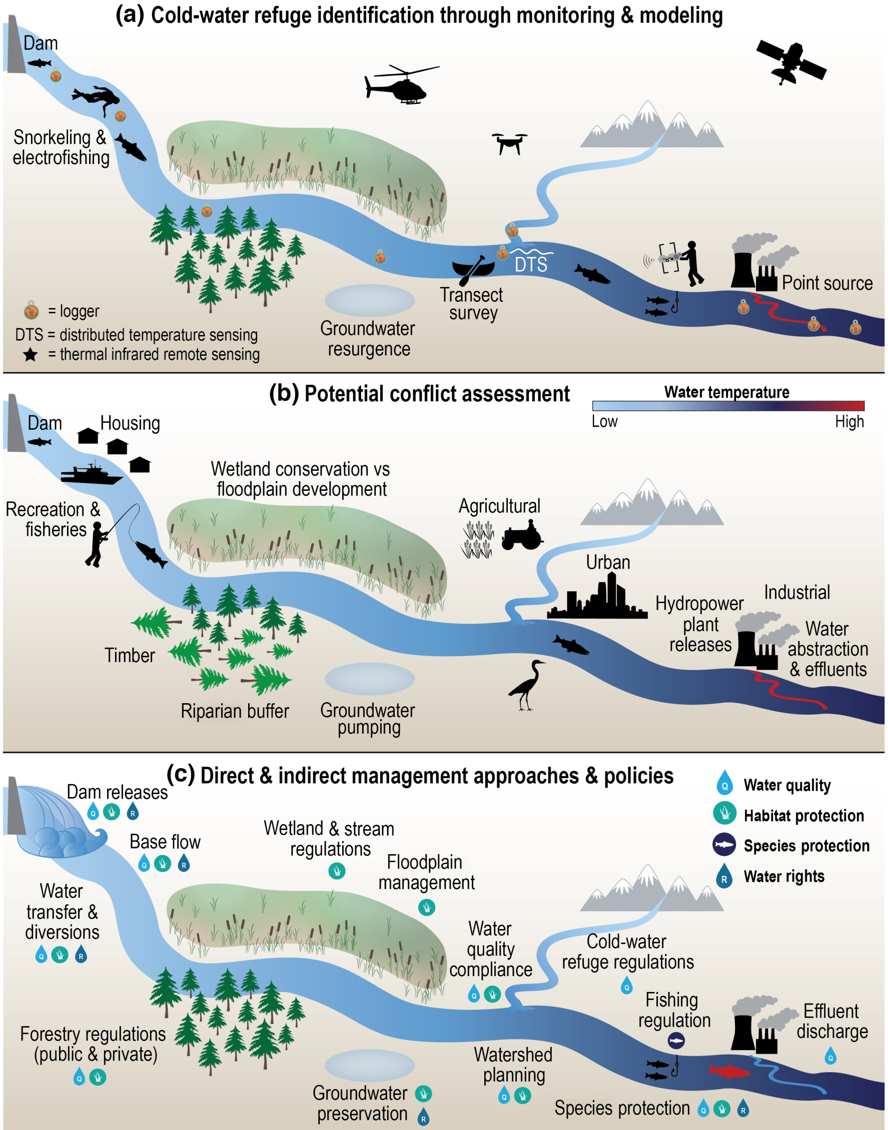

FIGURE 2 Linking science and policies to protect, enhance, and restore cold-water refuges and thermal heterogeneity: (a) identification of cold-water refuges through monitoring and modeling to map and prioritize areas of interest, (b) assessment of potential conflicts among interested groups to align policies and management, and (c) assessment of legal and institutional constraints by identifying direct and indirect management approaches and policies.

knowledge. CWRs are four-dimensional features, but tools used to assess their physical extent are often constrained to two or three dimensions and confined to small to moderate spatial scales (e.g., reach to river segment). Spatial mapping tools (Table 1, Figure 2) include remote sensing-based two-dimensional (longitudinal and lateral) mapping of CWPs at the water surface via thermal infrared (TIR) imaging from piloted aircraft (Dugdale et al., 2013; Fullerton et al., 2015; Wawrzyniak et al., 2016), drones (Casas-Mulet et al., 2020; Harvey et al., 2019), ground-based cameras (Tonolla et al., 2010), and walking surveys with hand-held cameras (Briggs et al., 2013). Mapping also can be done with fiber optic distributed temperature sensing (DTS; Hare et al., 2015; Rosenberry et al., 2016) or float surveys conducted by dragging temperature probes (Vaccaro & Maloy, 2006), which can extend monitoring into the temporal domain. Unlike TIR imaging, DTS and temperature probes can be used at depths within the water column and thus extend monitoring to the vertical domain.

With increasing water temperature, measuring the spatiotemporal variability of CWPs is critical to understanding how thermal heterogeneity in rivers and streams is changing. Conserving thermal heterogeneity is key to the climate resilience of coldwater organisms (Kefford et al., 2022). However, most water temperature monitoring networks rely on point-in-space temperature loggers and summarize data at coarse temporal scales (e.g., daily, weekly, monthly), effectively limiting the detection of finer (hourly) or longer (seasonally) temporal scale variability of CWPs. The discrete nature of loggers and small footprint (<1 m^2) also restricts the understanding of the spatial extent of CWPs. Nevertheless, monitoring of large-scale temperature heterogeneity can be combined with fine spatial scale and high temporal resolution data to capture both temporal dynamics and spatial heterogeneity (Daigle et al., 2019). Loggers also can be distributed longitudinally and laterally within river systems and vertically to capture deep CWPs and, when paired with air temperature sensors, can be used to characterize groundwater influence on CWPs (Hare et al., 2021). Data harmonization, that is, transforming data of the same type collected with comparable methodology into the same variable names, unit terms, and structural formats, can combine multiple fragmented data sources into large-scale regional

TABLE 1 Technologies available to monitor water temperature and organisms in cold-water patches (CWPs) and cold-water refuges (CWRs).

Technology	Spatial domain	Temporal domain	Related information	Relative cost, skills, and processing	References
Water temperature monitoring					
Thermal infrared (TIR) satellite imagery	Large rivers (e.g., >90 m wide) Targets large CWPs such as plumes of tributary confluences	Biweekly (retrospective sampling possible)	Limited to water surface Coarse pixel resolution (pixel size from 60 to 90 m)	Free to low cost Advanced Geographic Information Systems (GIS) skills Processing is time consuming	Belletti et al. (2012); Gao et al. (2022); Martí-Cardona et al. (2019); Wawrzyniak et al. (2011, 2013)
TIR airborne imagery	Network scale	Snapshot Repeat sampling possible over same day, or season	Limited to water surface	High cost Cost increases with repeat sampling Advanced GIS skills Processing is time consuming	Dugdale et al. (2013); Torgersen et al. (2001)
TIR drone imagery	Local scale to river segment	Snapshot Repeat sampling possible (same day or season)	Limited to water surface	Low to high cost Cost increases with repeat sampling Processing is time consuming	Casas-Mulet et al. (2020); Dugdale et al. (2019); KarisAllen and Kurylyk (2021); O'Sullivan et al. (2022)
TIR hand-held camera imagery	Fine (point) scale	Snapshot, repeat sampling		Low to moderate cost and skills	O'Sullivan et al. (2021); Figure 1
Fiber-optic distributed temperature sensing technology	Local scale	Fine (sub-hourly) to coarse (weekly summaries)		High cost Advance technological skills Processing is time consuming	Briggs et al. (2013); Hare et al. (2015)
Water temperature loggers	Single logger: point-scale Logger-network: segment to network	Sub-hourly to span years, decades	Can be paired with air temperature sensors to characterize groundwater influence	Cost depends on network size Complex analyses or modeling require moderate to advanced statistical skills	For review see: Dunham et al. (2005); Ouellet et al. (2020); Steel et al. (2017)
Boat mounted temperature probes	Segment to entire river	Snapshot, repeat sampling	Can be paired with other probes/sensors (Acoustic Doppler Current Profiler—ADCP, oxygen probe, and other sensors)	Cost increases with repeat surveys	Vaccaro and Maloy (2006)
Biological monitoring					
Drones (red, green and blue—RGB camera)	Local scale to river segment	Snapshot, repeat sampling possible (same day or season)	Can be paired with TIR sensor	Moderate cost	O'Sullivan et al. (2021)
Underwater RGB camera	Local scale	Snapshot, continuous sampling possible	Sampling may be limited during low flows	Low cost	
Hook and line angling, electrofishing, snorkeling	Local scale to network	Snapshot, repeat sampling possible (same day or season)	Sampling may be limited during low flows	Cost depends on accessibility and extent Moderate statistical skills, comparison across gears can be difficult	Brewitt et al. (2017); Kaya et al. (1977); Torgersen et al. (1999); Wang et al. (2020)
Biotelemetry and tags	Fine spatial resolution	Sub-hourly to daily/weekly/season		Moderate to high cost depending on tag functions and length of study	Capra et al. (2017); Frechette et al. (2018)

TABLE 2 Summary of modeling methods currently used for simulating water temperature and biota in cold-water refuges (CWRs).

Model type	Modeling method	Domain and scale of application	Area of interest or aspect of biology modeled	Reference
Physical				
Statistical	Partial least square regression (PLS)	Surface water, 2–100 km^2, 75 km linear distance	Stream networks, Longitudinal river profiles	Monk et al. (2013); O'Sullivan et al. (2019)
	Multiple linear regression	Surface water, 20–60 km linear distances	Confluences/mainstem dynamics	Daigle et al. (2015); Jeong et al. (2013)
	General linear and non-linear regression models	Surface water, 50–700 km linear distance	Longitudinal river profiles	Casas-Mulet et al. (2020); Dugdale et al. (2015); Wawrzyniak et al. (2016)
	Generalized additive models (GAM)	Surface water, 80 km, 300 km linear distances	Longitudinal river and estuary profiles	Mahardja et al. (2022); Mejia et al. (2020); Saadi et al. (2022)
	Multivariate adaptive regression splines (MARS)	Surface water, 80–90 km linear distance	Confluences/mainstem dynamics	Saadi et al. (2022)
	Random forest (RF)	Surface water, 0.2–200 km^2, 11,000 km total linear distance	Confluences/mainstem dynamics along stream networks, multiple longitudinal river profiles	Ebersole et al. (2015); Fullerton et al. (2018)
	Spatial stream network (SSN)	Surface water, 2000 km^2	Stream networks	Fuller et al. (2021)
	Maximum entropy modeling (MaxEnt)	Groundwater, 1700 km^2 (extent of network)	Areas of groundwater discharge in stream networks	Gerlach et al. (2021)
	Artificial Neural Networks (ANN) and Multilayer perceptrons Neural Networks (MLPs)	Surface water, <100 km linear distance	Confluences/mainstem dynamics along longitudinal river profiles	Daigle et al. (2015); Jeong et al. (2013)
Process-based/Numerical	River Modeling System (RMS)	Surface water, 1D, 300 km linear distance	Multiple longitudinal river profiles	Dzara et al. (2019)
	Simultaneous Heat and Water (SHAW)	Groundwater, 1D, up to 100 m depth	Coastal lagoon	KarisAllen et al. (2022)
	Variable saturated, variable-density fluid flow, and solute or energy transport (SUTRA)	Groundwater, 2D, 1000 m hillslope	Seep and cold tributary	Kurylyk et al. (2014)
	Distributed Hydrology Soil Vegetation Model and the River Basin Model (DHSVM-RBM)	Surface water, 2D, 1000–2000 km^2	Stream networks	Lee et al. (2020)
Biological				
Statistical	Linear mixed effects	<0.0001 km^2	Fish use (densities) in confluence plume	Wang et al. (2020)
	Logistic mixed effects	0.020 km^2 per confluence area	Fish use (movement behavior) refuge confluences and mainstem dynamics	Brewitt and Danner (2014)
	Cox Proportional hazards	0.125 km long plume	Mortality rates from exposure to parasites	Chiaramonte et al. (2016)
Process-based/Numerical	Spatially explicit behavioral and physiological model (HexSim)	2D, 70–300 km linear distance	Movement behavior and fish condition in confluences along migration corridor	Snyder et al. (2022); Snyder et al. (2020); Snyder et al. (2019)
	Bioenergetics		Effect of boat activity on fish condition in confluences along migration corridor	Reid (2007)
	Bioenergetics	<20 km linear distance	Growth potential and fish condition of different behavioral thermoregulation scenarios in river connected to lake and river connected to springs systems	Hasler et al. (2012); Westhoff et al. (2014)
	Bioenergetics	20 km—applied to stream network	Growth potential in stream network	Armstrong et al. (2021); Spanjer et al. (2022)

analysis (Boyer et al., 2016; Isaak et al., 2017; Jackson et al., 2020; Varadharajan et al., 2022).

Numerous water temperature models have been developed and applied to simulate reach-, segment-, and watershed-scale river thermal regimes and their responses to perturbations such as deforestation, dam operations, climate change (Benyahya et al., 2007; Dugdale et al., 2017; Ouellet et al., 2020). More recently, CWP and CWR modeling have integrated monitoring implemented at different spatiotemporal scales to predict how future changes to river hydrology and hydraulics or cold-water input may impact the ability of a CWP to provide refuge (Table 2). Process-based or numerical models have been applied at reach and watershed scales to identify thermally anomalous areas or reaches (Dzara et al., 2019; Fuller et al., 2021; Lee et al., 2020). Also, subsurface heat transfer models have been used to investigate the impacts of climate change on groundwater flow rates and temperatures at groundwater-sourced CWRs (KarisAllen et al., 2022; Kurylyk et al., 2014); but no in-channel surface mixing dynamics have been considered in these studies. To our knowledge, few studies have explicitly modeled the occurrence and dynamics of CWRs (Saadi et al., 2022; Wang et al., 2020). Monk et al. (2013) used partial least square regression to predict CWRs by pairing landscape variables with aerial TIR imagery in a novel application. They found that tributary-sourced refuges could be modeled based on their location in a river network, surrounding forest conditions, soil type, and wetland distribution. Ebersole et al. (2015) used random forest models to predict CWP occurrence at tributary junctions in relation to water surplus provided by snowpack and other climatic variables. Daigle et al. (2015) combined long-term water temperature monitoring, statistical models, and climate scenarios to project the impact of warming on rivers known to contain CWRs for salmon in eastern Canada. Other studies have applied statistical approaches to investigate the hydromorphological and physical habitat drivers of CWPs in riverscapes, aiming to improve the models' predictive capacity (Casas-Mulet et al., 2020; Dugdale et al., 2015; Mejia et al., 2020; O'Sullivan et al., 2019) or predict potential CWPs decline following channel changes (Wawrzyniak et al., 2016).

The dearth of water temperature modeling studies specifically considering CWRs may be due to the lack of modeling tools that can be leveraged to simulate CWRs, particularly across multiple spatiotemporal scales and domains (e.g., groundwater flowing to surface water). One-dimensional river temperature models do not capture the complex and multidimensional processes associated with CWRs, and this makes it difficult to accurately simulate these dynamics. Furthermore, modeling studies that specifically focus on CWRs demand detailed, high-resolution spatiotemporal data of CWR dynamics and physiographic, hydromorphic, and meteorological data. Mechanistic modeling of CWR space–time distribution over multiple scales, that is, reaches to riverscapes, is complex in terms of data and computational capacity requirements, and thus there is limited understanding of the interaction between processes driving CWP distribution.

From an ecological modeling perspective, CWR modeling also has integrated aquatic organisms' behavior including predation and parasite risk to quantify the benefits and energetic and ecological costs of fish using CWRs (Armstrong et al., 2021; Brewitt & Danner, 2014; Chiaramonte et al., 2016; McCullough et al., 2009; Snyder et al., 2019, 2020, 2022). New model applications such as Lee et al. (2020) have been implemented to inform CWR management by combining predictions from a mechanistic model and a salmon life cycle vulnerability analysis. However, human dimensions such as angler behavior, cultural beliefs, and social conflicts (all of which may impact management of CWRs) have yet to be incorporated into assessing impacts of human interactions on CWRs.

2.5 | Challenges and opportunities for integration

We found that although CWR research is increasing globally, large geographic, taxonomic, and conceptual gaps exist (Figure 3). Most research has focused on salmonid fishes in the northern temperate regions and has strictly considered physical or ecological

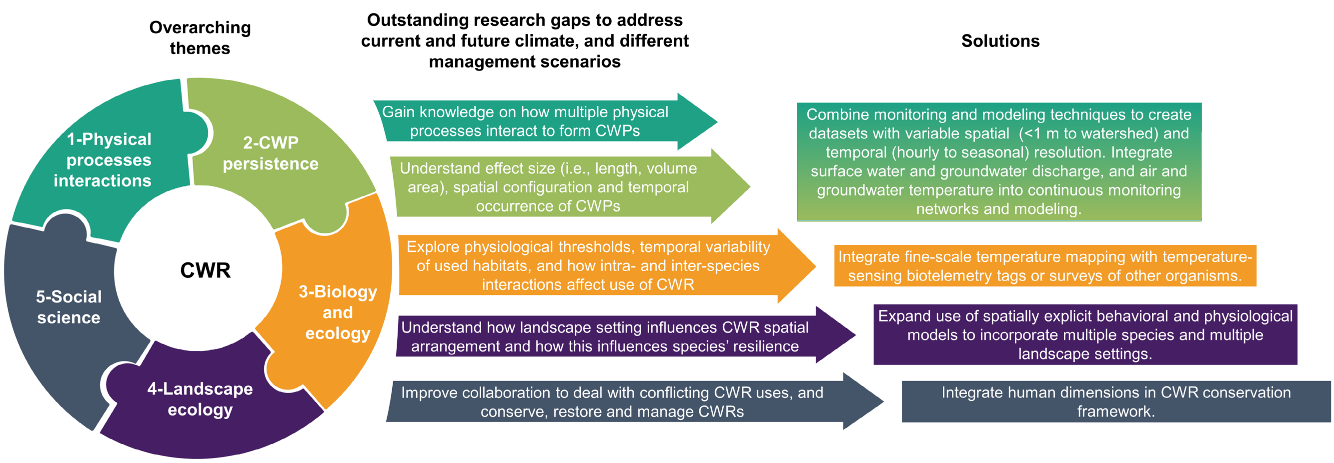

FIGURE 3 Overarching research gap themes, outstanding general questions, and proposed solutions to improve resilience of cold-water patches (CWPs) and cold-water refuges (CWRs).

questions relating to CWRs rather than integrated/interdisciplinary ones. Notwithstanding the need for greater geographic representation in CWR research, the research gaps that we identified can be grouped into overarching themes focused on understanding the interactions among CWRs' physical, hydrological, atmospheric, and biological processes, ecology, and humans (Figure 3). Narrowing these gaps may help to develop better strategies for conserving, restoring, and managing CWRs, with the overarching goal of improving species' climate resilience. Additionally, more integration across tools, approaches, and disciplinary boundaries is needed to design studies to monitor and manage CWRs and the species using them. Social sciences that focus on governance, environmental policies, culture, and economics may help institutions, policies, and practitioners develop collaborative CWR management approaches focused on integrating multiple interacting resources, tribal, state, and federal governments, interested groups, jurisdictions, and scales (Figure 3).

Scientists and managers may integrate tools, methodologies, and disciplines to capture the inherent complexity of CWPs and CWRs that makes it challenging to identify them and predict where and under what conditions they will occur. Scientific and technological advances in data integration are being made (Hare et al., 2021; Johnson et al., 2020) but have not been applied in a management context. This requires integrating data across multiple domains (i.e., air temperature, surface water, and groundwater) and tools (e.g., loggers, remote sensing) into routine water temperature monitoring networks and modeling CWRs (Figure 3, Themes 1 and 2). However, this is further complicated by problems of implementation scale and financial or institutional constraints. Nevertheless, scientists and managers now have opportunities to use new tools and methodologies to improve their understanding of CWRs.

Changes in size, distribution, and spatial configuration of CWPs will influence how coldwater organisms detect and use them. Combining fine–spatial scale and high–temporal resolution mapping with temperature sensing tags of individual organisms can address questions regarding the use of CWPs and intra- and inter-specific interactions within CWRs (Figure 3, Theme 3). Understanding the size and distribution of CWPs, as well as the consequences of decreased thermal heterogeneity, are also critical to answer management questions at a population level and in a landscape context (Figure 3, Theme 4; Breau et al., 2011; Fullerton et al., 2018; White et al., 2019; Woolnough et al., 2009). Thus, scientists and managers may combine modeling techniques to assess long-term effects of CWR use, including life cycle models, individual-based models, spatially explicit models, and behavioral and physiological models. Such techniques may also broaden the scientific understanding of how CWR use by individuals translates to population-level effects, and how ecological interactions among multiple species and landscape settings affect the costs and benefits of CWR use. Addressing these gaps also may provide information on cumulative heat stress effects and impacts on body growth, survival, reproductive success, and population persistence (Snyder et al., 2020, 2022).

3 | MANAGEMENT AND CONSERVATION

Despite the importance of water temperature to the health of freshwater ecosystems, many countries do not have explicit, ecologically relevant water temperature and CWR standards or guidelines. This presents challenges for managing and conserving CWRs and thermal heterogeneity. Globally, adoption of water quality standards or guidelines for protecting aquatic life is mostly limited to high-income countries such as Australia, New Zealand, Canada, Japan, European Union (EU) countries, and USA (Sun et al., 2021; United Nations Environment, 2017).

The United Nations Environment Program (UNEP) links national-level monitoring to global assessments and advises countries to develop water quality guidelines for ecosystems through the International Water Quality Guidelines for Ecosystems (IWQGE) program and the Global Environment Monitoring System for Freshwater (GEMS Water; United Nations Environment Programme, 2018). Enrollment in the IWQGE program is voluntary, and guidelines only encourage monitoring of physical and chemical stressors such as water temperature. The IWQGE uses remote sensing to monitor changes in surface area of waterbodies over time in aquatic ecosystems but does not monitor or protect specific habitats or biota of cultural, economic, or ecological importance, such as salmonids. The GEMS program, one of the largest global databases of in-situ measurements of water quality (Desbureaux et al., 2022), collects river water temperature from 72 countries, of which 38 have salmonids. The UNEP proposed benchmarks for "high integrity systems" to ensure no deviation from water temperature background values or identifying optimum temperature ranges of relevant species (United Nations Environment, 2017). Large-scale and long-term integrative programs such as GEMS Water (with 267 basins and 5081 river stations) are critical to track water temperature changes in transboundary rivers.

3.1 | Overview of CWR regulatory structure

We reviewed policies and management practices that directly and indirectly affect water temperature and CWRs (i.e., water quality, fishing, wetlands, riparian, and groundwater). We focused on five case studies from North America, Europe, and Australia (Table 3; see https://conservationrefuge.com/ for more details) where the authors have local knowledge. We compared policy and management differences and inferred the level of integration or lack of policies and management by reading and conducting a text mining analysis (Table 4) on 58 environmental regulations and management documents (Table S1; see methods and results described in Table 4 and Figure S2).

We determined that CWRs were not identified in regulatory frameworks in most countries (except USA and Canada). The establishment of temperature standards and guidelines and fishing regulations are the two main ways by which water temperature, CWRs, and the fish that use them are managed or regulated directly. Temperature standards and guidelines are critical components of the assessment of water quality or ecological status for many

TABLE 3 Key attributes of the five case studies and connection to the proposed cold-water refuge framework: Lower Columbia River in Oregon, USA (Columbia), Upper Housatonic River in Connecticut, USA (Housatonic), Restigouche River in Quebec and New Brunswick, Canada (Restigouche), streams within the Rhône basin in the Southeast of France (Rhône), and Ovens River in the Murray Darling basin, Australia (Ovens).

Attributes	Connection to framework	Case studies: Columbia	Housatonic	Restigouche	Rhône	Ovens
Country		USA	USA	Canada	France	Australia
Primary management goals	Defining management question/goal (step 1—Figure 4)	Identify approach for incorporating CWRs into temperature standards, including methods for evaluating "sufficiency" of CWR for the protection of ESA-listed salmon (*Oncorhynchus* spp.)and steelhead (O. mykiss) populations	Protect trout from recreational angling in summer when they concentrate at cold tributary confluences	Identify location & type of CWRs at the watershed scale	Identify CWP location of river reaches	Identify and characterize CWPs as a tool to support decision-making in the control of groundwater extraction for irrigation, to ensure the preservation of riverine ecological values, with a focus on fish
Secondary (or additional) management goals	Defining management question/goal (step 1—Figure 4)	Identify steps and demonstrate methods for identifying, protecting, and restoring cold water refuges		Protect and enhance CWR habitat	Locate and classify CWPs	Baseline CWPs for future monitoring
Datasets	Assessing data availability (step 2—Figure 4)	Use data from regional water temperature network NorWeST to identify data needs	Local water temperature monitoring and data on CWRs occupancy monitoring	Airborne thermal infrared surveys of CWRs, CWRs classification table, water temperature monitoring	Satellite thermal infrared from Landsat—The Enhanced Thematic Mapper Plus (EMT+)	Drone-Based Thermal Infra-Red (TIR) imagery
Physical monitoring	Mapping and prioritization of area of interest (Figure 2, step 3—Figure 4)	Temperature, bathymetry, dissolved oxygen (1 refuge only where high aquatic vegetation densities indicated potential for concern)	Temperature and hydrodynamic data collected at a subset of the confluences	Airborne thermal infrared (TIR) surveys, temperature loggers, water chemistry, drone flight revisits, ground-based thermal refuge validation, bathymetry, and drivers of confluence configuration	Airborne TIR surveys, mainly diagnosis step	50 km baseline Drone TIR survey in April 2017 (end of Australian summer) to detect CWP and identify their drivers
Biological monitoring	Mapping and prioritization of area of interest (Figure 2, step 3—Figure 4)	Temperature- and depth-sensitive radio-tags, visual surveys, PIT tag detections, dam passage counts (including quantification of migratory delay associated with refuge use)	Yearly electrofishing and fish counts, species identification	Electrofishing, thermal habitat selection, habitat suitability modeling, PIT-tags and visual surveys	None	None
Physical modeling	Evaluating modeling options and needs (Figure 2, step 4—Figure 4)	Spatial stream network (SSN) models of temperature including shade and flow covariates; thermal plume modeling using COR-MIX	None	RivTemp and associated products, statistical models at sub-catchment level to understand drivers of CWRs	Statistical models mainly to predict water temperature	Statistical model to predict drivers of CWPs

(Continues)

TABLE 3 Continued

Attributes	Connection to framework	Case studies: Columbia	Housatonic	Restigouche	Rhône	Ovens
Biological modeling	Evaluating modeling options and needs (Figure 2, step 5—Figure 4)	Spatially explicit bioenergetics model; thermal exposure modeling	None	Habitat selection and drivers of onset of aggregations	None	None
Target species/group of species	Assessing biological linkages (step 5—Figure 4)	Summer steelhead (*Oncorhynchus mykiss*), fall Chinook salmon (*O. tshawytscha*)	Brown (*Salmo trutta*) and rainbow trout (*O. mykiss*), primarily stocked)	Atlantic salmon (*S. salar*)	Brown trout (*S. trutta*) and "lotic" cyprinids (Cyprinidae)	Murray cod (*Maccullochella peelii peelii*)) (endangered, conservation), brown trout (*S. trutta*) and rainbow trout (*O. mykiss*) (introduced for recreation)
Life history/life stage	Assessing biological linkages (step 5—Figure 4)	Adults, anadromous species listed under the Endangered Species Act	Adult and juvenile stages, resident species	Adult and juvenile life stage, anadromous species	Adult and juvenile stages, resident species	Adult and juvenile, resident species
Ecological relevance	Assessing biological linkages (step 5—Figure 4)	Thermoregulation during migration; climate change "adaptation"	Recreational fishing, promotes wild spawning of stocked fish	Thermoregulation, biodiversity, climate resiliency	Adaptation to global change	Conservation of one of the last unregulated rivers in the Murray Basin and its unique groundwater resources; adaptation to climate change with a focus on droughts and extreme low flow events
Interested groups (i.e., stakeholders and rightholders)	Assessing CWRs use to align policies and management (Figures 2 and 5)	Columbia River Basin governments, Columbia River Inter-Tribal Fish Commission, NOAA, EPA, State Fish and Wildlife Agencies, hydropower managers (US Bureau of Reclamation, Bonneville Power Administration), commercial and recreational fisheries	Connecticut state agencies, private fishing groups that stock fish, the public that participate in recreational fishing	Watershed level NGOs, Indigenous Nations, municipalities and counties, and academic institutions * *note that this case study is led by the Gespe'gewaq Mi'gmaq Resource Council	Rhône Mediterranean Water Agency, fish agencies	North East Catchment Management Authority (NECMA, Victoria)
Social importance	Assessing CWRs use to align policies and management (Figures 2 and 5)	Historical and contemporary fishing, cultural	Years of data collection have shown that some of the key refuges are essential for allowing brown trout (*Salmo trutta*) to hold over multiple years and grow large in the river. Large holdover brown trout (*S. trutta*) are highly valued and are key to the rare quality of the Housatonic trout fishery	Historical and contemporary fishing, cultural	Identification of refuges/threads, planning adaptation to global change	Historical, fishing, recreational area
Potential conflicts of use	Assessing conflicts of CWRs use to align policies and management (Figures 2 and 5)	Irrigation, fishery closures, hydropower management	Can interfere with fishing for warm water species near the managed refuge (such as smallmouth bass)	Fishery closures and transboundary management	Agriculture (if riparian afforestation planned or need to share water resources)	Irrigation, fishing, recreational activities

TABLE 3 Continued

Attributes	Connection to framework	Case studies: Columbia	Housatonic	Restigouche	Rhône	Ovens
Legal and institutional structures	Assessing legal and institutional constraints (Figure 5)	Clean Water Act (33 USC §1251 et seq. 1972) and the Endangered Species Act (16 USC §§1531–1544 et seq. 1973). Oregon and Washington states water quality regulations and fishing regulations	Clean Water Act (33 USC §1251 et seq. 1972) and the Endangered Species Act (16 USC §§1531–1544 et seq. 1973). Connecticut and New York states fishing regulations. No specific water temperature or CWR regulations	Canada Water Act (R.S.C. 1970 [1st Supp.], c.5.), The Fisheries Act (SC 1985, c. F-14). New Brunswick fishing regulations, MRC Avignon (municipality-local) protections under provincial wetlands and watercourse management plan. No specific water temperature or CWR regulations	European Water Framework Directive (WFD) 2000/60/EC, Habitats Directive (Council Directive 92/43/EEC), France Environment Code, Rhône prefectural decrees. No specific water temperature or CWR regulations. No fishing regulations	Australian 2007 Water Act (C2007A00137), The Environment Protection and Biodiversity Conservation Act, Murray-Darling Basin Agreement. No specific water temperature or CWR regulations. No fishing regulations
Limitations/ challenges	Implementing and evaluating (step 5—Figures 4 and 6)	Difficulty to quantify dynamics of refuge volume and temperature; snapshots only; lack of quantitative estimates of refuge "carrying capacity"; tradeoffs between refuge use (thermoregulatory benefit) and migration timing (delayed mortality, delayed exposure) difficult to evaluate	Data regarding when and how many trout use specific refuges are limited	CWR size variability (expansion and contraction) based on flow and groundwater interactions	Limited temporal variability (snapshots only) and biological functions	Spatial data only. No temporal data on physical habitat
Habitat: Policies/ management implementation	Implementing and evaluating (step 6—Figures 4–6)	Individual contributing watersheds identified for limiting factors, restoration potential	Signs posted, prevent summer angling for 30 m from the sign. Enforcement is opportunistic by Environmental Conservation Officers. The state Fisheries Agency has partnered with angler groups to actively enhance a subset of the refuges (e.g., arranging rocks, logs, and cut brush to increase the size of CWPs and provide overhead cover to deter avian and human predation. CWRs, were a key element in the hydropower relicensing of the dams, influencing change of operations	Municipality-level management plan for wetlands and watercourses (PRMHH) includes protection of CWRs: land-use restrictions to favor persistence of prioritized CWRs	Not focused specifically on CWP but on river temperature (different strategies implemented: share water/limit water/groundwater consumption, replant riparian forest, increase minimum flow, restore braided patterns/gravel augmentation)	North East Catchment Management Authority (NECMA)—Ovens Water Supply Protection Area (WSPA) Water Management Plan—one of the first to consider the importance of groundwater

(Continues)

TABLE 3 Continued

Attributes	Connection to framework	Case studies: Columbia	Housatonic	Restigouche	Rhône	Ovens
Species: Policies/ management	Implementing and evaluating (step 6—Figures 4–6)	Fishery closures at select tributary plumes	These managed refuges are chosen based on the observed presence of salmonids. If a previous refuge location seems to no longer hold trout in summer, it can be dropped from the active management list	Warm water protocol for fishery closures	Not focused specifically on CWP but on river temperature.	Focus on low flows periods/ droughts- to manage groundwater extraction for irrigation
Research gaps	Implementing and evaluating (step 6—Figure 4)	Factors determining carrying capacity; physical models to capture effects of hydropower management on plume depth and temperature; better understanding of tradeoffs associated with refuge use (e.g., increased susceptibility to angling)	Better understanding how these natural confluence zones could be physically manipulated to house more fish during warm flow times- the refuges can be "maxed out" on the warmest days, with fish grouped so tightly one cannot see the river' bottom	Biodiversity (other species benefiting), groundwater influence, watershed-scale CWR persistence	Understanding of biological functions of CWPs	Quantification of groundwater versus surface water contributions over time, better links between CWPs and ecological processes
Research/policies adaptation	Implementing and evaluating (step 6—Figures 4–6)	Current water temperature standard only accounts for cold-water refuges within specific migratory corridors. Thermal heterogeneity is not incorporated into water temperature standards. CWRs not always included into TMDLs implementation plans (total maximum daily loads—the regulatory method for implementing water quality improvements)	Regulations and management have been implemented on an individual as-needed basis. Refuge regulations are generally applied only to stream sections where the state stocks and manages trout	Contrasting fishing regulations between Quebec and New Brunswick	CWPs not currently considered in river management	CWPs not explicitly included in the management plan, more data required to influence the management plan
References		Fuller et al. (2021); EPA (2021); Ebersole et al. (2020); Snyder et al. (2019, 2020); Keenan (2019)	DEEP (2022); Sullivan et al. (2021)	Dugdale et al. (2015); Dugdale (2014); MRC Avignon (2022)	Wawrzyniak et al. (2011); Marteau & Moatar (2023); Rhône-Méditerranée Bassin (2019); Agence française pour la biodiversité/ Armines (2017)	GMW (2023); NECMA (2023) Kuhn et al. (2021); Casas-Mulet et al. (2020)

Abbreviations: CWP, cold-water patch; CWR, cold-water refuge.

TABLE 4 Text mining analysis workflow and main results. Analysis was conducted using R (R Core Team, 2020), RStudio (RStudio Team, 2020), and using the R packages *Quanteda* and *tm* (Benoit et al., 2018; Feinerer & Hornik, 2020).

Workflow	Methods and results
Documents sources (n = 58, Table S1)	Documents were selected based on the workshop participants' experience working in the areas of the case studies and their ability to identify relevant policy and management documents related to water quality, fishing, wetlands, riparian, and groundwater and basin management plans. Documents represented policies at multiple scales (i.e., continental, national, state, provincial, basin)
Documents preparation	Standard text pre-processing steps were applied (i.e., removing word stems and stopwords) to the collection of documents (Benoit et al., 2018; Feinerer & Hornik, 2020)
Dictionary creation (Table S2)	Terms or sets of words to create keywords were based on the classes of cold-water refuges identified by Torgersen et al. (2012) and Dugdale et al. (2015), the species known to occur in the case studies, and terms known by the workshop participants' to be used in these geographic areas to describe cold-water refuges. We had a set of keywords for each language, English and French
Frequency and keyword associations analyses	We calculated frequencies for all the terms in the documents and for the keywords. We also developed keyword associations using cosine similarity scores. Data matrices with sparsity percentages (i.e., percentage of cells in a database table that are not populated) greater than 60% were considered too sparse to calculate associations. The cosine similarity scores range from 0 to 1. We applied the inverse document frequency (IDF) weight to the cosine similarity score. Lastly, we inspected word associations for all case studies except for the Rhône River case study because its data matrix was too sparse (sparsity of 68%)
Results—main finding #1	Keywords related to CWRs (Table S2) were not among the most frequent words in the analyzed documents (Tables S3 and S4). The term *temperature* was mainly associated with water quality standards and salmonids. The term *refuge* was broadly associated with all keywords and was inconsistent across case studies. These results highlight a concern for warming water for salmonids in the different policy and planning documents and they may also suggest a lack of existing policies and targeted management actions on CWRs
Results—main finding #2	Words capturing potential formative processes or CWR-associated structures (e.g., *confluence*, *pool*, *spring*, *and seep*) were inconsistently mentioned in documents (Tables S3 and S4, Figure S2). This suggested that most of the processes and riverine features important in creating and maintaining CWRs were not explicitly included in the reviewed policies and management documents

countries. However, water temperature is not always a metric that is included in water quality assessments (United Nations Environment Programme, 2014). Fishing restrictions due to warm summer water temperatures are in place in many cold-water rivers, regardless of "formal" CWR designations in North America and parts of Europe, such as Spain, which was not a case study.

Policies may indirectly affect CWRs and water temperature by addressing key drivers of river thermal regimes (Figure 2). In the case studies, we identified three policy and management categories that indirectly affect the physical aspects of CWRs. The first category is associated with instream flows and may include water transfers and diversions, dam and hydropower plant releases, and base flows. The second category is related to groundwater connectivity and hyporheic exchange and may include aquifer recharge/discharge or storage and wetland and floodplain management. The third category is associated with riparian buffer management along riparian corridors that may be managed differently depending on adjacent land-use practices, such as agriculture, forestry, or urban development. We also identified policies and management actions that relate to the biological aspects of CWRs, such as management of species occupying these features, and the trade-offs between protecting one set of species versus another. Species management also requires consideration of potential sources of conflict, such as conservation status or invasive status, and their cultural, recreational, provisioning, and economic values.

There are multiple policies that can affect the physical and biological aspects of CWRs. For example, we found that many regulations and policies affect directly CWRs by managing the organisms that use CWRs during thermal stress and protecting species of conservation interest via fishing restrictions. Most regulations and policies do not protect the cold-water patch per se, except in the Restigouche River case study. In the Restigouche River, protections of the confluence plume and tributary drainage area were established at the local level to protect CWPs under the provincial wetlands and watercourse management plan (MRC Avignon, 2022). Lastly, policies and regulations may specify river temperature guidelines or standards but rarely contain specific CWR guidelines, except for the Lower Columbia River case study.

The Lower Columbia River in the state of Oregon (USA), is the only place in the world that has a CWR standard and a temperature standard for the mainstem of the river. The Oregon Department of Environmental Quality (ODEQ) set a water temperature standard of 20°C for the Lower Columbia River to protect migrating salmon and steelhead listed under the Endangered Species Act. It also defines CWRs as "those portions of a water body where, or times during the diel temperature cycle when, the water temperature is at least 2°C colder than the daily maximum temperature of the adjacent well mixed flow of the water body" (OAR 340-041-0002(10)). Regulations by ODEQ further stipulate that the Lower Columbia River "must have cold-water refugia sufficiently distributed so as to allow salmon and steelhead migration without significant adverse effects from higher water temperatures elsewhere in the water body." However, like all temperature standards based on maximum temperatures, this does not fully incorporate the spatiotemporal variability of the thermal regime (Poole & Berman, 2001). This variability is important to fish growth at times of the year when fish are not thermally stressed (Armstrong et al., 2021).

In the Lower Columbia River case study, CWR and temperature standards are integrated, in part, into fishing regulations and designation of cold-water habitat as an aquatic resource of special concern under the Oregon Department of State Lands (Rule 141-085-0510), which can affect the permitting of impacts to "cold-water habitat" designated areas and compensatory mitigation requirements for those unavoidable permitted impacts. For CWRs provided by tributaries, maintenance of CWR function can be partially achieved through riparian shade management implemented through various waterbody-specific plans that target meeting temperature standards. Still, CWRs are not yet integrated into groundwater or wetland policies, which have been associated in the literature with CWR persistence (Monk et al., 2013; Wawrzyniak et al., 2016) or sufficiency (Fullerton et al., 2018; Snyder et al., 2020).

3.2 | Existing water temperature and CWR policies and management

In the text mining analysis, we found that terms or keywords associated with CWRs were not used frequently in the documents that we examined (Table 4). Also, the term "temperature" was mainly associated with water quality standards and salmonids. In contrast, the term "refuge" was broadly associated with other keywords and its associations were inconsistent across case studies. Reading through the documents helped us establish the context where these terms were mentioned, and we determined that the term "refuge" generally was related to stressors such as flooding and temperature, or it was used to describe wildlife management areas. The environmental regulations and planning documents of the case studies also confirmed that most keywords associated with CWRs (except temperature) were found in only two documents related to fishing regulations and water quality standards in North America; this suggested a lack of policies that specifically addressed CWRs. Moreover, we identified that large watersheds crossing state or provincial boundaries were inconsistently covered by some policies, such as fishing restrictions or closures. For example, warm water protocols are only on the New Brunswick portion side of the Restigouche River (and not on the Quebec side), thermal angling sanctuaries are only on the Oregon State side of the Lower Columbia River (and not on the Washington State side), and summer fishing closures are in state-designated "Trout Management Areas" that include nine cold-water tributary confluences only in the portion of the Housatonic River in Connecticut (and not in New York State).

In conducting this review, we found that policies or management actions generally do not explicitly recognize the physical, hydrological, and atmospheric processes that create and maintain thermal heterogeneity and CWRs. Therefore, they are not incorporated into active CWR management. There are rare exceptions as part of waterbody-specific implementation plans under the Clean Water Act or in the relicensing of hydropower projects in the USA. For example, in the Housatonic River case study, CWRs had been identified as part of "Trout Management Areas." In the current North American context, Indigenous peoples and local interested groups also have limited opportunity to provide input for CWR protection because protection is primarily driven by top-down policies, but there are exceptions, such as the Restigouche River's county-level protections (MRC Avignon, 2022). In the Restigouche River case study, interested groups have willingly gone beyond the federal and provincial (large scale) mandates and created local protections that surpass existing regulations. This is an example of top-down regulatory structure where large-scale regulatory structures are flexible to anticipate responses that can vary from one jurisdiction to another (Chang et al., 2014). Creating and restoring physical processes that conserve thermal heterogeneity and CWRs may be accomplished through a bottom-up approach when communities engage, and community priorities align with top-down conservation priorities. For example, restoring thermal heterogeneity and CWRs may be a by-product of restoring other processes or habitats at different scales. However, a bottom-up approach can have drawbacks when there is not a strong regulatory or incentive framework or external funding (Gaymer et al., 2014).

4 | TOWARDS BUILDING A CWR CONSERVATION FRAMEWORK

Other reviews on conserving, enhancing, and restoring CWRs have mentioned the need for scientists and resource managers to work together to link science and management to support CWR conservation (Ebersole et al., 2020; Morelli et al., 2016; Torgersen et al., 2012). Here, we propose a framework that integrates CWR science, policy, and management and adapts to the changing science and environment. The framework (see Table 3 with framework components and their connections to case studies; Table 5 summarizes framework components and linkages) creates possibilities to safeguard coldwater organisms against the effects of climate change by embedding CWRs within larger considerations of thermal heterogeneity (Poole et al., 2004) and other environmental stressors that may affect coldwater organisms in the future (Myers et al., 2017). The framework integrates information on how to evaluate CWR resilience to climate change and future management needs (Figure 4) and calls for coordination among regulatory jurisdictions (Figure 5) and incorporating adaptive management (Figure 6).

Together, Figures 4 through 6 build the foundation of our proposed CWR conservation framework. Figure 4 presents a sequential approach to help researchers and managers identify and evaluate CWRs and their biological linkages to implement protection and conservation actions. Coordination across multiple regulatory jurisdictions at the watershed scale is challenging but is necessary to align consistent strategies guided by common socioeconomic values and objectives of all interested groups (Figure 5). Finally, there is an abundant literature on adaptive management, but this concept has yet to be applied to CWR conservation as described in Figure 6. The triple-loop approach is appropriate given the dynamic nature of

TABLE 5 Components for linking science, policy and management in the cold-water refuge (CWR) framework.

Target audience	Framework component	Science/policy/management linkages
Scientists and resource managers	Follow sequential approach from identifying management goals to implementing and adaptively evaluating management (Figures 2 and 4)	Link traditional ecological and cultural knowledge with scientific knowledge to co-produce science and management (e.g., monitoring, modeling, planning, and restoring)
Environmental regulators	Align existing policies and incorporate new policies that directly and indirectly affect CWRs to promote consistency among regulatory jurisdictions (Figures 5 and 6)	Link landscape-level processes that drive CWR formation and maintenance by recognizing CWRs as distinct operational landscape units within a watershed context. Link evolving science or management needs to adopt or refine water temperature and CWR standards or guidelines
Resource managers	Implement adaptive management when evaluating management outcomes (Figure 6)	Link spatio-temporal CWR dynamics with management under changing climate or conditions

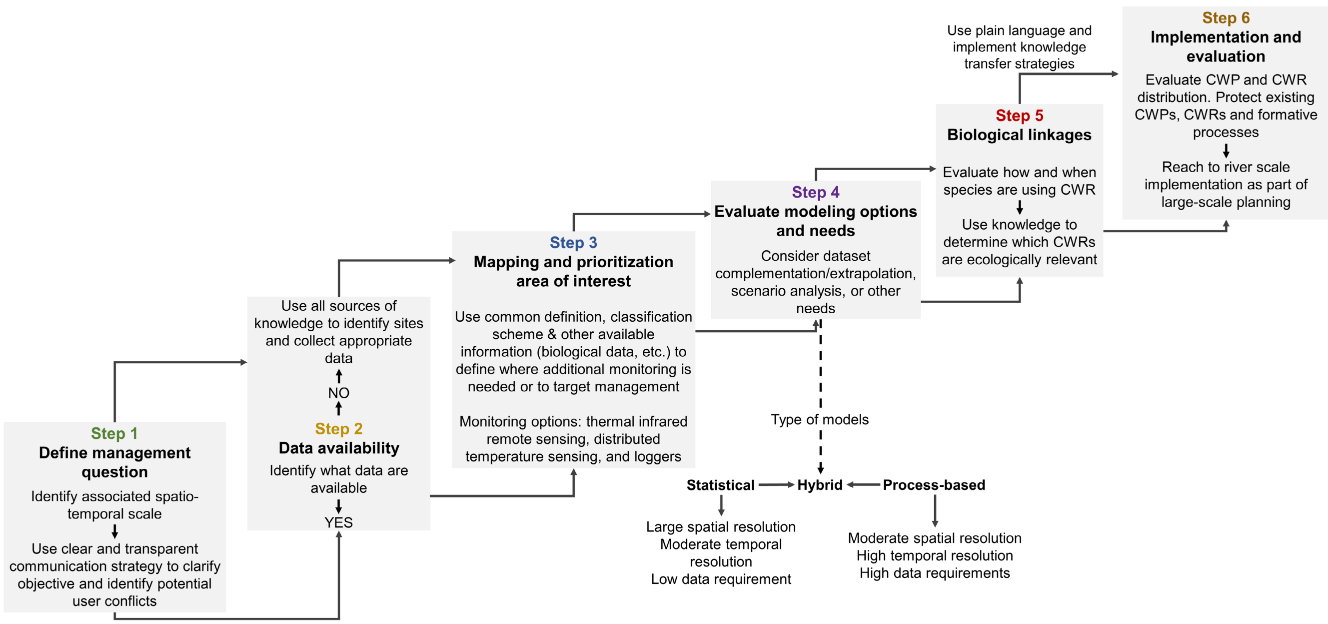

FIGURE 4 Sequential approach to implement and evaluate science-based management and policies related to cold-water refuges and thermal heterogeneity.

CWRs, in that it allows for the periodic re-evaluation of assumptions and considers whether to alter rules for decision-making and changing governance.

Collaborative research between scientists and managers, termed "co-production of knowledge" (Cook et al., 2013; Cooke et al., 2021; Djenontin & Meadow, 2018; Kurle et al., 2022), occurs early in the proposed framework when the focus is on identifying management goals and characterizing CWRs (Figure 4). It is important to adopt a common terminology across disciplines (sensu Sullivan et al., 2021) to define CWRs, distinguish between CWRs and CWPs, and apply consistent CWR classifications (Dugdale et al., 2013; Ebersole et al., 2003a; Torgersen et al., 2012). The framework accounts for human dimensions and integrates traditional ecological and cultural knowledge (sensu Dunham et al., 2018). Using multiple sources of knowledge can provide a nuanced context and develop trust among interested groups (Reid et al., 2021). For instance, Indigenous peoples and river users (e.g., kayakers, anglers) can identify CWR locations and share information on CWRs to help guide management. In addition, economic and cultural values and competing uses from multiple interested groups affect the protection, management, and restoration of CWRs. Thus, clear and transparent discussions generate trust and reciprocity, and promote sharing of cultural knowledge, conflict resolution, and the development of an effective framework for CWR conservation and management (Ebersole et al., 2020).

Where temperature regulations do not exist, some jurisdictions may designate areas as "cold water habitats" or "habitats of special concern" through fishing, water resource, or habitat protection regulations rather than setting temperature standards. These areas are important because they provide functions, values, and habitats that are limited in quantity or have been disproportionately lost due to prior impacts. Additionally, integrating CWR management within existing policies that influence the formation and persistence of CWRs (e.g., riparian buffers, wetlands, groundwater, water use management) may require either a modification of existing policies recognizing their interdependencies with other policies or the development of new policies (Dunham et al., 2018; Ebersole et al., 2020). Policy modifications or creation of new policies also may help manage

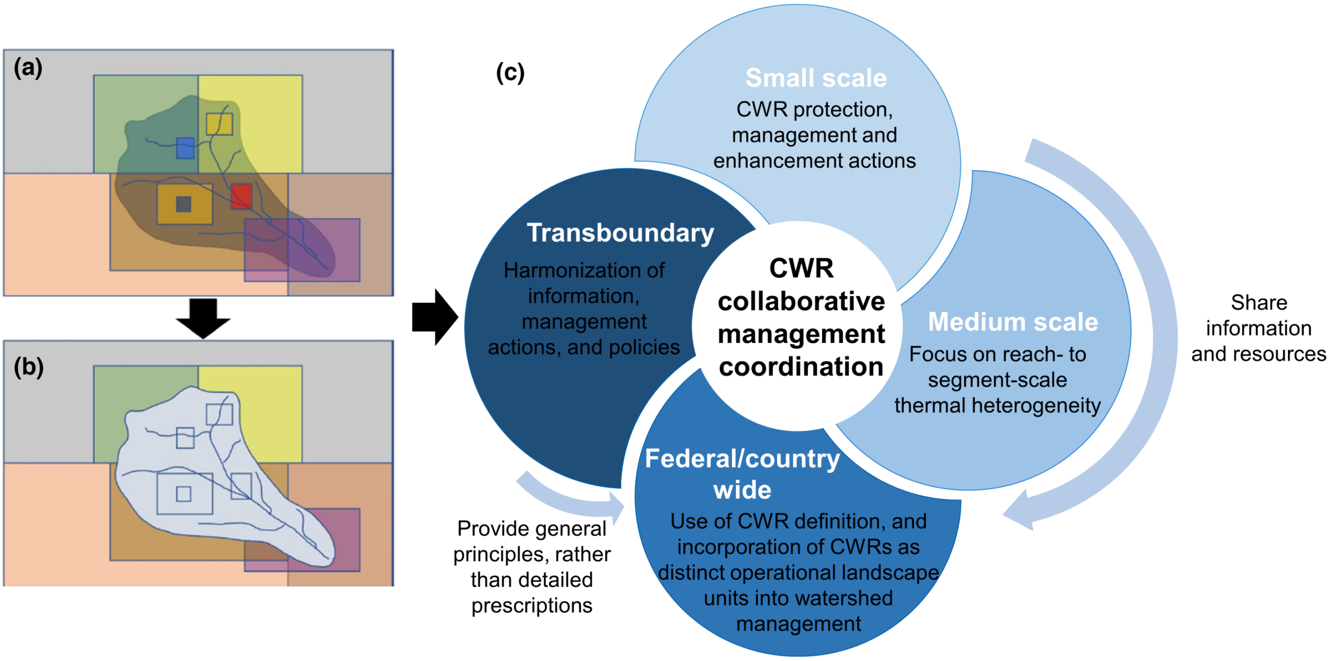

FIGURE 5 Spatial alignment of policies and management strategies of cold-water refuges (CWRs). Example shows: (a) watershed with multiple jurisdictions and interested groups (as represented by different colors and boxes) with potentially conflicting values and objectives that lead to unstructured and inconsistent management and policies; (b) watershed as the planning unit, where strategies align to create a consistent management plan guided by common socioeconomic values and converging objectives of all interested groups (multiple jurisdictions and interested groups are still in place); and (c) scales of organization with corresponding management prioritization.

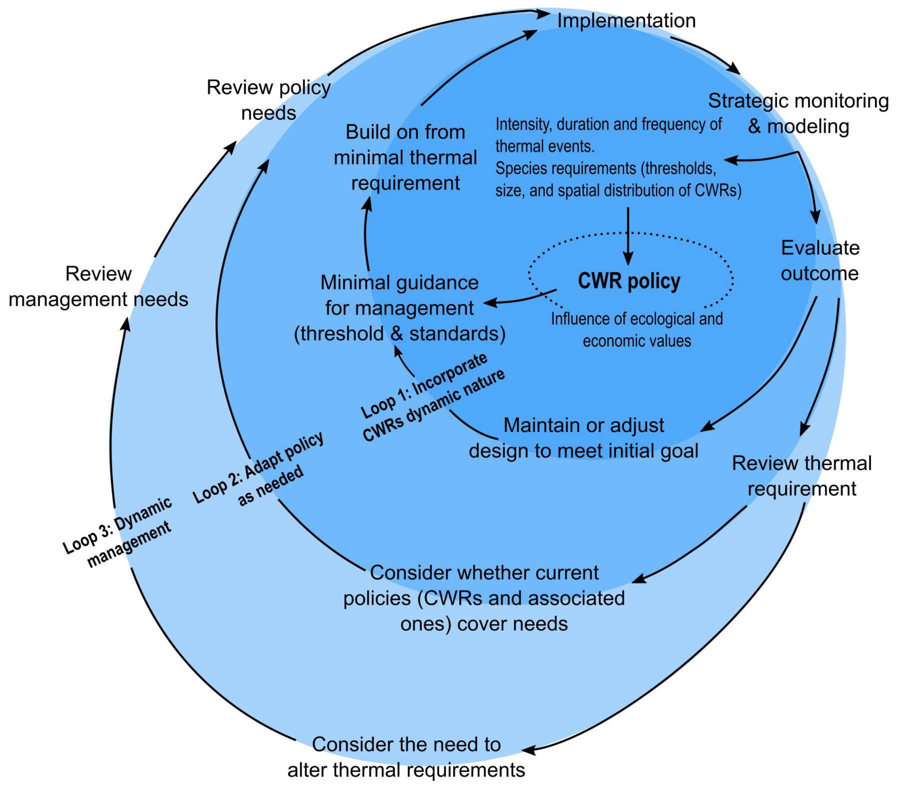

FIGURE 6 Triple-loop learning adaptive management approach showing the different pathways and outcomes of cold-water refuge (CWR) policies. Policy provides a baseline to support management, while implementing an adaptive management approach to account for the spatial and temporal variability of CWRs. Each loop involves re-evaluating assumptions to decide whether to alter the decision-making framework. Figure adapted from Kittinger et al. (2011) and Morelli et al. (2016).

CWRs as part of watershed management and coldwater species conservation programs.

In regions where temperature standards exist, it is important to define CWR standards (e.g., the Lower Columbia River case study) after reconciling inconsistencies regarding thermal thresholds of target species. It is also essential to propose definitions that enable enforcement (where applicable) and to explicitly acknowledge the dynamic nature of CWRs while supporting management objectives. For example, salmonids respond to temperature changes of less than 1°C (Berman & Quinn, 1991), yet some assessment tools have a margin of error greater than 1°C (Whittier et al., 2020). Furthermore, the physiological consequences of thermal exposure (frequency and magnitude) vary depending on life stages and species-specific tolerances. This creates challenges when dealing with multiple thermally sensitive species. Thus, it may be helpful to define CWRs as areas that (1) have lower warm-season water temperature (at least 1°C baseline) than the mainstem, (2) maintain temporal persistence, and (3) have thermal thresholds (magnitude difference or thermal sensitivity of the targeted species) that minimize cumulative effects of heat stress.

Temporal persistence and threshold criteria for the CWR definition may need to be adjusted through a process involving interested groups and a spatially or temporally dynamic adaptive management approach (Figure 6). While it is difficult to provide a universal standard given the highly species-specific and geographically dependent nature of thermal and habitat requirements, an overarching goal can be to maintain thermal heterogeneity at multiple temporal scales (i.e., acute, diel, seasonal) and to promote functional thermal niches for aquatic life (McCullough, 2011). As mentioned above in the section on direct and indirect policies and management, the only example of a CWR temperature standard is in the Lower Columbia River case study. Using the thermal requirements of the most sensitive coldwater organisms that currently exist—or historically existed—may ensure that CWRs provide sufficient protection to all affected species.

Physical and hydrological processes, that is, incomplete mixing of thermally and hydrologically distinct flows or thermal stratification, and the geomorphological settings that create and sustain cold water, such as channel slope, channel confinement, floodplain geometry, and planform patterns, are maintained by multi-dimensional connections to the adjacent landscape (Dugdale et al., 2015; Sullivan et al., 2021; Torgersen et al., 2012). The framework identifies CWRs to be recognized and treated as distinct operational landscape units that are separate from the mainstem and have their own unique management considerations that integrate landscape level processes (e.g., physical and hydrological) that drive CWR formation and maintenance (Verhoeven et al., 2008). Using operational landscape units also raises managers' awareness of the importance of spatial processes and connectivity in the landscape (Bernhardt et al., 2017; Verhoeven et al., 2008), which are fundamentally important to CWR management and conservation. In this manner, CWRs may be identified and characterized as part of larger watershed or basin management efforts. Managers may find it instructive to prioritize these operational landscape units using physical and biological criteria by considering spatial tradeoffs when distributions shift under varying conditions. Physical criteria may include size (areal extent and volume), temporal persistence, mainstem connectivity, and thermal response magnitude. Biological criteria may include use by target species, prey availability within CWRs and adjacent habitats, and presence of predators.

Managers may be able to improve coordination and prioritization across jurisdictions by adapting the scale of protection and management. For example, such an approach may involve setting goals and monetary structures, sharing resources and technical expertise, and following the nested hierarchical organization of CWRs. Small- and medium-scale or bottom-up organizations, such as watershed groups and local governments, may find it useful to concentrate on protecting and restoring processes that create and maintain CWRs. At broader scales, large or top-down organizations, such as federal and transboundary entities and governments, may be able to provide the legal framework to develop regulatory or incentive-based structures to promote multi-objective policies (Figure 5). The proposed framework incorporates the inherently multidimensional nature of CWRs by linking science, policy, and management across scales in space and time (Table 5).

5 | CONCLUSIONS

Bridging the gap between science and management of CWRs requires interdisciplinary approaches to understanding complex interactions among physical, ecological, social, and cultural factors. This review showed that, while there are many opportunities for scientific advancement, the current state of the sciences is sufficient to begin informing policy and management. However, most of the available research on CWRs has focused on salmonids in northern temperate regions, and current modeling tools do not capture the complex and multidimensional processes associated with CWRs. Addressing critical research gaps is essential to support CWR adaptive management. Areas in need of further investigation include interactions among physical, hydrological, and atmospheric processes that affect CWRs and the adjacent landscape and among multiple species (including humans) and ecological communities using CWRs.

Our review of policies and management practices revealed that many countries lack ecologically relevant water temperature guidelines. Where they do exist, these guidelines are often not integrated with other regulations that may affect CWRs. Furthermore, the guidelines may not be coordinated within watershed management plans. There also is a disconnect between the ecological understanding of water temperature and the policies that ultimately affect the ability of practitioners to conserve CWRs. The framework outlined here is a path forward for managing CWRs using existing and new policies.

We identified four tasks to address thermal heterogeneity and CWR policy needs. First, addressing science gaps requires an interdisciplinary approach with collaboration among physical, biological, and social scientists as well as with policymakers and resource managers. Open conversations about legislation and funding mechanisms can foster better coordination. Such collaboration is essential to address research gaps, increase knowledge transfer, facilitate targeted funding, and improve engagement in CWR conservation. Second, CWR policy intersects with diverse interested groups, policies, territories, and institutions. Some measures to protect CWRs may be controversial or involve trade-offs. Early participation by a wide range of interested groups—including Indigenous peoples—is important for identifying common values and building trust, which can help to avoid conflicts as policies are implemented (Chapman et al., 2020). Third, regulatory, incentive-based, and monetary structures can promote multi-objective policies. Fourth, management and regulation of CWRs as operational landscape units integrated into watershed and species conservation efforts may be a particularly effective approach.

Specific measures to conserve CWRs include designating "cold-water habitats," restricting or closing fishing during warm periods, and having temperature standards or guidelines. Existing water temperature standards also may be modified to include a CWR definition that is specific, clear, implementable, and recognizes their dynamic nature. Cold-water refuges are a key element of cold-water habitat and species management that has been largely overlooked but could prove essential in a changing climate. Managers may not be able to control rising water temperatures due to global change, but conserving and restoring CWRs and thermal heterogeneity, and the processes that create and maintain them, may improve short-term survival of fish and other coldwater organisms during warm periods.

AUTHOR CONTRIBUTIONS

Francine H. Mejia and Valerie Ouellet sought funding for this project, led and managed the workshop that inspired this manuscript. They also drafted the manuscript outline, led the group throughout the editing process, curated data and analysis, and produced the visualizations. All other authors contributed to the editing, the conceptualization of the visualizations, and reviewed and approved the submission.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the Supplementary Information. These data were derived from resources available in the public domain, and all URLs are listed in Table S1.

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