Preserving, augmenting and creating cold-water thermal refugia in rivers: Concepts derived from research on the Miramichi River, New Brunswick (Canada)

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Abstract

Summer water temperatures are rising in many river systems in North America, and this warming trend is projected to intensify in the coming decades. One option for cold-water fish to alleviate thermal stress in summer is by aggregating in discrete cold-water plumes that provide thermal refuge from high ambient river temperatures. Reliance on cold-water thermal refugia is expected to increase in a warming climate, and many river reaches already lack suitable thermal refugia due to an absence of thermal diversity. A comprehensive fish management strategy could proactively address this imminent threat to cold-water fish populations across North America by preserving existing thermal refugia, augmenting thermal anomalies to improve performance as refugia, and creating new thermal refugia in uniformly warm river reaches. We provide practical recommendations on how these measures can be accomplished based on insight derived from recent research focused on the Miramichi River, New Brunswick. Opportunities include limiting land use change, construction aggregate extraction (*e.g.*, sand and gravel pits), and groundwater pumping/consumption. Existing thermal anomalies can be enhanced by controlling advective thermal mixing between cold-water tributaries and the river mainstem flow, installing riparian shading, and adding temporary structures for protection from avian predators. New refugia can be created by temporarily pumping groundwater to discrete points within the river during periods of thermal stress. These concepts are discussed in the context of a comprehensive thermal refugia management strategy.

1. Introduction

In summer, discrete cold-water plumes within rivers provide thermal refuge for cold-water fish (*e.g.*, salmonids) when ambient river temperatures exceed critical, species-specific temperature thresholds (Berman and Quinn, 1991;Ebersole *et al.*, 2003a; Kaeding, 1996; Kaya *et al.*, 1977; Sutton *et al.*, 2007; Tate *et al.*, 2007; Torgersen *et al.*, 2001). During high temperature events, cold-water fish often engage in behavioural thermoregulation to alleviate physiological stress (Breau *et al*., 2007; 2010) by moving to and aggregating within available cold-water refugia (Gibson 1966; Baird and Krueger, 2003; Berman and Quinn, 1991; Goniea *et al.*, 2006). The presence of thermal refugia enables cold-water fish to overcome temporary periods of habitat unsuitability induced by high water temperatures and allows them to survive in reaches that would otherwise be prohibitively warm (Sutton *et al.* 2007). Thermal refugia are thus critical to the preservation of cold-water fish populations at lower latitudinal or elevational extents of their range (Mackenzie-Grieve and Post, 2006; Wenger *et al.*, 2011; Williams *et al.*, 2009).

The principal characteristics and/or hydrologic processes that create thermal refugia have been identified and categorized in previous studies. Bilby (1984) classified thermal refugia morphologies as groundwater seeps, cold-water tributaries, shade-induced anomalies, deep water impoundments, or streambed hyporheic flow (Figure 1). Ebersole *et al.* (2003b) characterized cold-water patches as cold alcoves (emergent floodplain/gravel bar groundwater), floodplain spring brooks, cold side channels, and lateral seeps. They defined thermal refugia as any plume with a temperature at least 3°C less than the ambient water temperature, a surface area ≥ 0.5 m^2, and a dissolved oxygen level ≥ 3 ppm. Thermal refugia often result from fluvial geomorphic features and landscape topographies that induce groundwater-surface water interactions (Figure 1) because groundwater temperature is relatively insensitive to short term air temperature variability (Constantz, 1998; Guenther *et al.*, 2014; Hayashi and Rosenberry, 2002; Tague *et al.*, 2007).

Existing thermal anomalies may not function as effective refugia for target species because of physical or chemical conditions, including: limited temperature difference from the ambient river temperature, insufficient cover including water depth (for protection from avian predators), or inadequate dissolved oxygen levels due to anoxic groundwater discharge and/or the reduced oxygen carrying capacity of water as temperature increases. Thermally-stressed salmonids often encounter a trade-off between thermal relief and increasing exposure to predators or hypoxic water (Ebersole *et al.*, 2001, 2003b; Keefer *et al.*, 2009; Matthews and Berg, 1997), and these trade-offs can either delay movement into refugia until river temperatures reach lethal thresholds or prevent utilization altogether.

Many North American river systems have exhibited warming trends in summer water temperatures (*e.g.*, Isaak *et al.*, 2012; Kaushal *et al.*, 2010), and changing river thermal regimes have been linked to altered migratory patterns of salmonids across northern latitudes (Juanes *et al.*, 2004; Kennedy and Crozier, 2010; Kovach *et al.*, 2013; Otero *et al.*, 2014). Numerous

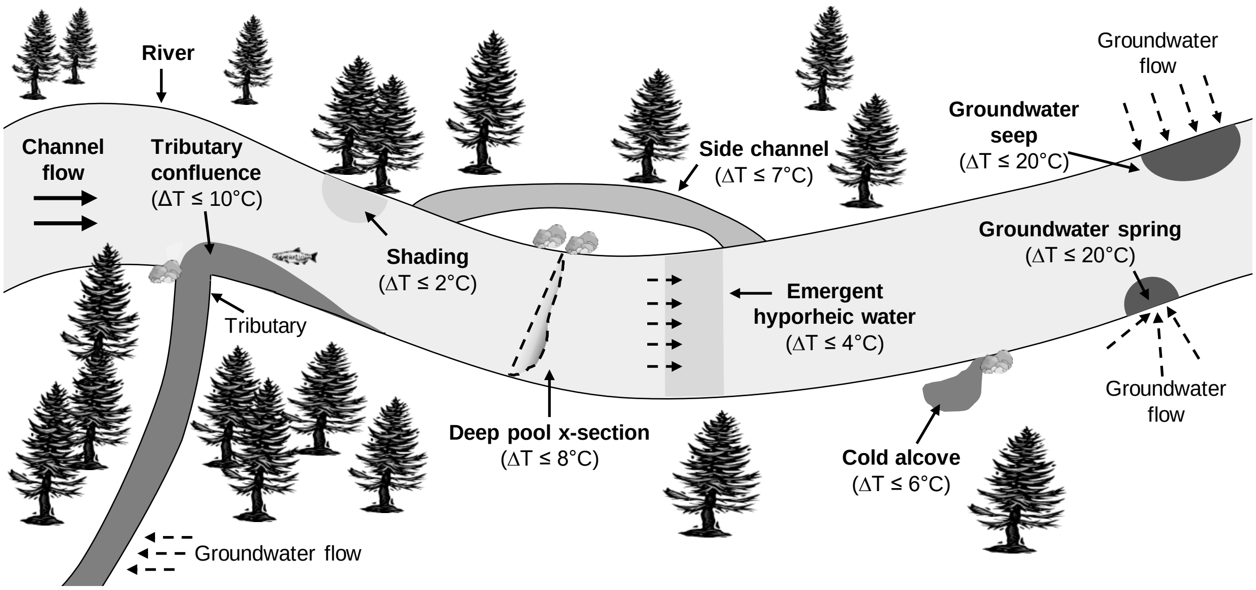

Figure 1. A conceptual overview of mechanisms that induce thermal diversity in rivers and create suitable thermal refugia. The estimated maximum temperature differences between a particular thermal anomaly and the ambient river temperature given in brackets are derived from other literature sources (Ebersole *et al.*, 2003b; Nielsen *et al.*, 1994) and extensive aerial infrared images and in-stream thermal surveys of the Little Southwest Miramichi River and other branches of the Miramichi River (*e.g.*, Wilbur, 2012). Darker colors indicate colder water.

studies have considered future climate change-induced increases in river or stream temperature and the associated reduction in cold-water fish habitat (Chu *et al.*, 2005; Jones *et al.*, 2014; Jonsson and Jonsson, 2009; Moore *et al.*, 2013; van Vliet *et al.*, 2011). These studies have generally indicated that cold-water fish will experience a significant loss of thermally suitable freshwater habitat, particularly under the most extreme climate warming scenarios. Several studies have noted that cold-water refugia should be considered in land use management strategies for preserving future fish habitat (*e.g.*, Brewer, 2013; Goniea *et al.*, 2006; Torgersen *et al.*, 2012), but very few guidelines have been proposed that provide practical examples of how refugia may be protected or enhanced (*e.g.*, Torgersen *et al.*, 2012).

The objective of this article is to highlight several threats to thermal refugia and to provide guidance on (1) preserving existing thermal refugia, (2) augmenting thermal anomalies to increase their potential to provide thermal refuge, and (3) creating new refugia in rivers of eastern North America. Thus the discussions are focused on enhancing thermal diversity rather than reducing ambient summer water temperatures.

2. Study area

The concepts proposed in the present paper are derived from several years of detailed field investigations and modeling of thermal refugia and cold-water fish ecology in the Miramichi River in New Brunswick, Canada (Breau *et al.*, 2007, 2011; Caissie *et al*. 2007; Cunjak *et al.* 2005, 2013; Daigle *et al.*, 2014; Kurylyk *et al.* 2013, 2014; Monk and Curry, 2009; Monk *et al.*, 2013; Wilbur, 2012). The Miramichi River is the second largest river in the Canadian Maritime provinces with a drainage basin of 14,000 km^2 (Caissie and El-Jabi 1995; Cunjak and Newbury, 2005). It flows northeast from its headwaters in central New Brunswick and discharges into Miramichi Bay (Figure 2b). The entire basin was glaciated during the Wisconsin glaciation, (Cunjak and Newbury, 2005), and thus much of the Miramichi River system is surrounded by glaciofluvial deposits that facilitate shallow groundwater flow (e.g., Kurylyk *et al*., 2014). The Miramichi River is an excellent case study because it is the largest producer of wild Atlantic salmon (*Salmo* salar) in North America and has been extensively studied (Cunjak and Newbury, 2005). Atypically high measured summer water temperatures that threaten the viability of wild salmonid stocks in the basin have been measured in the Miramichi River in the past decade (Breau *et al.*, 2007; 2011; Cunjak *et al*. 2005). Furthermore, a general warming trend of 2.3°C over 110 years has been observed in the air temperature for this basin (Cunjak *et al*., 2013).

Previous thermal refugia research for the Miramichi River has been predominantly focused on the Little Southwest Miramichi River (LSW), which is a sixth order branch of the Miramichi River (Figures 2b). The LSW has a mean annual flow of 32.5 $m^3 s^{-1}$ and drains a surface area of 1340 km^2 (Caissie, 2006a). The LSW catchment is primarily forested with a mixed coniferous (65%) and deciduous (35%) canopy. The region experiences a humid-continental climate characterized by arid, cold winters with mean monthly air temperature ranging from -11.8°C (July) to 18.8°C (January) (Cunjak *et al*., 1993). The LSW has an average width and depth of 80 m and 0.55 m respectively, and is thus classified as a wide, shallow river (Caissie, 2006a). Daily maximum LSW water temperatures have been previously documented in the range of 25-30°C (Breau *et al*., 2007; Caissie *et al*., 2007). Thus, thermal refugia within the LSW are critical for sustaining salmonid populations during high temperature events (Breau *et al*., 2011).

Identification of thermal anomalies in the Miramichi system has been carried out via thermal infrared imaging (see Monk *et al.*, 2013). Overall, 408 km was imaged in 2008-09, in sections varying from third to sixth stream order. For context, Figure 2c shows a thermal infrared image of a reach of the LSW and the location of two thermal anomalies. The thermal anomaly formed by the cold-water tributary (Figure 2c) has been shown to function as a biologically-significant thermal refuge with an estimated 6,000 to 10,000 Atlantic salmon parr aggregating in the plume in July 2010 (Figure 2d) when the mainstem river temperature exceeded 30°C (Emily Corey, Pers. Comm., 2014). It is believed that the concepts proposed here will contribute to cold-water fish species management strategies for the Miramichi River and other unregulated, alluvial rivers that are currently experiencing summer water temperature maxima that approach or exceed critical temperature thresholds for cold-water fish.

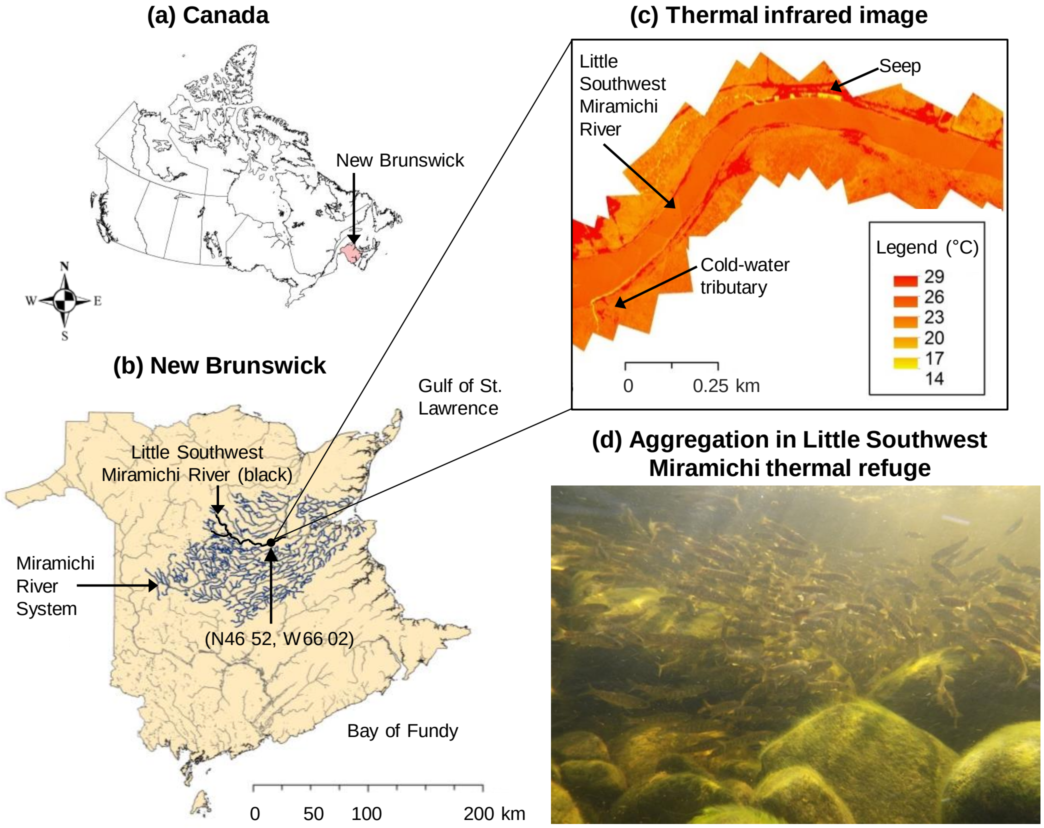

Figure 2. (a) Canada, (b) New Brunswick and the Miramichi River, (c) a thermal infrared image of a reach of the Little Southwest Miramichi River (two thermal anomalies, a groundwater seep and a cold-water tributary, are visible) and (d) juvenile Atlantic salmon aggregation in a thermal refuge within the Little Southwest Miramichi River.

3. Anthropogenic threats to existing thermal refugia

There are many potential mechanisms for increasing *ambient* water temperatures in streams and rivers. These threats have been addressed in previous studies and include climate change (van Vliet *et al*., 2011; Woo *et al*., 2012), river impoundments that release epilimnetic water (Lessard and Hayes, 2003; Risley *et al*., 2010), warm water return flows from power plants (Madden *et al*., 2013), paved surface runoff (Herb *et al*., 2008), and modified channel morphology (Poole and Berman, 2001). However, the processes that may impact groundwater-sourced thermal refugia, or more generally riverine thermal diversity, have received less attention in the literature.

The integrity of groundwater-sourced thermal refugia are subject to a number of human factors that may warm or reduce discrete groundwater discharge to streams and rivers, including (1) land use change (e.g., deforestation, Alexander *et al*., 2003; Caissie, 2006b; Moore *et al*., 2005), (2) aggregate extraction (*e.g*., sand and gravel pits, Markle and Schincariol, 2007), (3) groundwater extraction (Barlow and Leake, 2012; Risley *et al.*, 2010; Stark *et al.*, 1994), (4) flow manipulations (Curry *et al.*, 1996), and (5) atmospheric climate change (Deitchman and Loheide, 2012; Kurylyk *et al.*, 2014a, b; Taylor and Stefan, 2009).

Forest canopies influence ground surface and shallow groundwater temperatures through a variety of mechanisms including reduction of incoming solar radiation by shading, and altering convective exchanges between the lower atmosphere and ground surface (Bonan, 2008). Up-slope groundwater temperature, and consequently the temperature of groundwater-sourced thermal refugia, may increase in response to clear cutting regardless of the presence of a riverine forest buffer (Alexander *et al.*, 2003; Curry and Devito, 1996; Curry *et al*., 2002; Guenther *et al*., 2014; and Figure 3a,b).

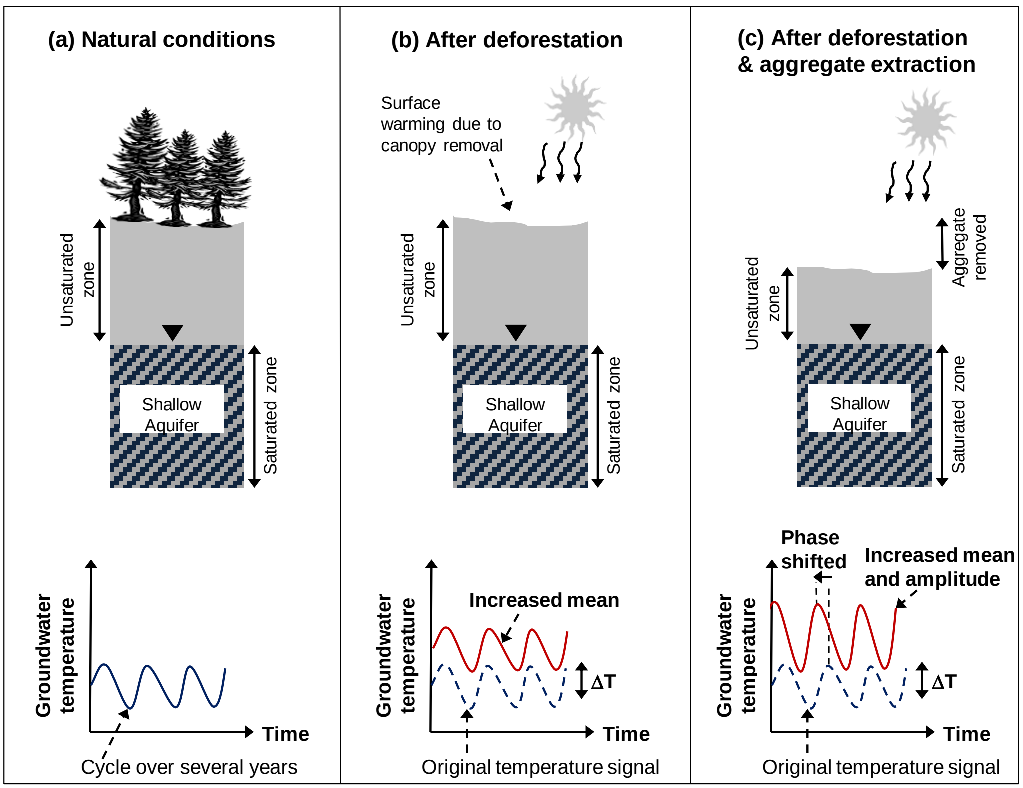

Figure 3. A depiction of the seasonal variability of shallow groundwater temperature for (a) natural conditions, (b) after deforestation, and (c) after deforestation and aggregate removal.

In the Miramichi River catchment, many glaciofluvial deposits form aquifers that provide cool groundwater discharge and are composed of coarse-grained soils that are valued for construction purposes. Aggregate extraction from a sand or gravel pit generally reduces the thickness of soil above the groundwater table. The heat capacity (thermal inertia) of the unsaturated zone causes the seasonal shallow groundwater temperature cycle to be lagged and attenuated with respect to the seasonal surface water temperature cycles and thus produces riverine thermal diversity at points of discrete groundwater discharge. Aggregate extraction may first increase the mean annual groundwater temperature due to initial deforestation (Figure 3b) and then enhance the amplitude of the seasonal groundwater temperature cycle by reducing the depth of overlying soil (Figure 3c). If the aggregate extraction produces pits that are below the groundwater table, water may pool above the sediment and absorb direct solar radiation, thereby altering the natural aquifer thermal regime. For example, Markle and Schincariol (2007) studied groundwater emanating from a site with aggregate extraction below the groundwater table and found that the amplitude of the groundwater temperature in a sand and gravel pit was 10°C higher than the temperature amplitude of up-gradient groundwater. Aggregate extraction may also reduce the lag in the seasonal groundwater temperature by decreasing the thickness of overlying soil (Figure 3c). Increases to the mean and amplitude of the seasonal groundwater discharge temperature cycle and decreases to the seasonal groundwater temperature lag will likely contribute to increases in groundwater discharge temperature during the summer months when refugia are critical (Kurylyk *et al*., 2014a).

Groundwater pumping creates a hydraulic perturbation in the subsurface thereby lowering the groundwater table near the pumping well and creating a so-called 'cone of depression' (Freeze and Cherry, 1979). The hydraulic capture zone of the well can intercept groundwater that would otherwise discharge to surface waters. In the case of diffusive groundwater discharge, groundwater pumping can result in reduced baseflow contributions to the river and a consequent rise in ambient river temperature, as groundwater generally cools summer river temperature (Risley *et al*., 2010). Furthermore, when a well is placed close to a river, or when the pumping rates exceed a critical value, wells can induce a hydraulic gradient from the river to the well and thereby extract surface water from normally gaining rivers (Barlow and Leake, 2012). Thus, excessive pumping can produce shallower rivers, which have been shown to experience a greater thermal sensitivity to radiation than deeper rivers (Caissie, 2006b). More importantly in the context of this paper, the source water for focused groundwater discharge points may be depleted due to groundwater pumping, resulting in a loss of critical salmonid refugia habitat.

Climate change is expected to warm groundwater (Gunawardhana and Kamaza, 2011; Kurylyk and MacQuarrie, 2014; Taylor and Stefan, 2009), and shallow aquifer warming would in turn increase the temperature of groundwater-sourced thermal refugia. Rising air temperatures are related to warming land surface temperatures due to their mutual dependence on solar radiation and due to altered convective exchanges between the lower atmosphere and the land surface (e.g., Bonan, 2008). As reviewed by Kurylyk *et al*. (2014b), the warming signal at the land surface is propagated through the subsurface via heat conduction and advection and increases shallow groundwater temperature. Kurylyk *et al.* (2014a) demonstrated that the lag between a future increase in air temperature and the subsequent rise in groundwater discharge temperature can be very short in shallow aquifers (< 5 years). Their simulation results also demonstrated that in seasonally snow-covered catchments, certain shallow aquifer morphologies may be more resilient to climate change than others.

4. Preserving existing cold-water refugia

Given the threats to refugia integrity noted above, it is imperative that water and land use managers begin to develop procedures for detecting existing thermal refugia (Section 3.1) and consequently limiting catchment activities that may induce refugia warming (Section 3.2).

4.1 Identifying and monitoring existing refugia

The spatial distribution of cold-water plumes that provide potential refuge during high water temperature events can be detected through a number of methods. *A priori* estimates of the distribution of thermal refugia may be obtained via GIS models that predict the occurrence of thermal refugia from geospatial landscape variables such as catchment slope, forest type, and wetland density (Monk *et al.*, 2013). More precise determination of riverine thermal anomalies have been obtained from thermal surveys with handheld thermometers (Ebersole *et al.*, 2003b), a distributed array of temperature loggers (Johnson *et al*., 2014), fiber optic distributed temperature surveys (Buck and Null, 2013), manned aerial infrared surveys (Dugdale *et al.*, 2013; Loheide and Gorelick, 2006; Torgersen *et al.*, 2001) or some combination of these techniques (Drake *et al.*, 2010). An infrequently employed approach that has potential for identifying thermal diversity in long river reaches is the thermal profile method (Vaccaro and Maloy, 2006) in which temperature probes at different depths in the water column are towed behind a watercraft. Finally, emerging drone technology can be employed to conduct inexpensive, unmanned aerial infrared surveys (Wawrzyniak *et al*., 2013).

The identification of thermal anomalies is the first step towards preserving existing cold-water refugia and identifying the candidate thermal anomalies that may be enhanced. If management is targeting protection of thermal refugia, then detected thermal anomalies should be monitored during high temperature events to ascertain if they function as biologically-significant thermal refugia. It should be noted, however, that the aggregation behaviour exhibited by juvenile salmonids is a complex phenomenon, and fish may not necessarily aggregate within a cold-water plume precisely at the species-specific temperature threshold reported in scientific literature (*e.g.*, Cunjak *et al*., 2005). Initial or temporary thermal relief can be found in shaded regions and possibly, within the hyporheic zone (Figure 1).

As an example, although the cold-water tributary shown in Figure 2c has been shown to function as an important thermal refuge in the past two decades, no salmonid aggregations were observed in this plume on 15 July 2013 when the mainstem river temperature reached 28.6°C (tributary temperature was only 20.0°C). This temperature drastically exceeds previously described ‘trigger temperatures’ for behavioural thermoregulation for juvenile Atlantic salmon in the Little Southwest Miramichi River (Breau *et al.*, 2007). Therefore, monitoring activities for thermal anomalies, if performed in single point in time, will likely underestimate the biological significance of a potential thermal refuge. It is possible that the water temperature that triggers aggregations for a particular species will vary with life-stage (e.g. Breau *et al*., 2007) and season (Cunjak and Power 1986) as well as be dependent on other factors such as food deprivation, physiological condition, and population (Emily Corey, unpublished data). Also, our observations in the Miramichi system suggest that, contrary to the refugia definition employed by Ebersole *et al.* (2003b), a temperature differential of ≤ 3°C between the mainstem and cold-water plume will induce certain fish to utilize thermal anomalies as refugia. Atlantic salmon parr readily utilize anomalies with smaller differentials (*e.g.*, 2°C) during extreme heat events (Emily Corey, Pers. Comm., 2014). Thus, knowledge of species-dependent minimum temperature differentials that invoke use of refugia are key to successful identification and management of thermal refugia.

4.2 Preventative land use management strategies

Proactive land use management strategies can be employed to prevent or mitigate a decrease in the distribution of suitable thermal refugia due to the anthropogenic factors discussed above. Techniques for the preservation of groundwater-sourced refugia could include limiting land use change, groundwater pumping, and aggregate extraction within critical (sub)catchments. However, due to ongoing demands for timber and aggregate resources, it is extremely unlikely that every thermal refuge will be protected via stricter land-use management. Consequently, a hierarchy should be established to prioritize refuge morphologies or locations (Torgersen *et al.*, 2012). Such a prioritized hierarchy should consider the species present and the distribution of refugia within a catchment. For example, juvenile salmonids have limited, albeit poorly understood, capabilities to disperse during physiologically demanding high water temperature conditions (Breau et al., 2011) which limits their capacity to find suitable thermal refugia at distance.

The hierarchy must also consider refuge potential today and for future climate conditions. The resilience or sensitivity of thermal refugia to climate change is a relatively unstudied phenomenon (e.g., Daigle *et al*., 2014; Deitchman and Loheide, 2012), particularly for groundwater-sourced refugia. Previous studies have suggested that the thermal impact of future climate change must be considered in habitat restoration activities (*e.g.,* Beechie *et al.*, 2013) but these studies have focused primarily on ambient water temperature rather than thermal refugia. In lieu of hydrogeological thermal modeling, the thermal damping factor (ratio of the amplitude of the seasonal groundwater discharge temperature cycle to the amplitude of the seasonal air or surface temperature cycle) for groundwater discharge can be utilized to infer a first-order estimate of the thermal sensitivity of that refuge to climate change. For example, Kurylyk *et al.* (2014a) found that an aquifer with a thermal damping factor of 0.7 exhibited a thermal sensitivity (ratio of the multi-decadal change in summer groundwater discharge temperature to the multi-decadal change in summer air temperature) of approximately 0.95, whereas an aquifer with a thermal damping factor of 0.2 exhibited a thermal sensitivity of only 0.60. It should be noted that these disparate thermal sensitivities arise due to simulated complex snowpack evolution dynamics in a warming climate (Kurylyk *et al.*, 2013), and thus the relationship between the measured thermal damping factor and aquifer thermal sensitivity may only be valid in catchments that are expected to experience a reduction in the thickness and duration of winter snowpack. More research is required to establish an improved understanding of how atmospheric climate change may influence surface/subsurface thermal dynamics and to develop effective thermal refugia management strategies (Kanno *et al*., 2013).

5. Augmenting existing thermal anomalies

In certain locations where thermal anomalies are not functioning as refugia, their conditions may be improved through application of ecological and hydraulic principles.

5.1 Enhancing the spatial extent or preserving the temperature of cold-water plumes

The potential for an existing thermal anomaly to provide thermal refuge may be potentially increased by enhancing the thermal difference between the cold-water plume and the river mainstem. The spatial extent and temperature of cold-water plumes are primarily controlled by thermal mixing due to the mainstem channel flow (Fischer *et al.*, 1979; Tanaka, 2007). Advective thermal mixing is limited along the river bank due to increased shear stress (Fischer *et al.*, 1979). The influence of shear stress on the spatial extent of thermal anomalies is evidenced by the fact that cold-water plumes can extend along river banks for significant distances downstream of the point of cold-water input (*e.g.*, cold-water tributary plume, Figure 2c). Thus, the spatial extent can be increased and the temperature of cold-water refugia may be preserved by limiting hydraulic and thermal mixing between the cold-water plume and the river mainstem. A channel deflector constructed of boulders or other material is presented in Figure 4 as one option for physical manipulation and control of flow. However, fluvial geomorphological principles should be employed to design any such channel modifications, because the installation of channel deflectors can lead to scouring problems and bank erosion, particularly when the deflector is submerged at high flow (Biron *et al*., 2004; Rodrigue-Gervais *et al.* 2011). In addition, river ice may damage the designed deflectors in seasonal latitudes (Biron *et al*., 2005), and thus it may be beneficial to design easily removable, temporary deflectors. Hydrodynamic thermal mixing models, such as CORMIX3 (Jones *et al.*, 1996) can be employed to model the temperature dynamics of thermal refugia (Gendron, 2013) and evaluate the impact of changing deflector lengths and angles on the spatial extent of the cold-water plume.

While thermal refugia may be enhanced by temporary physical structures such as deflectors, it is important to consider potential ecological uncertainties introduced by such installations. Our unpublished data on stream salmonids suggest that the juvenile fish seek thermal refuge during high temperature events by progressing up- or downstream along the river edges until finding a suitable refuge. We do not yet understand how temporary physical structures may influence the ability of salmonids to seek and find thermal refugia.

Increasing or creating riparian shading is another mechanism to increase the spatial extent of existing cold-water plumes. This manipulation may be facilitated by an understanding of river flow regimes. Prolonged high temperature events occur in the summer when river levels are typically low, the near-shore zone of the river is exposed to solar radiation, and the cooling influence of natural riparian shading is reduced. Thus artificial shading may be installed to

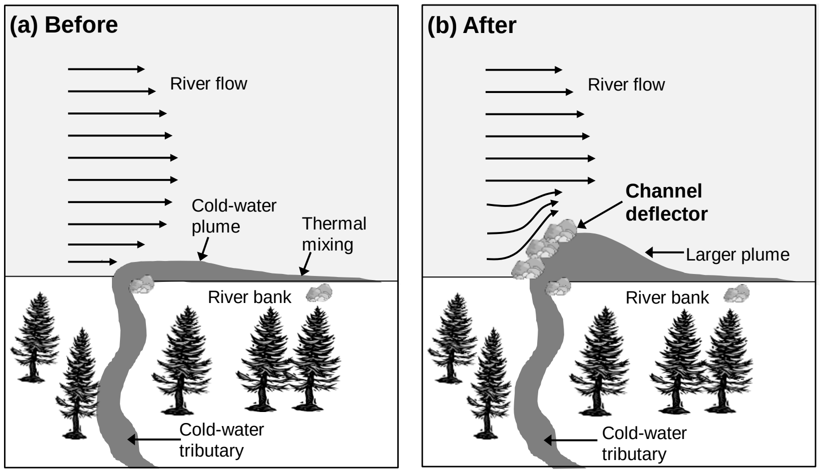

Figure 4. A cold-water plume at the mouth of a tributary before (a) and after (b) installation of a channel deflector to limit advective thermal mixing (adapted from Bilby, 1984).

further decrease the temperature of existing thermal anomalies. For example, Ebersole *et al.* (2003b) installed experimental shade covers and observed a subsequent 2-4°C decrease in the daily maximum temperature of cold-water plumes. The effectiveness of installing artificial shading will, of course, depend on the ability of shade to influence a specific in-stream temperature regime (Ebersole *et al*., 2003b).

5.2 Enhancing the cover of cold-water plumes

Salmonids may be threatened by avian predators when aggregating in refugia (Keefer *et al.*, 2009). The enhanced shading described previously is one potential method for decreasing predator risk during aggregation. Also, the installation of appropriately sized substrate on the bed of the thermal refuge can enable salmonids to be concealed (Bradford and Higgins, 2001) and may explain why Wilbur (2012) found that juvenile Atlantic salmon parr avoided thermal anomalies with substratum finer than sand, instead preferring substrate sizes ranging from sand to boulder. However, gregarious behaviour can be triggered by high water temperatures (Breau *et al*., 2007) when aggregations of juveniles form within the water column (Figure 2d). The exact cause for such behaviour is not clear but may be related to the physiological burden imposed by anaerobic metabolism during thermal stress (Breau *et al*., 2011).

A broken water surface has also been postulated as a source of overhead cover for the protection of juvenile salmon from avian predators (Heggenes, 1991), and Atlantic salmon have been shown to exhibit a preference for refugia with higher velocities and a broken water surface (Wilbur, 2012). In the Little Southwest Miramichi River, the cold plumes not occupied by juvenile Atlantic salmon during extreme heat stress events in July 2010 (ambient river water temperature > 30°C) were typically shallow, slow moving pockets of cold water. Fish were observed in equally shallow parts of the refuge, where the broken water surface was sufficient to obscure a clear vision to the river bottom. The water surface can be disturbed via the installation of large boulders that extend beyond the water surface during the low flow period, although such measures will still require a minimum velocity to induce a broken water surface (e.g., Lacey and Roy, 2008). Another example of a structure to reduce the potential effect of avian predation on refugia aggregations is an array of wires installed above the water surface. These have been used downstream of hydropower dams (Jones *et al.*, 1999) and may provide additional protection from predators. This temporary structure may be most effective in shallow floodplain thermal refugia where flow may have a lesser impact on the structure itself. In this case, the stakes and wires would be protected from minor increases in river stage, and it would be difficult for swimming birds or mammals to dive under the array.

6. Creating new thermal refugia

Many river reaches lack thermal diversity and thus cannot provide suitable thermal refugia for cold-water fish species. One example is the lower reach of the Fraser River (British Columbia), where significant mortalities of sockeye salmon were reported as a result of thermal stress (Martins *et al.*, 2011). In some situations, it may be feasible to create the thermal diversity necessary to produce useful thermal refugia to limit stress-induced mortalities. A critical unknown to be determined prior to utilizing these, possible costly, solutions is the spatial frequency at which thermal refugia are needed for different target species, *e.g.*, a linear distance which various fish species are capable of moving under physiologically stressful conditions to seek cold-water refugia.

6.1 Inducing thermal anomalies via groundwater pumping

Natural groundwater discharge is a source of cool water during the summer period when surface waters are at their annual temperature maxima (Figure 1). Inducing points of focused groundwater discharge may be a viable mechanism by which to create new thermal refugia. This could be achieved by pumping groundwater from upslope locations in adjacent aquifers to a discharge point along the river (Figure 5). Pumping and immediately discharging the cold, intercepted groundwater to the river will not significantly change the total groundwater input to the river. Rather, it will transform groundwater discharge from a diffusive input that slightly cools the ambient river temperature to a focused input that significantly cools a smaller plume and thus creates a cold-water refuge (Figures 5b, 5c). A proposed design for an automated system is presented in Figure 5 in which a solar panel provides energy to power the pump, and the pumping is triggered by a signal from a water temperature sensor programmed to a species-specific temperature threshold, *i.e.*, the refuge is created only when it is most urgently needed. In most cases, the high-capacity pump selected for this application would require a battery array charged by the solar panel(s) to provide the required voltage and power. In some cases, these refugia could be developed at locations where wells have already been drilled to pump groundwater to the river to exceed low flow criteria during the dry season (e.g., Foster and van Steenbergen, 2011).

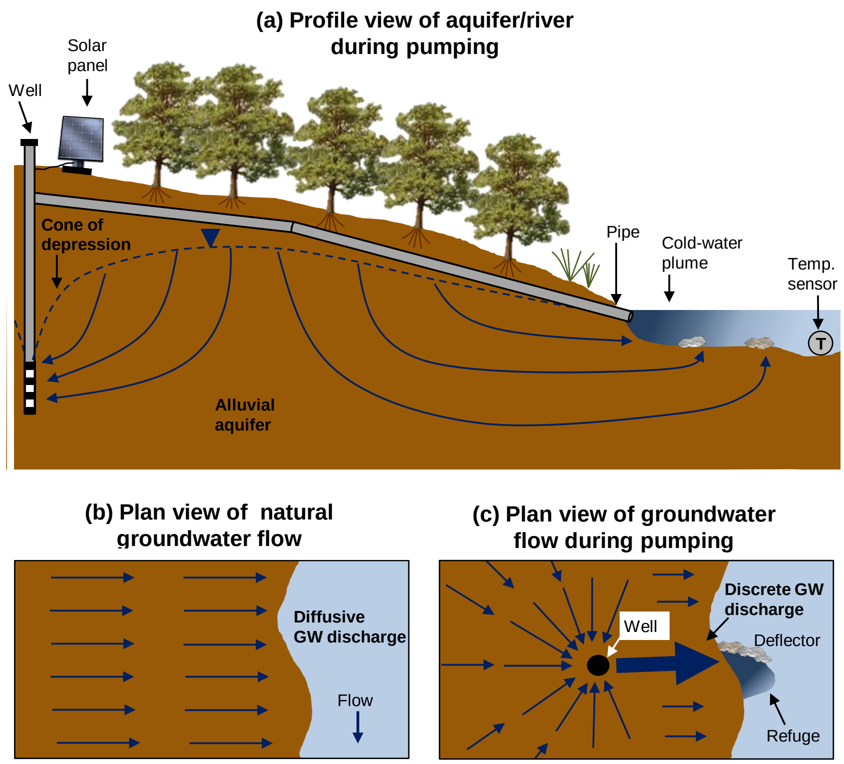

Figure 5. (a) Conceptual model for creating a temporary thermal refuge by pumping water from alluvial aquifers and discharging the groundwater at a discrete point. The groundwater pumping and redirection to the river transforms the groundwater discharge to the river from a (b) diffusive input to a (c) discrete input.

Extensive well drilling should be preceded by in-depth, local hydrogeological analyses, including pumping tests and aquifer characterization, to avoid potential hydrogeological issues and to maximize the ecological function of the created thermal anomalies. Wells placed close to a river may reverse the natural flow direction from the aquifer to the river and thus draw warm water from the river. This situation can be avoided by drilling a well a sufficient distance from the river and limiting pumping rates and durations. Once site hydrogeological information has been obtained, quantitative tools can be employed to analyse potential interactions between pumping rates, pumping durations, well spacing from the river, and river depletion. One option, STRMDEPL08 (Streamflow Depletion Version 8, Reeves, 2008), computes results from different analytical solutions designed to simulate river or stream depletion (i.e., the combined effects of a reduction in river discharge by either extracting water directly from the river or intercepting groundwater flow that would otherwise discharge to the river) due to aquifer pumping. The simplest solution applies in the case of an aquifer with no excess riverbed hydraulic resistance and with a river depth that fully penetrates the aquifer (Jenkins, 1968). More details on the conceptual models and the hydrogeological assumptions employed for each of these solutions can be found in Reeves (2008).

Figure 6 presents results for a simple illustrative example that demonstrate the application of STRMDEPL08 to investigate the influence of the well distance and pumping duration on river flow depletion using the simple solution by Jenkins (1968). In all these cases, a pumping rate of 20 L·s^{-1} was assumed as this is a reasonable well yield for a highly permeable aquifer and is close to the lowest discharge recorded in the refuge-generating tributary shown in Figure 2c. Two pumping scenarios are presented to demonstrate how pumping only during the 12 hours of the day when surface water is warmest (Figure 6b) can reduce river depletion in comparison to continuous pumping (Figure 6a). Figure 6 also indicates that increasing the distance between the well and the river from 100 m to 250 m reduces the rate of river depletion and that wells spaced further from the river are not as sensitive to high frequency (*e.g.*, daily) pumping rate variability. Analyses such as these must be conducted on a site-specific basis with knowledge of local hydrogeology and the biological implications of aquifer pumping.

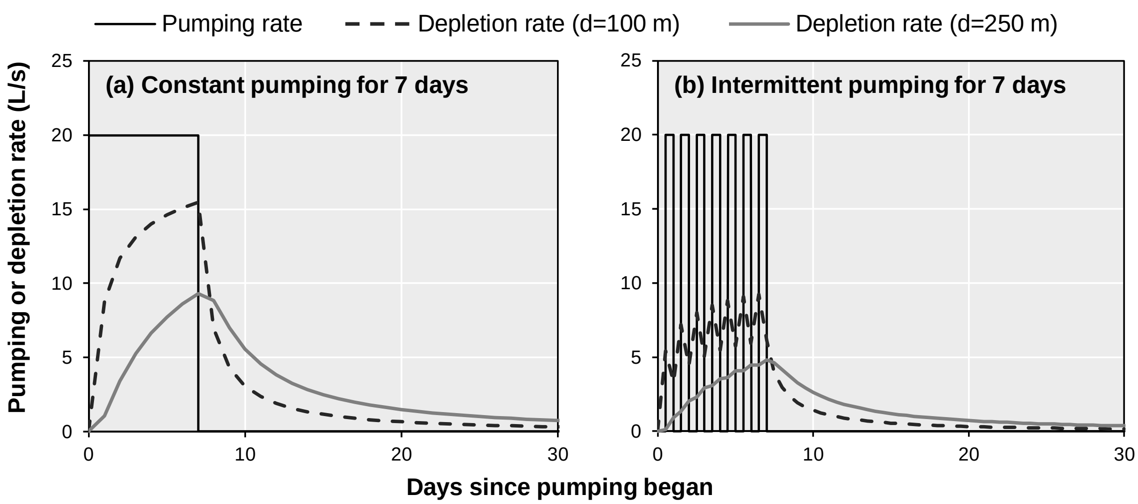

Figure 6. River depletion (i.e., combined effects of groundwater flow interception and, if applicable, river water extraction) due to the pumping of wells a radial distance of 100 or 250 m from the river for the case of (a) constant pumping for 7 days and (b) intermittent pumping (12 hours on and 12 hours off) for seven days. The curves were generated with a superimposed version of Jenkins (1968) solution via STRMDEPL08 (Reeves, 2008) with unconfined alluvial aquifer properties (transmissivity = 0.03 m^2·s^{-1} and specific yield = 0.3) taken from Kurylyk *et al*. (2014a).

6.2 Inducing thermal anomalies via hyporheic exchange

Many rivers may also have thermal diversity restored or enhanced by the installation of in-stream geomorphic structures that initiate hyporheic exchange (Briggs *et al*., 2012; Gordon *et al*., 2013; Menichino and Hester, 2014). Hyporheic exchange has been shown to both reduce diel water temperature fluctuations (*i.e*., reduce the daily maximum ambient water temperature) and create thermal anomalies (Acuña and Tockner, 2008; Hester *et al*., 2009; Hester and Gooseff, 2010). However, the ability of these structures to create thermal anomalies pronounced enough to provide significant thermal refugia has, to our knowledge, not been reported. The temperature difference induced by an in-stream structure would depend on the residence time and rate of the hyporheic flow.

7. Thermal refugia management strategy

The concepts proposed in this study are presented within the comprehensive thermal refugia management strategy shown in Figure 7. The flowchart progresses from thermal refuge identification (A) to augmentation or creation (B) and preservation (C). This differs from the framework proposed by Torgersen *et al*. (2012) who considered thermal refuge identification and preservation in more detail than in the present study but did not address refugia creation and only briefly considered restoration or augmentation.

Each of the sections within this thermal refugia management framework (Figure 7) offers future research opportunities. For example, emerging drone technology (Figure 7.A) provides researchers and managers an affordable alternative to flying manned aerial infrared surveys. However, few studies have utilized this technology for identifying thermal refugia in large river systems. Also, few, if any, field studies have been conducted to assess the viability of the concepts proposed in Figure 7.B for augmenting existing thermal anomalies (e.g., installing channel deflectors to limit mixing and larger substrate to provide cover) or creating new refugia via groundwater pumping and focused discharge. Finally, long term studies should be initiated to assess the influence of preservation activities (Figure 7.C) on the thermal diversity of selected stream and river reaches in comparison to nearby reaches that have not been targeted for thermal diversity preservation.

8. Conclusions

Cold-water fish are threatened by rising water temperatures caused by many factors, including catchment deforestation, aggregate and groundwater extraction, river impoundments, and atmospheric climate change. There appears to be increasing public awareness of the threat that rising river temperatures pose to salmonid and other cold-water fish populations in North America (*e.g.*, Hume, 2011) and a willingness to invest public money to combat this threat (*e.g.*, Gardner Pinfold Consultants Inc., 2011). This provides the impetus to develop simple cost-effective strategies to preserve and enhance cold-water thermal refugia at the southern margins of cold-water fish distributions. We have presented a thermal refugia management strategy that proposes several approaches for preserving, augmenting and creating thermal refugia, and we recommend that proof-of-concept field studies be conducted to assess the viability of the ideas presented herein. These concepts are proposed for the Miramichi River, but they should also be relevant to many other unregulated, alluvial channel rivers that are inhabited by cold-water salmonids.

These concepts may work most effectively when applied in concert with one another. For example, a cold-water refuge created by inducing focused groundwater discharge may be most effective when coupled with a channel deflector, enhanced riparian zone shading, and appropriately sized substrate. Further research should investigate the costs and benefits that may be achieved by implementing one or more of the approaches proposed herein and how the

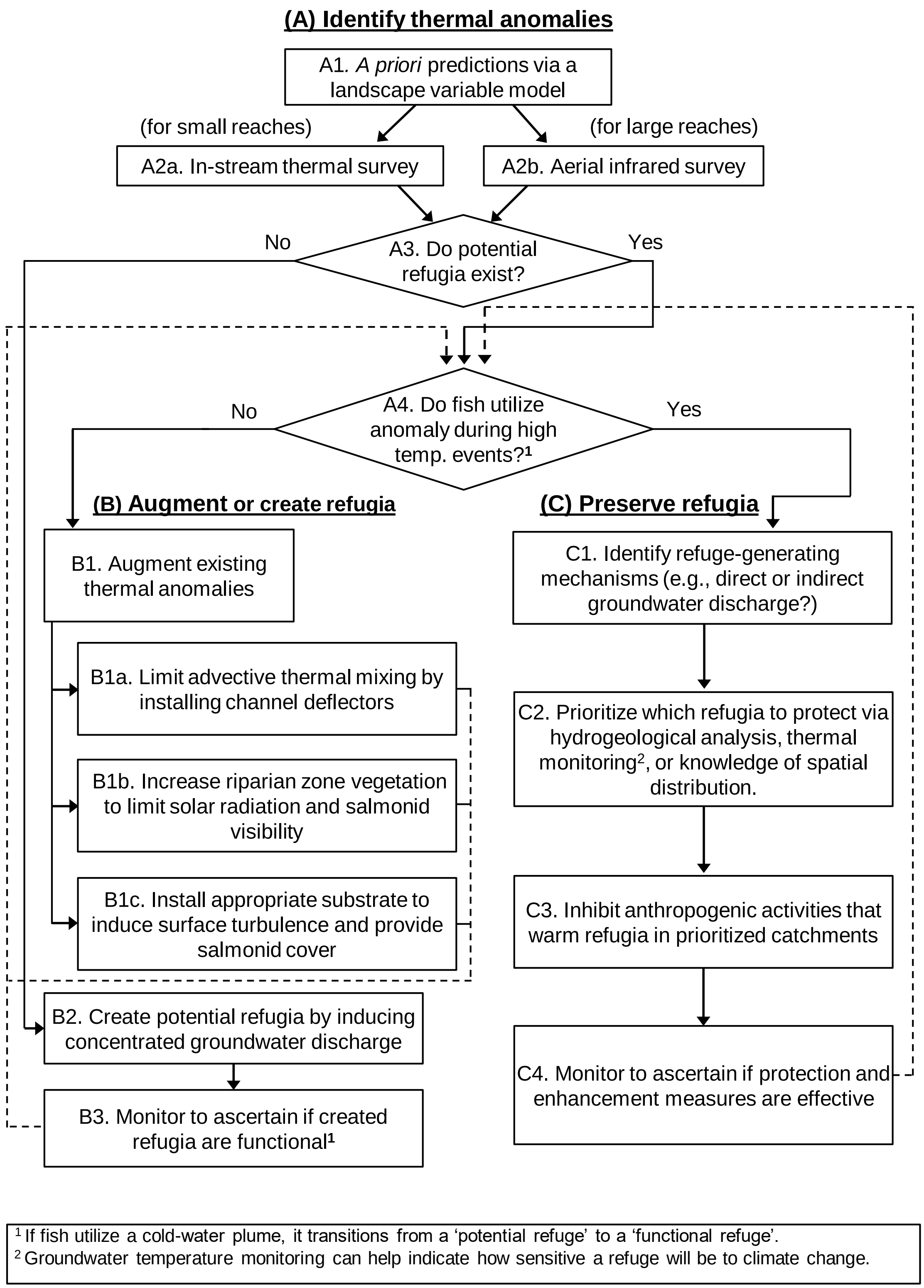

Figure 7. Comprehensive thermal refugia management strategy that includes (a) identifying, (b) augmenting/creating, and (c) preserving (natural and engineered) thermal refugia.

specific site conditions (water depth, refugia morphology, and climate) may dictate the most appropriate measure for a particular location. Ideally such studies should investigate whether (1) augmenting existing thermal anomalies leads to larger or more frequent fish aggregations during high water temperature events and/or (2) creating new thermal anomalies results in biologically significant fish habitats that are utilized when ambient river temperatures exceed specific thresholds. Finally, naturally occurring or engineered thermal refugia should be protected to prevent exploitation from recreational or aboriginal fisheries or other anthropogenic activities.

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