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Pumping Groundwater to Create Cold-Water Thermal Refuges in Warming Rivers

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ABSTRACT

Thermal refuges in rivers and streams provide critical habitat for cold-water species during periods of thermal stress. In this study, we created a new cold-water thermal refuge by pumping cool groundwater to a warm coastal river in Nova Scotia, Canada. Thermal infrared imagery revealed a notable thermal plume, measuring approximately 55 m^2 at the water surface during low-flow conditions, with mixing limited by the installation of a flow deflector. Above-water and underwater cameras recorded several fish utilizing the created cold-water plume during periods of high ambient river temperatures (up to 30°C). Thermal numerical modelling was conducted to interpret the field data and assess the impact of alternative designs and conditions. Model results revealed that the extent of the created thermal plume substantially increased (+202%) with the use of a deflector and that the plume size was controlled by several factors including the river flow rate and temperature, the pumping rate and the groundwater temperature. The study findings demonstrate the efficacy of creating cold-water habitat in the face of a warming climate and lay the foundation for future proactive thermal management strategies aimed at maintaining thermal diversity in warming rivers.

1 | Introduction

Rivers are warming globally, which is driving loss and fragmentation of cold-water habitat (Isaak et al. 2017) and eliciting interest in proactive thermal management in rivers. River water temperatures strongly influence the physiological processes and distribution of poikilotherms (Bowen et al. 2020; Breau, Cunjak, and Peake 2011; Morash et al. 2020). High summer water temperatures have begun to reach or exceed optimal temperature thresholds for cold-water organisms in many rivers throughout North America (e.g., Isaak et al. 2012; Linnansaari et al. 2023). Accordingly, summer heat waves are already causing fish mortalities (e.g., Garrabou et al. 2022), and projected river warming trends (Caldwell et al. 2015; Isaak et al. 2017; Liu et al. 2020) will likely exacerbate present-day riverine thermal challenges.

When water temperatures exceed the upper temperature thresholds for cold-water fish that behaviourally thermoregulate, they will seek out thermal refuges to alleviate thermal stress (e.g., Breau, Cunjak, and Bremset 2007; Frechette et al. 2018; Goetz and Quinn 2019; Wilbur et al. 2020). In the context of high summer temperatures, Sullivan et al. (2021) defined a thermal refuge as a discrete patch or plume that has (1) a notable thermal offset with the main river of ≥ 2°C and (2) at least one cold-water organism preferentially occupying it during periods of thermal stress. It should be noted that cold-water fish are capable of detecting temperature differences of < 1°C, but we use a 2°C offset as the thermal refuge threshold in line with this recent thermal refuge typology (Sullivan et al. 2021) and the US Environmental Protection Agency primer (Torgersen, Ebersole, and Keenan 2012). Cold-water refuges often naturally occur due to inflows from cooler tributaries and groundwater discharge (e.g., Dugdale et al. 2018; Fullerton et al. 2018; Kurylyk et al. 2015) and can be further cooled by riparian shading (e.g., Ebersole, Liss, and Frissell 2003). These refuges promote resilient aquatic ecosystems that can withstand both short-term heat waves and potentially long-term climate warming (Fullerton et al. 2018; Ouellet et al. 2020), although the relative warming rate of thermal refuges compared with rivers remains poorly understood (Kurylyk, MacQuarrie, and Voss 2014). There is increased interest in mapping thermal refuges and understanding how aquatic species utilize them, with common tools being remote sensing (e.g., Dugdale, Bergeron, and St-Hilaire 2015; Selwood, Cunninham, and Mac Nally 2019) and acoustic telemetry (e.g., Frechette et al. 2018; Keefer, Peery, and High 2009). Different fish species and life stages have distinct temperature thresholds that trigger aggregations in thermal refuges. For example, Wilbur et al. (2020) showed that brook trout exclusively occupied cold-water plumes for mainstem temperatures > 21°C, whereas Atlantic salmon parr began to aggregate when mainstem temperatures exceeded 25°C and exclusively occupied refuges when temperatures were > 27°C.

Given the loss or fragmentation of cold-water habitat and associated deleterious impacts on cold-water biodiversity (Hahlbeck et al. 2023), researchers have called for a holistic management approach to aid in the mapping and protection of thermal refuges (Linnansaari et al. 2023; Mejia et al. 2023). Habitat distribution modelling has indicated that added policies and management actions geared towards protecting cold-water refuges may increase the likelihood of Pacific salmonid persistence in a warming world (Snyder et al. 2022). Likewise, simulations of varying levels of refuge availability in four warming rivers indicated that pools cooled by groundwater can allow salmonid populations to persist under substantial warming (Railsback and Harvey 2023). Unfortunately, such thermal refuge mapping or modelling projects may not be useful in thermally homogeneous rivers that do not have the thermal 'patchiness' that generates thermal refuges. In general, understanding present thermal refuge distribution and preserving, augmenting, and creating new thermal refuges are topics that have gained more attention recently because of river warming (Kurylyk et al. 2015; Steel et al. 2017).

Enhancing or creating thermal refuges through anthropogenic means may be considered 'ecological renovation' (Prober et al. 2018) rather than ecological restoration. Despite the considerable interest of local watershed groups in thermal refuge mapping, only a few studies have attempted to enhance existing thermal refuges (e.g., OWE Board and EM Soil 2021), and we are not aware of any peer-reviewed studies documenting the creation of new thermal refuges. The overall goal of this study was to create a new thermal refuge that cold-water fish could utilize during periods of thermal stress. This was attempted by pumping cool groundwater directly to a warm river with minor in-stream channel modifications. Field monitoring was conducted using aerial thermal infrared (TIR) imagery, temperature and water level loggers, and above-water and underwater visual cameras. We also used a numerical model of coupled hydrodynamic and thermal dynamics to interpret the field data and assess the impact of alternative designs and conditions.

2 | Materials and Methods

2.1 | Study Site

This study was conducted in Rights River (drainage area 27.2 km^2), one of three main tributaries that feed into Antigonish Harbour along the north shore of Nova Scotia, Canada (Figure 1). This area primarily consists of forests, farmland and rural residential properties, with the lower river reaches (~5 km) running through the northern portion of the town of Antigonish. The Rights River ecosystem is productive and has known populations of sea trout (*Salmo trutta trutta*) and Atlantic salmon (*Salmo salar*; Antigonish Rivers Association 2022), which has a long documented history of cold-water refuge use in Nova Scotia (Huntsman 1942).

The Antigonish region experiences a modified-continental climate with total annual precipitation of 1315 mm and mean annual and mean summer (June–August) air temperatures of 6.8°C and 16.9°C, respectively for 1981–2010 (ECCC 2024). The study site overlies a surficial alluvial aquifer (MacPherson and Peters 1972; Stea et al. 2006), with the deeper bedrock geology in the Windsor Group with Lime-Kiln Brook, Churchville and Hood Island formations (Keppie 2000).

The Municipality of the County of Antigonish has a groundwater abstraction and treatment facility within 25 m of Rights River (Figure 1). The facility is used as a backup town water supply during summer droughts. The facility consists of two wells that were drilled in 1993 within a surficial aquifer (Table 1; well logs in supplement, Figure S1) and pumps with control and monitoring systems. Well 1 (45.6297°, −61.9977°) has a diameter of 203 mm, total depth of 17.7 mbgs, casing depth of 0–12.5 and 15.5–17.7 mbgs and screened interval from 12.5 to 15.5 mbgs. Well 2 (45.6293°, −61.9962°) has a diameter of 203 mm, screened interval from 10.7 to 13.9 mbgs and total depth and casing depth of 19.7 mbgs. The wells undergo quarterly water quality monitoring to ensure the water meets drinking water guidelines. The water is pumped from the edge of the facility for a 2-week duration during quarterly testing, and the well discharge runs off into the river during this time. The facility has an approved watercourse withdrawal in place for a safe yield of 32 m^3 h^{-1}. The pumped groundwater has an effectively constant temperature year-round of ~9.5°C (range of 9°C°C–10°C), as would be expected at these depths for this region (Smith et al. 2023).

2.2 | Study Period

There was sufficient precipitation during summer 2023 to sustain the primary water supply for Antigonish. Therefore, the backup water supply was not needed during this period, and the well was available for pumping to the river. Accordingly, in summer 2023, we conducted two separate studies to increase the chance of having measurements coincident with heat waves when cold-water organisms are most likely to rely

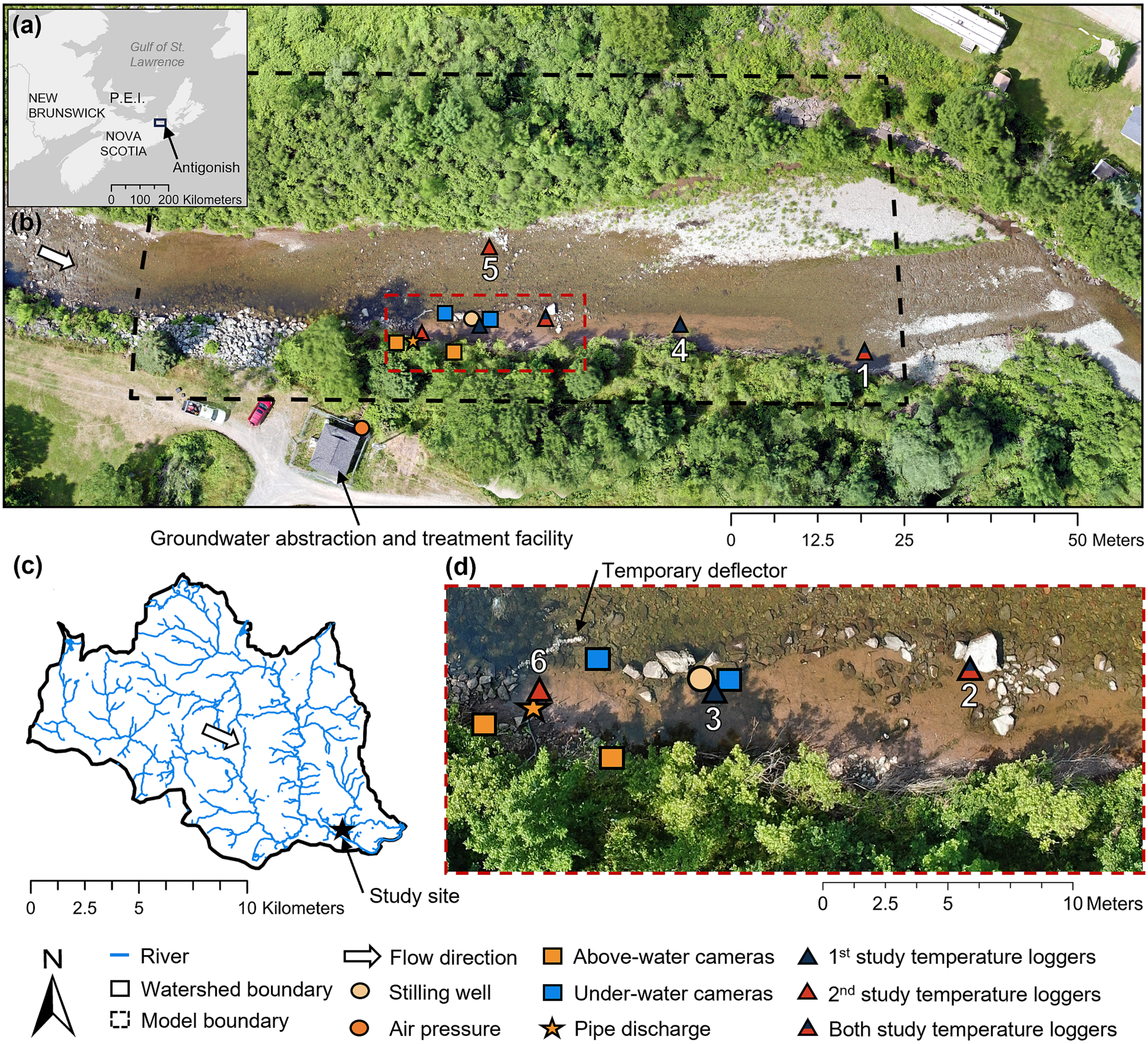

FIGURE 1 | (a) Location of Antigonish in Nova Scotia and Atlantic Canada. (b) Locations of the groundwater abstraction and treatment facility, temperature loggers, stilling well, above-water and underwater cameras, and air pressure logger. (c) Watershed boundary of Rights River. (d) Zoomed-in section of the pipe discharge location.

on thermal refuges. The first study took place during a warm period that began on July 11 and lasted 14 days. Groundwater was discharged via a hose from the facility to the river at a constant flow rate of $32\,m^3\,h^{-1}$ and temperature of 9°C°C–10°C. The second study began on August 14 and lasted 5 days. For the second study, groundwater was discharged at a constant flow rate of $25\,m^3\,h^{-1}$ and temperature of 9°C°C–10°C. Groundwater temperatures presented herein were recorded in the well or groundwater abstraction facility because these data were continuously available for both study periods. However, the temperature of the groundwater discharging from the hose to the river recorded during the second study period indicated only minimum heating (0.5°C) along the hose due to exposure to sunlight. For both studies, a temporary flow deflector (Figure 1d) (Kurylyk et al. 2015) was constructed in the river channel with large rocks to minimize the immediate thermal mixing of the generated cold-water plume with the warm river mainstem.

2.3 | In Situ Loggers and Monitoring

A total of eight and four HOBO® TidbiT MX2203 temperature loggers were installed during the first and second study periods, respectively. Water temperature loggers were placed along the streambed at the pipe outlet and within and outside of the created thermal refuge to record the thermal contrast and cold-water plume extent (Figure 1b,d). On July 22, there was a flash flood during the first study period (Figure 3b) that resulted in several loggers being lost. Therefore, some logger locations were adjusted slightly during the second study period to ensure they were adequately secured. A stilling well

TABLE 1 | Model simulations and conditions.

Run ID	Groundwater temperature (°C)	Groundwater discharge ($m^3 h^{-1}$)	Upstream river discharge ($m^3 h^{-1}$)	Deflector? (Yes/No)
1	9.5	32	1800	Yes
2	9.5	32	1800	No
3	9.5	16	1800	Yes
4	15	32	1800	Yes
5	15	16	1800	Yes
6	9.5	32	10,800	Yes

with a Solinst Levelogger® 5 water level logger was installed just downstream of the thermal refuge at the same location for both studies (Figure 1b,c) to yield a river stage time series. A Solinst Barologger® 5 pressure transducer was attached to the groundwater abstraction and treatment facility to record air pressure to correct the stilling well pressure readings. All loggers recorded data in 15-min intervals. Above-water and underwater cameras were installed facing the thermal refuge to record fish utilizing the thermal refuge. Above-water cameras recorded images every 30 min, whereas underwater cameras recorded images every 10 min. Hourly air temperature, air pressure, relative humidity, wind speed and precipitation data were recorded at a nearby Environment and Climate Change Canada weather station (< 20 km; Climate ID 8201001; ECCC 2023). Stream gauging was conducted twice per study period using an acoustic Doppler velocimeter (SonTek Flow Tracker2).

2.4 | Drone TIR Imaging

TIR imaging was conducted periodically throughout both study periods to detect thermal anomalies at the water surface. A preprogrammed flight spanning the entire study area at an elevation of approximately 42 m and with 90% front and side image overlap was flown during the first study period on Friday, July 14 at 2:30 PM (shown later in Figure 5). During this time, TIR imagery were collected with and without the groundwater being discharged to the river from the groundwater abstraction and treatment facility (i.e., the pump turned off and on). Additionally, a TIR video was recorded to investigate the early thermal plume dynamics once the pump was turned on in the well. Because of aircraft restrictions in the area associated with a nearby airport, a specially licensed drone operator was contracted to operate the drone for the preprogrammed flight on Friday, July 14. Also, a handheld device was built to affix the drone in the air and capture additional TIR images from a static position. TIR imagery was collected using the DJI Matrice 300 RTK drone equipped with a visual and uncooled thermal camera (Zenmuse H20T) with a pixel resolution of 640 × 512, focal length of 13.5 mm and wavelength of 8–14 μm (DJI 2020). Given issues associated with thermal drift in drone-mounted TIR sensors (Dugdale et al. 2019), we only use the TIR imagery to assess the cold-water plume geometry and dynamics based on the *relative* temperatures of the plume versus the ambient river.

2.5 | Thermal and Hydrodynamic Numerical Modelling

Numerical modelling of water flow and temperature was conducted to interpret the field data and assess the impact of alternative conditions for creating cold-water thermal refuges. The coupled hydrodynamic and thermal dynamic simulations were performed in MIKE 21/3 coupled FM (DHI 2023a, 2023b). This model uses a flexible mesh approach with a cell-centred finite volume method to solve the incompressible Reynolds-averaged Navier–Stokes equation invoking the assumptions of Boussinesq and hydrostatic pressure (DHI 2023b). The temperature module considers vertical heat transfer via an energy balance at the water surface and longitudinal heat transfer due to advection and dispersion. The MIKE 21/3 coupled FM model is a widely applied model for both hydrodynamic and temperature modelling (e.g., Ranjbar, Etemad-Shahidi, and Kamranzad 2020; Sokolova et al. 2013). Further details on the well-established governing equations can be found in MIKE 21 and MIKE 3 flow model hydrodynamic and transport module scientific documentation (DHI 2017).

The numerical model domain spans approximately 120 m in length (along channel) and 50 m in width (Figure 2). The cross-channel dimension includes the river channel and floodplain, whereas the along-channel model domain extent was selected to surpass the downstream extent of the cold-water plume observed in the TIR imagery as discussed in Section 3.1. The computational mesh for Rights River was created in MIKE using 347 differential GPS (DGPS) points taken within the study region using an Emlid Reach RS2 (Budapest, Hungary, 5- and 10-mm horizontal and vertical accuracies, respectively) connected to a real-time kinetic network (HxGN SmartNet). Several channel-submerged cross-sections were measured, and LiDAR point cloud data (Government of Nova Scotia 2024) were used to extend the model domain to include the floodplain. The horizontal domain used an unstructured triangular mesh, and the vertical domain consisted of a structured mesh (equidistant containing three layers). As the study area was small, a dense mesh was created with the total number of elements and nodes respectively 32,802 and 16,688.

Boundary conditions were specified for the 3D hydrodynamic model (Figure 2b). The sides and bottom boundaries were set as no-flow conditions, the upstream boundary was a specified flux based on flow measurements during the stable flow (pre-flood)

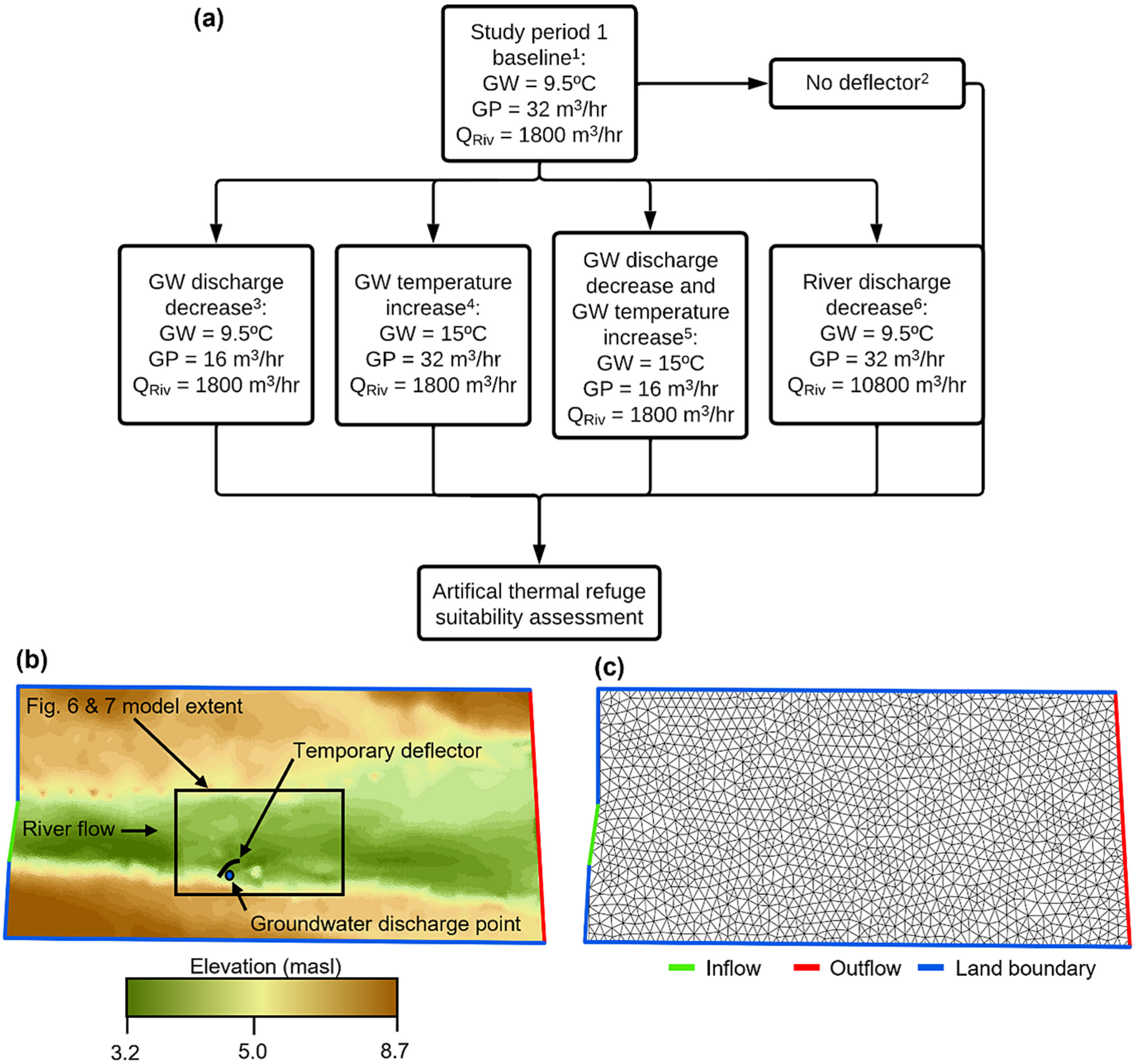

FIGURE 2 | (a) Flow chart of model simulations with superscript numbers referring to model run numbers described in Table 1. (b) Elevation of study area (based on LiDAR data for floodplain and DGPS points for channel) with the groundwater discharge point and temporary deflector location in the field and model. (c) Boundary conditions and model mesh for visual purposes only as the actual mesh was denser (Section 2.5). Figure 1b presents the model domain extent overlaid on aerial imagery. GW = groundwater, GP = groundwater pumping rate, Q_{Riv} = Upper boundary river discharge rate.

period, and the downstream boundary was set to free flow. The temperature module in MIKE 21/3 was used with water density specified as a standard function of temperature (DHI 2023a). Recorded water temperature data were used for the inflow boundary. The temperature module considers vertical heat exchange at the water surface via latent heat, sensible heat, short-wave radiation and long-wave radiation (DHI 2023b). Atmospheric heat fluxes were computed based on standard MIKE 21/3 algorithms (DHI 2023a) and required air temperature and relative humidity as inputs. These were obtained via the nearest ECCC climate station (ID: 8201001). A clearness coefficient of 70% and a constant roughness height of 0.05 m were specified for initial model runs, with other parameters set to the model default values (see Table S1).

The pumped groundwater discharge was specified as a constant discharge and temperature source in the model (Figure 2b), in line with temperature and flow measurements available directly from the groundwater abstraction and treatment facility flow meters and temperature sensors. The 'dike structure', available as a MIKE FM structure (DHI 2023b), was incorporated in the model to function as the flow deflector constructed in the field (Figure 2b). The deflector geometry was developed from DGPS points collected along the deflector during its installation.

To assess the influence of different river and groundwater conditions on the thermal plume size, six thermal numerical scenarios were computed using the model with different upstream, groundwater source (flow, temperature) and deflector conditions (Table 1 and Figure 2a).

Model Runs 1 and 2 used baseline data with and without the deflector, respectively, to consider how the deflector influences the thermal mixing of the river and the discharged groundwater; all runs other than Run 2 included the deflector (Table 1). A decrease in groundwater discharge (half of baseline data) was used to simulate a reduction in the well yield (Run 3). Run 4 used baseline data with an increase in groundwater temperature to simulate groundwater temperatures sourced from a different aquifer depth and associated seasonal thermal signal (e.g., Kurylyk, MacQuarrie, and Voss 2014). A run with a paired reduction in groundwater discharge and an increase in groundwater temperature was simulated to assess combined effects (Run 5). Finally, an increase in the upper river boundary discharge to $3\,m^3\,s^{-1}$ (sixfold increase) was used to assess the impact of high flows and associated hydrodynamic mixing on the thermal plume extent (Run 6).

Each model was simulated with 15-s timesteps for the period with the highest water temperatures (July 14 at 9 AM to July 18 at 10 PM). A spin-up period of 4 h was selected for each model with initial water temperatures of 20°C. The DHI MatLab Toolbox (Version 19.0.0; DHI 2021) was modified to calculate the 3D thermal plume extent for the time steps on July 14 at 5:15 PM and July 18 at 5:45 PM for all model simulations, with the modified code accounting for 3D plume calculations, and included in the Supporting Information (see Data Availability Statement). These two times were chosen because of observations of fish aggregations during these periods. Thermal data were interpolated over the mesh grid based on average temperature from cell centres. A reference point upstream of the groundwater discharge location was selected to represent the ambient river water temperature. Following Sullivan et al. (2021), the modelled thermal plume was classified as nodes with water temperatures that were > 2°C colder than the reference water temperature.

2.6 | Thermal Advection due to Groundwater Inflows

Advective thermal inflows due to mass inflows (e.g., pumped groundwater) are conveyed to the downstream end of the model domain and increase the advective thermal outflows. Accordingly, here, we calculate the 'apparent heat advection', which accounts for both the mass/heat inflow and the mass/heat outflow downstream and thus yields the net warming (positive net advection) or cooling (negative net advection) effect of the groundwater inflows on the model domain (Kurylyk, Moore, and MacQuarrie 2016):

$$H_{gw} = c_w \rho_w Q_{gw} \left(T_{gw} - T_{amb} \right) \tag{1}$$

where H_{gw} is the apparent (or net) heat advection due to groundwater inflow (Watts), $c_w \rho_w$ is the volumetric heat capacity of water ($4.186 \times 10^6\,J\,m^{-3}\,°C^{-1}$), Q_{gw} is the groundwater discharge inflow rate ($m^3\,s^{-1}$), T_{gw} is the groundwater inflow temperature (°C) and T_{amb} is the ambient river temperature (°C), herein taken as the upstream boundary temperature. This equation yields the apparent heat inflow at a point (the pipe mouth). Rather than calculate a full energy balance, which is already resolved in the model, we compare the apparent heat advection (Watts) due to groundwater pumping (Equation 1) to the downwelling solar radiation across the river surface area in the model domain ($1485\,m^2$), as downwelling solar radiation is typically the dominant heat flux during a summer day (e.g., Leach et al. 2023). Given the lack of radiation data measured at a local climate station, we extracted radiation data at this location from the gridded radiation dataset from NASA Power (2024).

3 | Results

3.1 | In Situ Flow and Temperature Measurements and Fish Presence

3.1.1 | First Study Period (11–24 July 2023)

The second warmest day of 2023 occurred during the first study period on July 14th with local air temperatures reaching 30.4°C (Figure 3a). However, a heavy rainfall event also occurred during the first study period (on July 22nd), with 113 mm of precipitation over a 24-h period (Figure 2a). Water levels prior to the rainfall event were consistently between 0.40 and 0.43 m and increased to a maximum of 2.1 m during and following the heavy rain (Figure 2b). Because of lost temperature loggers during the flood event, water temperature time series recorded within the created thermal plume were not available for the first study period. However, water temperature data were available outside of the plume during the first study period, and the groundwater abstraction and treatment facility recorded values between 9°C and 10°C for the groundwater that was pumped into the river. Excluding water temperature data during the flood as all loggers were thermally uniform during this period (Figure 3d), the minimum, average and maximum river water temperatures were 17.6°C, 22.3°C and 30.8°C, respectively, for the first study period. The thermal difference between the maximum water temperatures recorded by a logger (1A; Figure 1b) and the constant groundwater discharge temperature (10°C) was calculated and yielded minimum and maximum thermal differences of 9.7°C and 20.8°C, respectively (Figure 3d,e).

For this study, we define a fish aggregation in the thermal refuge as the presence of ≥ 5 fish. Fish aggregations were observed throughout the study period, with an increased number of fish (fry and parr) captured with above-water and underwater cameras during warm periods on July 13th, 14th, 15th and 18th. Several fry (> 20) of an unidentified species aggregated in the cold-water plume on July 13 (maximum mainstem water temperatures of 27.2°C). Images of fry and parr (> 20) of suspected Atlantic salmon (*S. salar*) or brown trout (*S. trutta*) were captured periodically on July 14 and during the entire day on July 15 via underwater cameras (Figure 4a). The fry was observed to stay near the discharge point, whereas the parr tended to occupy the middle of the created plume. An adult brown trout was identified at approximately 2:30 PM on July 14 near the back of the thermal plume and was not recorded via underwater cameras (Figure 4d).

Water temperatures reached a daily maximum of 28.9°C (at 4:15 PM) on July 14th, exceeding the critical thermal threshold for cold-water species such as brown trout and Atlantic salmon. On July 16, onset aggregation temperatures of 27.5°C were found for a brown trout or Atlantic salmon (unidentified) parr. A single white lake chub (*Couesius plumbeus*) occupied the thermal refuge from 11:50 AM to sunset on July 15 and was in the same location the following morning at 5:20 AM where it stayed at least for the remainder of the day. A site investigation on July 18 revealed an aggregation of white lake chub (> 20) occupying the outer limits of the thermal refuge outside of the underwater cameras' fields of view (Figure 4b). During the first study period, additional fish were observed

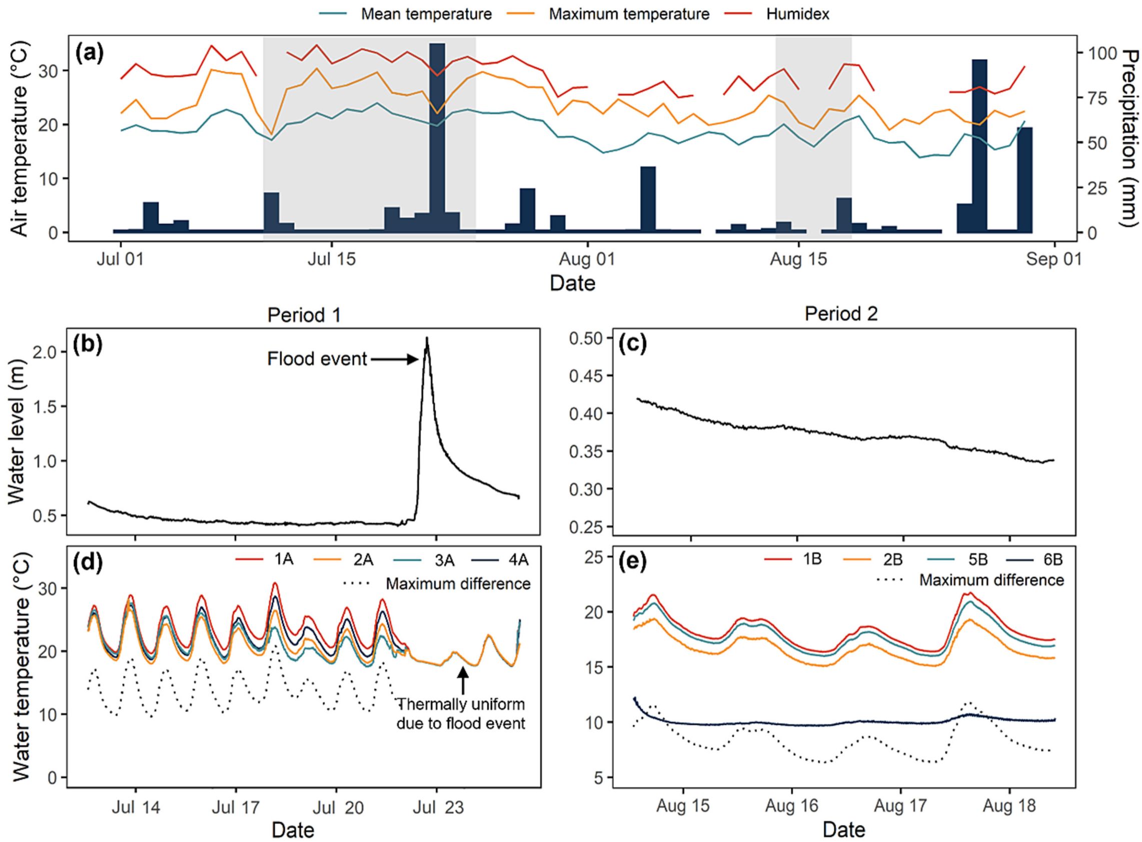

FIGURE 3 | (a) Daily air temperature and precipitation recorded from the Collegeville Auto weather station (45.4912°, −62.0150°; ECCC 2023) (grey bands indicate Study Periods 1 and 2). Water level during (b) Study Period 1 and (c) Study Period 2. Measured water temperatures during (d) Study Period 1 and (e) Study Period 2. The maximum difference indicates the offset between groundwater and the highest river temperatures at any point in time. 'A' refers to the first study period, and 'B' refers to the second study period. Numbers correspond to logger locations shown in Figure 1.

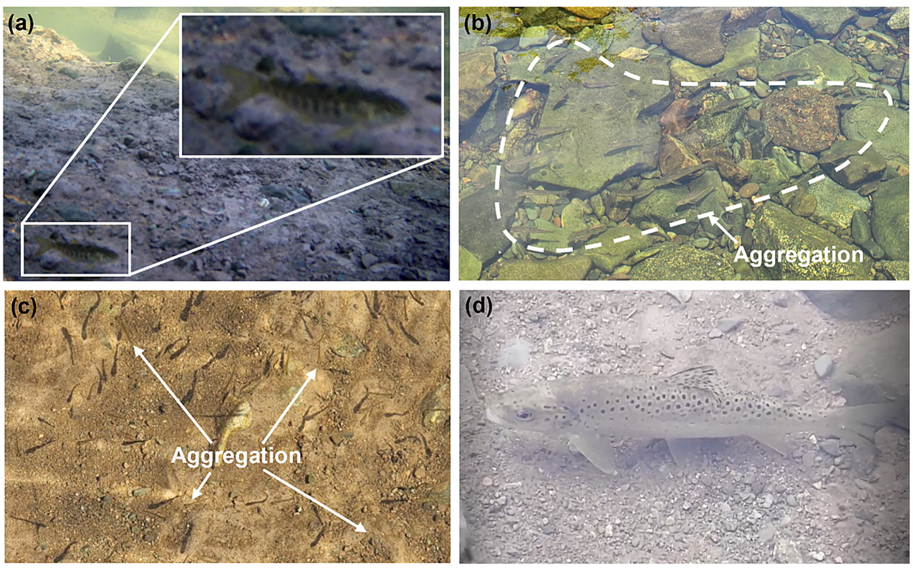

FIGURE 4 | (a–d) Underwater visual images of fish within the created thermal refuge recorded during the first study period (11–24 July 2023). Images are described in the text.

aggregating near the groundwater discharge point (fry) and near the middle of the thermal refuge (parr) as water temperatures reached the study maximum of 30.9°C. The final onset of thermal refuge occupation occurred on July 21 when water temperatures were 28.3°C.

3.1.2 | Second Study Period (14–18 August 2023)

Two of the four water temperature loggers were moved to ensure they were not lost during the second study period (Figure 1). The water temperature loggers (excluding Logger 6 in the cold-water plume; see Figure 1) recorded minimum, average and maximum river water temperatures of 15.1°C, 17.7°C and 21.8°C, respectively. In the cold-water plume near the groundwater discharge outlet (Logger 6), the minimum, average and maximum water temperatures were 9.7°C, 10.1°C and 12.4°C, close to the groundwater temperature monitored in the groundwater abstraction and treatment facility (9°C°C–10°C). The minimum and maximum thermal difference between Logger 1B (maximum water temperatures recorded by a logger) and groundwater (10°C) was 6.4°C and 11.8°C. There was only one underwater camera installed during the second study due to one camera being lost in the earlier flood. Despite lower water temperatures compared with the first period, fish (~6 parr) were observed sheltering near rocks towards the back of the thermal refuge throughout the entire second study period. Because of the distance from the camera and image quality, the species could not be identified.

3.2 | Drone TIR Imaging

TIR imagery delineated the thermal anomalies associated with the created thermal refuge extent, with an estimated surface area of 55 m^2 (Figure 5). The TIR video revealed the thermal plume dynamics when the groundwater pump turned on (see Video S1) and revealed that cool groundwater discharge was redirected off the deflector, reaching the outer limits before creating eddies that forced the discharged groundwater to the south bank. Because of several punctures in the hose pumping groundwater to the river, leaks were detected near the facility and south bank, with and without groundwater pumping (Figure 5e,f). Thermal anomalies were also apparent because of groundwater seepage on the north bank, but field investigation revealed that the small plume was likely too shallow for fish to occupy (< 10 cm in depth; Figure 5b).

3.3 | Thermal Numerical Modelling

Root mean squared error (RMSE), Nash–Sutcliffe efficiency (NSE) and the coefficient of determination (R^2) were calculated to determine the model performance. RMSE, NSE and R^2 were calculated to be 0.49–0.51, 0.96–0.97 and 0.96–0.97, respectively, indicating that the model performed well at simulating water temperatures within the model domain (Figure 6). Two times—July 14 at 5:15 PM and July 18 at 5:45 PM—were selected for further investigation of model results due to observed fish aggregations during these times. To investigate the role of the deflector in limiting immediate thermal mixing, velocity magnitude and direction results from Model Runs 1 and 2 were simulated (Figure 7). With the use of a deflector, the velocity magnitude decreased within the groundwater discharge zone from 0.12 to 0.04 m s^{-1}, which limited mixing and enabled the plume to persist over a larger area (Figure 7a). Additionally, the position of the pre-existing rock near the groundwater discharge location (Figure 7) allows the plume size to extend further downstream and provides aggregating fish protection from river currents and avian predation. The utility of the deflector was further evident in the plan view of simulated river temperatures (Figure 8a,b), for which there was an increase in the thermal plume extent.

To quantify the influence of the different model conditions (i.e., deflector presence or absence, groundwater inflow rate and temperature, and river flow rate and temperature) on the simulated plume sizes, calculated 3D plume volumes at the times of aggregations (July 14 at 5:15 PM and July 18 at 5:45 PM) are presented in Table 2 for each model run. Results from run 1 yielded the largest thermal plume (10.25–10.98 m^3; Table 2) due to the high rates of groundwater discharge (32 m^3 h^{-1}), low groundwater temperatures (9.5°C) and use of a deflector. This

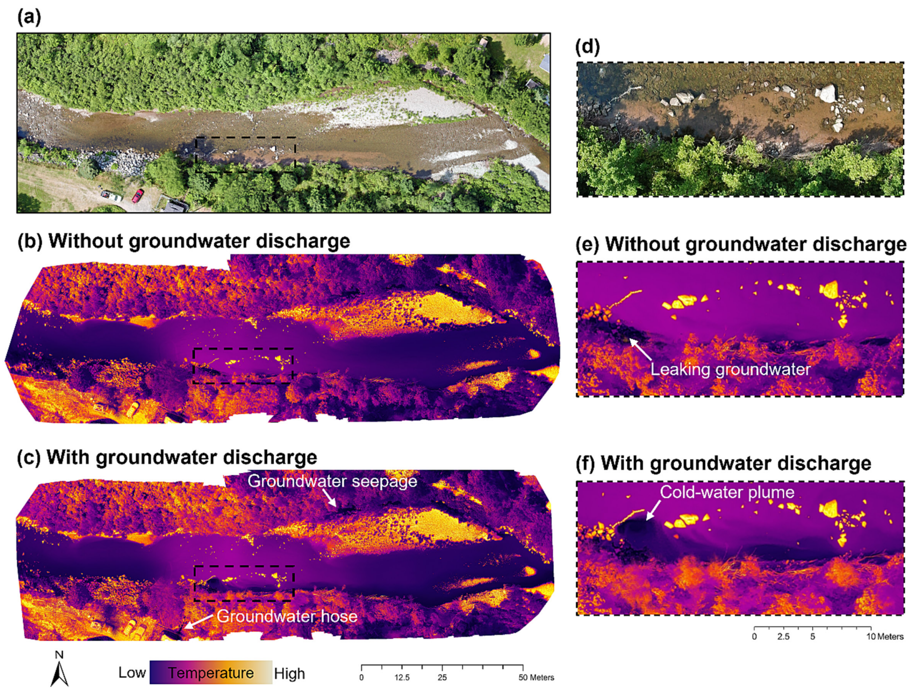

FIGURE 5 | Visual imagery (a) and thermal infrared imagery without (b) and with (c) groundwater pumping. Panels (d–f) are zoomed-in sections of the created thermal refuge extent corresponding to panels (a–c). Both flights were conducted within minutes of each other on July 14 at approximately 2:30 PM.

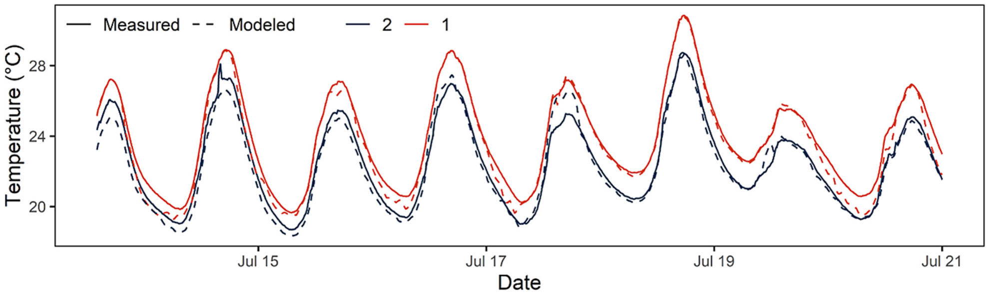

FIGURE 6 | Measured and modelled water temperature during the first study period at Logger Locations 1 and 2 (see Figure 1).

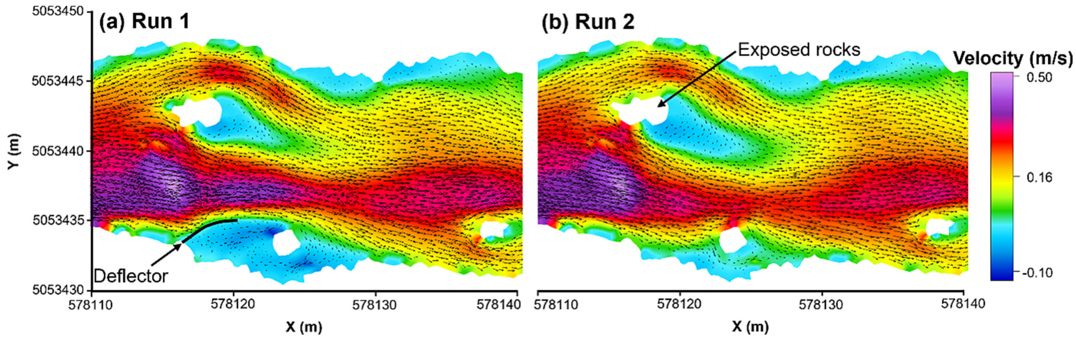

FIGURE 7 | Velocity magnitude and direction (vectors) of the top layer for Model Runs 1 (a) and 2 (b) on 18 July 2023, at 5:45 PM with the highest recorded water temperature.

combination also resulted in vertical thermal stratification within the plume, with denser, cooler water near the streambed (Figure 9a). In contrast, when the deflector was not included in the model domain, the thermal plume experienced a 62% to 67% decrease in volume (Figure 8b and Table 2) because of thermal mixing between the warm ambient river water and cool groundwater (Figure 9b). Despite the low groundwater temperatures (9.5°C) in Model Runs 1, 2, 3 and 6, a decrease in groundwater discharge decreased the thermal plume extent in these simulations (run ID: 3; Figures 8 and 9c and Table 2). The greatest decrease in the thermal plume volume occurred for Run 5, which had lower groundwater discharge and higher groundwater temperature (Figures 8e and 9c and Table 2), expectedly indicating that both factors strongly influence the thermal refuge spatial extent.

3.4 | Calculated Heat Fluxes

The net advective heat flux (Equation 1) based on the measured thermal difference between the groundwater and ambient river (Figure 3d,e), the groundwater pumping rate and the heat capacity of water was calculated to be on average −5.37E5 Watts for 13–21 July 2023. This is larger but of a similar magnitude to the integrated solar radiation across the water surface of the model domain (+3.20E5 Watts) during this period. These results indicate that although solar radiation tends to dominate the energy budget of long reaches of streams and rivers (Webb and Zhang 1999), the net heat advection due to focused groundwater inflows can dominate the heat budget locally, enabling the groundwater discharge to generate a pronounced thermal anomaly.

4 | Discussion

4.1 | Engineered Thermal Refuge Performance

Although thermal management is still a relatively new topic in aquatic science and management (Mejia et al. 2023; Ouellet et al. 2020), past approaches for thermal management in rivers include riparian vegetation (e.g., Dugdale, Malcolm, and Hannah 2024; Ebersole, Liss, and Frissell 2003), habitat restoration for fish passage (e.g., Lavelle et al. 2021), thermal refuge enhancement (e.g., ASF 2024) and controlled release of impounded river water (Null, Ligare, and Viers 2013). The goal of this research was to present an innovative thermal management approach via pumping cool groundwater to a river to *create* a thermal refuge during the summer. The goal was to not cool the *entire* river reach but rather to impose thermal complexity to sustain ecosystem diversity. Our approach was successful in creating an adequate thermal refuge (approximately 10 m^3 plume ≥ 2°C colder than the ambient river) that cold-water fishes utilized during periods of thermal stress. Specifically, we captured several aggregations of Atlantic salmon or brown trout, as well as white lake chub. Fish aggregations commonly occurred at water temperatures > 27°C during the first study period. However, thermal occupancy was exhibited at much lower temperatures during the second study period in August (~21°C). Our findings are generally in alignment with other studies (Morgan and O'Sullivan 2022; O'Sullivan et al. 2023) that have shown that temperature thresholds that trigger aggregations are highly variable and depend on factors such as antecedent temperature conditions, species, age and river system. Similar to other studies (e.g., Frechette et al. 2018), cold-water fish were observed occupying

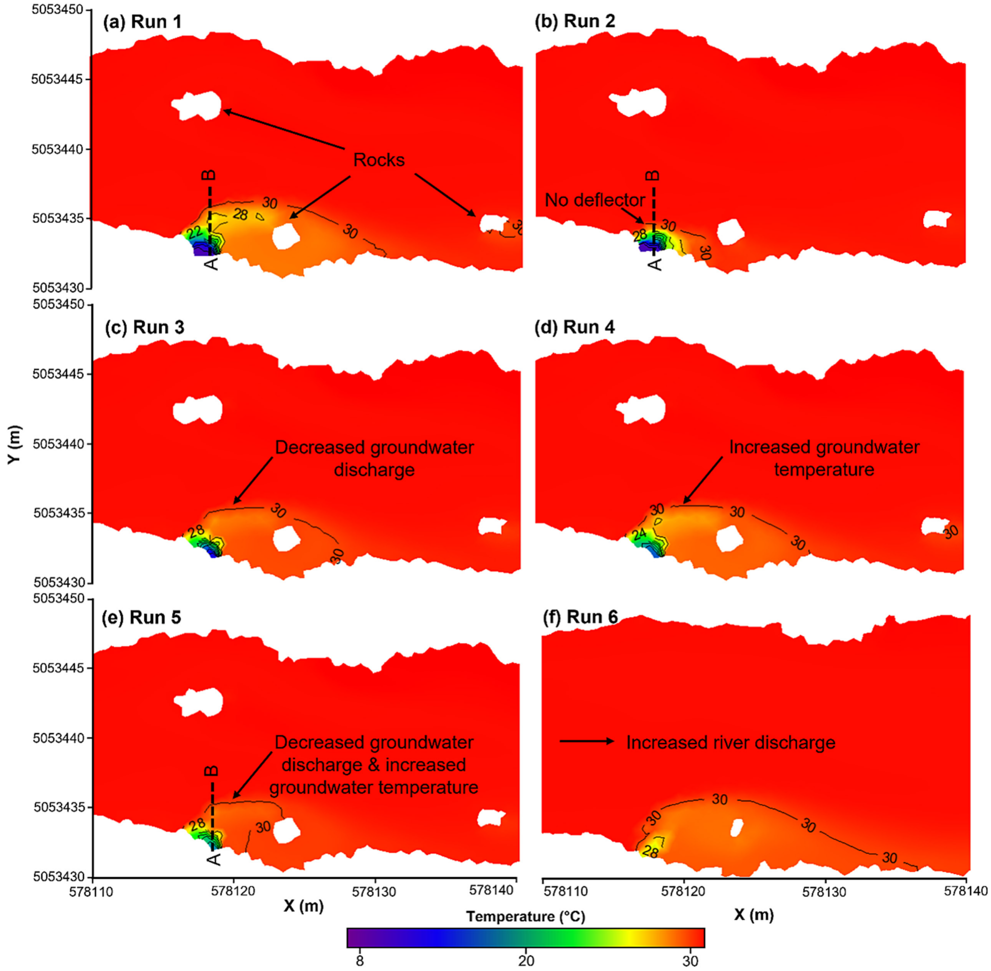

FIGURE 8 | Plan view of surface water temperatures for each model run in Table 1 (Panels a–f) for 18 July 2023, at 5:45 PM. Black lines in each pane represent isolines to highlight the plume spatial extent. Outer isolines represent 30°C and decrease by 2°C in the direction to the groundwater discharge point. Figure 2b shows the location in the model domain.

TABLE 2 | Calculated thermal plume volume for each model run and percentage difference compared with baseline (run ID 1) for July 14 at 4:15 PM and July 18 at 5:45 PM (peak water temperatures).

	July 14 at 5:15 PM			July 18 at 5:45 PM		
Run ID	Ambient river water temperature (°C)	Calculated volume (m^3)[a]	% Difference than baseline	Ambient river water temperature (°C)[a]	Calculated volume (m^3)	% Difference than baseline
1	28.9	10.25	—	30.8	10.98	—
2		3.40	−67		4.22	−62
3		4.22	−59		4.62	−58
4		6.82	−33		7.77	−29
5		2.43	−76		2.77	−75
6		3.54	−65		4.63	−58

[a]The temperature threshold for the thermal plume was different on July 14 and 18 because the plume was defined as areas ≥ 2°C colder than the mainstem, and the mainstem temperatures differed for these dates.

the thermal refuge predominantly during the afternoon, when the ambient river temperatures were highest.

We acknowledge that the aggregations observed in this study are small compared with those reported in some natural thermal refuges (e.g., Linnansaari et al. 2023; O'Sullivan et al. 2023). However, in many rivers in the Canadian Maritimes, large aggregations only occur every few years when temperatures rise above typical annual maxima, and many of those well-studied systems have a higher density of cold-water fish than Rights

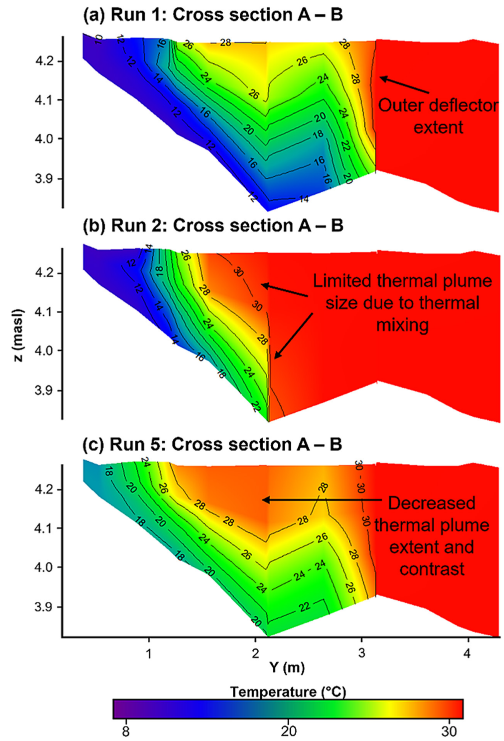

FIGURE 9 | Cross-section profile of A–B (shown in Figure 8a,b,e) for Model Runs (a) 1, (b) 2 and (c) 5 on 18 July 2023, at 5:45 PM.

River. Further studies at this location or others could be conducted with more intensive fish monitoring (e.g., more cameras or tagging) to help reveal how engineered systems compare to large, natural thermal refuges in terms of fish presence and dynamics. Other water quality parameters such as dissolved oxygen are important factors for fish that vary among thermal refuge sources, and further water quality monitoring may yield insight into the effectiveness of the created thermal refuge in providing suitable habitat for cold-water fish when other quality indicators are considered.

Although the present study demonstrated the potential for pumped groundwater to create a cold-water refuge, the high pumping rates may not be sustainable for extended periods, at least for certain aquifers (Hiscock and Bense 2021, 598–599). This could cause groundwater levels to 'drawdown' beneath desired thresholds and deplete the aquifer, at least locally. To ensure groundwater is abstracted sustainably, instead of continuously pumping throughout the summer, targeted, intermittent pumping during high-temperature events could be conducted as previously proposed (Kurylyk et al. 2015). Information regarding resident aquatic species and their associated thermal tolerances, along with continual aquifer and river monitoring (levels and temperatures) and known locations of existing thermal refuges would allow water managers the tools to implement a groundwater pumping program that generates thermal refuge(s) when specific criteria are met. The effectiveness of such a program may benefit from monitoring the ability of cold-water fishes to locate and utilize temporary thermal refuges during periods of thermal stress. Related, but more reactive, thermal management approaches are already adopted in many rivers by limiting angling when certain temperatures are exceeded (DFO 2019).

4.2 | Numerical Modelling of Thermal Refuges

Thermal refuges have been well-studied in natural settings, but very few process-based numerical models of river hydrodynamic and thermal dynamics have been conducted for refuges. Such models are useful tools to investigate the effect of 'what if' scenarios and design alternatives (e.g., groundwater inflow rates and temperatures and presence/absence of deflector). Herein, we focused on delineating the modelled thermal plume sizes, with plume volume estimates ranging from 2.43 to 10.98 m^3. With a deflector, smaller plumes resulted from decreased groundwater discharge and increased groundwater temperatures, with decreased discharge being the principal driver of decreased plume size. Two locations (1 and 2 in Figure 1b,d) with in-field water temperature data were selected to assess the baseline model performance (run ID 1). Calculated model performance parameters indicated strong model performance in predicting water temperatures within the model domain. This is expected given the local dominance of heat advection (Section 3.4), which was imposed as an internal sink in the model domain. Therefore, the precise algorithms selected for the surface heat fluxes would likely have little influence on the simulated plume sizes in this study. Also, because the atmospheric heat fluxes were applied across the entire wetted domain (including the refuge), minor changes to the computed atmospheric heat fluxes would not greatly impact the delineated size of the cold-water plume as the size was defined based on the *difference* ($\geq 2°$) from the ambient river temperatures. Additionally, the spatial river temperature patterns predicated by the model using baseline data showed strong agreement with TIR imagery captured during the study period. Although outside the scope of our study, future modelling could investigate the impact of deflector lengths and angles on the spatial extent of the thermal refuge and velocity profiles (e.g., Gendron 2013).

4.3 | Study Limitations and Future Opportunities

The field components of this study were limited by several factors. First, the time periods during which we could pump from the backup water supply were limited by the municipal water needs and by the flood that disturbed our experimental setup during the first study periods. The safe well yield was high ($32\,m^3h^{-1}$) and thus enabled the creation of an adequate thermal plume that cold-water fishes occupied. In other regions (e.g., Thielman 2020), it may be difficult to pump groundwater at a similar rate, as a relatively high-capacity well (such as the municipal water supply in this study) is required. However, many rivers have productive alluvial or glaciofluvial aquifers that could be pumped at a high rate (Weight and Sonderegger 2004, 217). Although the focus of our study was to monitor water temperatures and fish response, future work should consider dissolved oxygen, fish density, turbidity, predation risk and other factors that influence the functionality of a thermal refuge (Thorstad et al. 2008). Also, it is likely that the above-water and underwater cameras did not capture all fish that occupied the created thermal refuge during both study periods, and more extensive visual (camera) monitoring or fish tagging could help improve fish tracking. Nonetheless, this study provides a foundation for future research, including opportunities related to fish behaviour (e.g., how and when fish locate created thermal refuges) and long-term thermal refuge effectiveness to inform refuge management.

Thermal numerical modelling was limited by the mesh resolution, time step and computational resources. Because of the small residence time in the model domain, a small-time step and fine-resolution mesh was required to adequately model thermal plume dynamics. It is possible that fine-scale bathymetry that influences the thermal mixing of the plume may not have been captured. Although such modelling was tractable for the small domain considered in this study, it would become computationally challenging if larger river reaches were under consideration.

4.4 | Implications for Adapting to Climate Change

Many rivers are experiencing a loss or fragmentation of cold-water habitat (Isaak et al. 2017), and as a result, innovative thermal management strategies are critically needed to adapt. Our study results indicate the potential scalability of pumping groundwater to create thermal refuges, at least in river systems overlying productive aquifers. The impacts of groundwater pumping on other aspects of the river ecosystems, particularly for biota sensitive to biogeochemical changes other than temperature, warrant far more consideration. The feasibility to scale this method requires assessment methods using desktop GIS analysis, combining geospatial river water temperature data, with geology, hydrogeology and climate information. Such analyses should consider the potential for the aquifer itself to warm due to climate change, albeit perhaps lagged substantially if sufficiently deep (Benz et al. 2024). Although the present study focused on the physical sciences and engineering principles that underpin 'designed' thermal refuges, this proposed method is a more involved form of thermal management of rivers. Researchers in the social sciences should engage with stakeholders, including Indigenous communities, government agencies, watershed groups and the public to consider any social concerns or ethical concerns that could be raised. Furthermore, the effectiveness of the method proposed in this study for generating thermal refuges for target species should be addressed.

5 | Conclusions

In this study, we present, to our knowledge, the first successful attempt to create a cold-water thermal refuge by pumping groundwater to a river as a proactive thermal management strategy. Thermal infrared (TIR) imagery detected a notable thermal plume, measuring approximately 55 m^2 at the water surface during low-flow conditions with the installation of a river flow deflector. Field measurements of ambient river temperatures and pumped groundwater revealed a thermal offset of up to 21°C between the two source waters during the first study period. Above-water and underwater cameras recorded several fish utilizing the created thermal refuge during periods of thermal stress with ambient river water temperatures up to 30°C. Therefore, the created thermal refuge was considered successful as it created a notable thermal offset with the mainstem, and several cold-water organisms occupied it during periods of thermal stress.

To interpret the field data and assess the impact of alternative designs and conditions, we conducted 3D numerical modelling of the river and refuge hydrodynamics and thermal dynamics. Thermal numerical modelling of several scenarios revealed that the considered groundwater discharge rates and temperatures were adequate for creating a sizeable thermal plume, but its extent drastically decreased without the use of a deflector. This research lays the foundation for future thermal refuge creation projects aiming to proactively maintain or enhance thermal diversity in warming rivers.

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Conflicts of Interest

The authors declare no conflicts of interest.

Open Research Statement

Data for this study are published in a Borealis dataset available at: [https://borealisdata.ca/dataset.xhtml?persistentId=doi:10.5683/SP3/GMJCSF].

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.