Version: Post-print

Publisher’s version: KarisAllen, J. J., & Kurylyk, B. L. (2021). Drone-based characterization of intertidal spring cold-water plume dynamics. *Hydrological Processes*, 35(6), e14258. https://doi.org/10.1002/hyp.14258

Title: Drone-based characterization of intertidal spring cold-water plume dynamics

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Key words: drone-based remote sensing, thermal infrared imaging, thermal refuges, groundwater springs, estuary temperature, cold-water habitat

Introduction

Thermal infrared remote sensing from satellites and aircraft has been frequently applied to characterize marine and freshwater thermal regimes, including detection of marine heat waves (Holbrook et al., 2019; Oliver et al., 2018) and mapping thermal heterogeneity in rivers (Dugdale, Kelleher, Malcolm, Caldwell, & Hannah, 2019; Fullerton et al., 2018; O’Sullivan, Devito, & Curry, 2019; Torgersen, Price, Li, and McIntosh, 1999). The recent emergence of thermal remote sensing using small unoccupied aircraft vehicles (sUAVs or drones) has greatly reduced the costs and expanded the possibilities for local thermal investigations (e.g., Dugdale et al., 2019; Fitch, Kelleher, Caldwell, & Joyce, 2018). Thermal drift and other issues associated with inexpensive thermal sensors often complicate the quantitative interpretation of such thermal data (Kelly et al., 2019; Mesas-Carrascosa et al., 2018). Nonetheless, sUAV-based thermal sensing has been shown to be an impactful tool with which to study groundwater-surface water interactions and thermal anomalies in rivers (Dugdale et al., 2019) or along marine coastlines (Lee et al., 2016).

Cold-water anomalies (plumes) in rivers can provide critical thermal refuges for poikilotherms (Torgersen, Ebersole, & Keenan, 2012; Wilbur, O'Sullivan, MacQuarrie, Linnansaari, & Curry, 2020), including many anadromous, cold-water fish. For organisms that behaviourally thermoregulate or physiologically modulate their thermal tolerance, thermal plumes may influence their survivability by affecting their metabolic processes and by lowering the probability of exceeding critical thermal thresholds (Torgersen et al., 2012; Morash, Speers-Roesch, Andrew, & Currie, 2020). Only a few river reaches have been thermally mapped to delineate cold-water plumes, and, with rare exceptions (Dugdale, Bergeron, St-Hilaire, 2013), such river aerial thermal surveys have only been recorded at a single point in time. These single snapshots may obfuscate important temporal cold-water plume dynamics, particularly in tidal reaches where hydraulic and thermal interactions between groundwater and surface water are tidally influenced (Lee et al., 2016; LeRoux et al., 2021). The lack of temporal data for cold-water plumes has limited our understanding of the mechanisms that control their morphology and dynamics and how these conditions may impact cold-water species.

In this study, we used repeated sUAV-based thermal images to assess cold-water plume dynamics at the mouths of intertidal springs within a coastal lagoon ecosystem that is threatened by rising water temperatures (DFO, 2020). We consider this transitional coastal system given the foci of most previous thermal remote sensing studies on either freshwater or marine environments. Thermal refuges in transitional coastal waters (e.g., lagoons and estuaries) may be critical, as these corridors are physiologically taxing for anadromous fish due to sharp gradients in temperature and salinity (Thorstad et al., 2012). This study specifically examines how the longshore tidal current direction and water stage impact the size and shape of groundwater-sourced cold-water plumes in coastal waters.

Description

Basin Head lagoon in eastern Prince Edward Island (PEI), Canada is a Marine Protected Area under Canada's *Ocean's Act* (1996). This lagoon is protected due to the presence of giant Irish moss, which is endemic only to the lagoon and declined in abundance by 99.9% between 1999 and 2012 (Tummon Flynn, Garbary, Novaczek, Miller, & Quijón, 2018). The high water temperatures (occasionally exceeding 30°C), elevated nitrate concentrations, and invasive species have all contributed to the moss decline (DFO, 2020). The geology of the Basin Head lagoon watershed is comprised of several metres of clay-sand to sand-phase till overlying cross-bedded, highly fractured sandstone and interbedded mudstone layers (Francis, 1989; Government of PEI, 2019; MacDougall, Veer, & Wilson, 1988). The lagoon experiences a mixed semi-diurnal tide with a typical tidal range between 0.8 and 1.2 m. This project is part of a larger study examining the influence of groundwater-dominated streams and intertidal springs on the spatiotemporal distribution of lagoon water temperatures. Intertidal springs in PEI, including the ones in the Basin Head lagoon, are typically associated with vertical and horizontal bedrock fractures, and they supply relatively cool groundwater to coastal systems throughout the summer months (e.g., Danielescu, MacQuarrie, & Faux, 2009). The groundwater-dominated streams and diffuse and discrete groundwater discharge deliver anthropogenic nitrate to the Basin Head lagoon. Here we focus on the presentation and interpretation of periodic sUAV thermal infrared images collected during the summer over half of a tidal cycle to investigate the temporal dynamics of cold-water plumes sourced from intertidal springs.

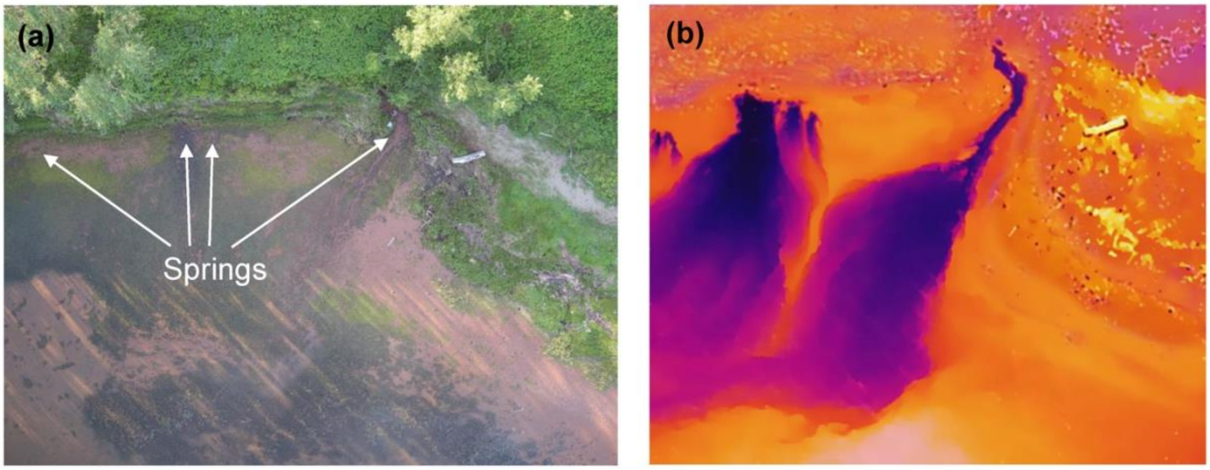

Figure 1: Thermal and visual images at one of the larger monitored springs ('Spring Complex 1') recorded with our sUAV close to low tide (July 22, 2020, 7:37 PM). The thermal image represents a snapshot of the processed thermal images in Animation 1.

Data were collected with a barometer and tidal logger (Solinst Levelogger Junior F15/M5) and an sUAV (DJI Matrice 210 v2 RTK) equipped with a combined visual camera and thermal sensor (DJI Zenmuse XT2 with 640 × 512 resolution and a 13 mm lens). Nadir thermal images were taken hourly on July 24th, 2020 from 11:30 to 20:30 local time (AST) at an approximate elevation of 60 m above mean sea level. As our focus is on the size and shape of the cold-water plumes, the raw images were post-processed to maintain similar land surface temperatures among snapshots, remove interference and artifacts, and correct minor orientation differences between images using a combination of GIMP (Version 2.10.22) and Inkscape (Version 1.0.2). The presented uncalibrated thermal images should only be used for qualitative analyses. Visual and thermal images of the larger spring complex (Spring Complex 1) during the lowest tide of the day are shown in Figure 1. The cold-water plumes from this spring complex disappear at high tide. While the uncalibrated thermal measurements cannot be interpreted quantitatively to obtain exact temperatures due to the sensor-related challenges noted earlier, they can reveal the presence or absence of a thermal anomaly like a cold-water plume. A substantial reduction or complete disappearance of cold-water plumes detectable using water surface temperature is generally observed for the > 30 springs throughout the lagoon. However, discrete measurements of salinity and temperature at high tide suggest that certain springs continue to discharge in some capacity. These temporal dynamics are explored further through qualitative analysis of time-lapse images of two separate spring complexes.

Animations 1 and 2 show thermal plume time series with paired tidal data recorded at a tidal station within 15 metres of the mouths of both springs. The time-lapse images reveal that the orientations of the plumes varied with the tide. During the falling (ebb) tide, the plumes are generally oriented to the left in the outflowing current direction (Animation 2). During slack tide, when tidal forcing is absent, the impact of local factors (e.g., channel morphology, vegetation, spring flow velocity) on plume shape may be more significant. Finally, during the rising (flood) tide, the cold-water plumes may briefly orient to the right with inflowing tidal currents before their areas of influence progressively shrink towards the mouth of the respective spring (Animation 2). The thermal observations of springs during flood tides were made separately from the time-lapse study and are not included herein. Both animations demonstrate that the tides also strongly control plume size and thus their capacity to function as thermal refuges, with plumes shrinking (growing) during flood (ebb) tides. We postulate that for intertidal springs, the cold-water plume sizes manifested in thermal infrared imagery are related to the volumetric rate of groundwater discharge from the springs, the channel hydraulic mixing dynamics, the discharge aperture shape and location, as well as the density and temperature differences between the spring and lagoon waters. The aquifer-to-lagoon hydraulic gradient will vary in magnitude and potentially direction due to tidal oscillations, with the greatest spring discharge occurring during falling and lower tides. The plumes may also shrink or disappear during high tide simply because the thermal loading is diluted with more channel water. Fresh groundwater discharge from intertidal springs should be buoyant in brackish water and thus visible from aerial thermal imagery, provided that the cold freshwater can rise to the surface before intensive in-channel mixing. We describe these effects on a ‘frame-by-frame’ basis for Spring Complex 1 (Animation 1) in the textual supplementary material. These processes could be further investigated in future studies at similar sites using loggers recording level, temperature, and salinity in the springs and throughout the plume.

A limited number of prior studies have used thermal imaging from planes (Danielescu et al., 2009), helicopters (Tamborski et al., 2015), or sUAVs (Lee et al., 2016; Young and Pradhanang, 2021) to study thermal plumes due to diffuse or focused groundwater discharge in coastal areas. However, these prior studies focused on submarine groundwater discharge quantification rather than studying plume dynamics. Prior studies also only present a single snapshot in time for the thermal plumes or consider temporal changes at lower frequencies than in the present study. Our thermal imagery shows that tidal oscillations influence the hydraulic and thermal exchanges associated with groundwater-surface water interactions in coastal settings (e.g., LeRoux et al., 2021). Our results further highlight the complex dynamics of the orientation and size of cold-water plumes sourced from intertidal springs. Anecdotally, fish aggregate around certain cold-water plumes in the Basin Head lagoon during extreme high temperatures, but more intensive ecological studies are required to conclusively demonstrate that these cold-water plumes function as thermal refuges (Sullivan et al., 2021). In other studies, cold-water plumes have been densely packed with aggregating fish (Kurylyk, MacQuarrie, Linnansaari, Cunjak, Curry, 2015), suggesting that the plume size impacts their ‘holding capacity’ as a refuge. Our results demonstrate that thermal refuges in tidal reaches may exhibit intra-daily variations in their ability to provide cold-water refuge due to changes in both their size and temperature, as influenced by tidal patterns. This variability may have a considerable effect on the lagoon’s ecology, as thermal stress often modulates the distribution and metabolic function of aquatic organisms. While we focus on tidal dynamics in this study, cold-water plumes in freshwater rivers may also experience high-frequency temporal variations due to sharp changes in spring and channel discharge arising from pronounced precipitation or hydropeaking from dams. Cold-water plume dynamics in rivers and estuaries have been largely unexplored despite their ecological significance, and our findings demonstrate the application of sUAVs to monitor their temporal and spatial dynamics.

Acknowledgements

Research funding was provided by the Ocean Frontier Institute through an award from the Canada First Research Excellence Fund. Fisheries and Oceans Canada and Souris Fish and Wildlife provided logistical and field support. J. KarisAllen was funded through a Canada Graduate Scholarship from NSERC. B. Kurylyk was supported through the Canada Research Chairs Program.

Supporting information legend

Two animations and one longer textual legend are provided in the supporting information material, but herein provided via Google Drive links. The first animation shows one visual image and time-lapse thermal imagery for Spring Complex 1 (see Figure 1), while the second animation shows a visual image and time-lapse thermal imagery for Spring Complex 2.

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