Investigating Controls on Stream Temperatures in a Small Watershed

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GEOL394

26/04/2022

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ABSTRACT

Stream temperature and temperature variations influence aquatic life and potentially global climate. Runoff from paved surfaces can rapidly raise stream temperatures during storm events, but mixing of runoff with groundwater could mitigate stream temperature changes, depending on the volume and temperature of groundwater mixed. It was hypothesized that groundwater mixing would result in restricted temperature ranges in an incised headwater stream compared to a non-incised stream. On a seasonal scale, this would result in depressed stream temperatures during warm months and elevated temperatures during cool months relative to a non-incised stream. On a diel timescale, this would manifest as a decreased amplitude in the generally sinusoidal water temperature fluctuations expected over the course of a day. On the timescale of a storm event, an incised stream would suffer less thermal shock or rapid temperature change due to runoff and subsurface flow. Interactions with groundwater were also hypothesized to occur in a constructed wetland, where groundwater exchange and mixing were predicted to restrict temperature ranges at surface water outputs relative to surface water inputs. These hypotheses were tested at a watershed on the University of Maryland Golf Course property from April 2021 through April 2022. The watershed has two headwater streams that receive runoff from roadways. One is incised to approximately 1.5 meters below the adjacent floodplain or terrace, with some portions incised in excess of 4 meters. The other stream is mostly non-incised, with incision generally well below 0.5 meters. Both streams feed into an approximately 1.7 hectare constructed wetland with a single surface outlet. In order to quantify the water temperature differences between the incised and non-incised streams and the wetland's inputs and outputs, two methods were employed: longitudinal stream temperature profile data, where data was collected in a short time interval along the longitudinal length of a stream, and timeseries data analyses. Longitudinal temperature profiles were measured in both streams during early autumnal low flow and early spring high flow conditions. Longitudinal stream temperature heterogeneity was dependent on season, with the non-incised stream having a range of approximately 4 °C and 2 °C for autumn and spring, respectively, and the incised stream having a range of 0.5 °C and 4.5 °C, respectively. The time series data were collected at 5 minute intervals and included temperature and water level data. While the intramonthly temperature ranges for the incised and non-incised streams were often comparable if slightly restricted for the incised stream, the incised stream remained statistically cooler than the non-incised stream throughout the year, not just during warm summer months. Outlet water temperatures had similar monthly ranges to the headwater streams but increased summer temperatures and depressed winter temperatures. Groundwater data exhibit profound variation in groundwater temperature variability and surface interactivity with season, with higher responsivity to air temperatures and mixing rates with surface water in winter and lower responsivity and mixing rates in summer. This supports the possibility that increased evapotranspiration rates decrease groundwater temperature sensitivity and surface interaction, with incision allowing for increased surface-subsurface interaction during periods of high evapotranspiration. Incision has potential for mitigating mean water temperatures but does not appear effective at reducing the potential for shock from runoff. The constructed wetland failed to mitigated temperatures and may have increased seasonal ranges; therefore, similar structures may exacerbate thermal pollution in certain situations.

INTRODUCTION AND BACKGROUND

Increases in stream temperature through thermal pollution, climate change, and other changes to stream temperature budgets can adversely impact local and global ecology. As stream temperatures increase, the metabolic rates for aquatic ectotherms increase faster than dissolved oxygen content, forcing sensitive aerobic species, such as trout or salmon, to evacuate or perish (Breau et al., 2011; Verberk et al., 2011). Decomposition rates for organic matter may also increase with temperature, decreasing carbon storage and potentially increasing the rate of greenhouse gas emissions from streams (Ferreira and Canhoto, 2014; Griffiths and Tiegs, 2016). When microbial activity is sufficiently high, warm anoxic conditions can persist along with elevated rates of methanogenesis (Jones et al., 1995). Methane is a potent greenhouse gas, being responsible for approximately 20% of anthropogenic climate forcing despite anthropogenic emissions being just 4% of those of CO_2 over the period of 2000 to 2012 (Saunois et al. 2016), meaning even a relatively small increase in methane emissions can have a substantial impact on global climate. This relationship between stream and climate warming may pose a risk in contributing towards a positive feedback loop. These factors together make increasing stream temperatures an immediate threat to local biodiversity and a long-term threat to global climate.

Here, thermal pollution is defined as the warming of waterways directly attributable to anthropogenic sources. These can be as direct as discharging spent cooling water or warm runoff into streams and as indirect as reducing stream sheltering and contributing towards a changing climate. To combat this negative impact, thermal mitigation practices (TMPs) are employed. Some of the more noteworthy TMPs include bioretention measures (greenspace), cool surfaces, forest canopies, detention ponds, and channel dimension modification and restriction (Ketabchy et al. 2019). These final two TMPs are of particular interest in this research.

A familiar TMP is the stormwater detention pond. The detention, retention, or stormwater pond is a ubiquitous construct designed for reducing peak stormflows and contaminants associated with stormwater runoff. However, small ponds are prolific sources of methane, accounting for approximately 8.6% of lake and pond surface area globally but 40.6% of lake and pond methane emissions (Holgerson and Raymond, 2016). Given the pond-like structure of stormwater detention ponds, they may contribute unnecessarily to the anthropogenic carbon footprint. Although they may mitigate peak runoff, detainment ponds have questionable efficacy in combating thermal pollution. Herb et al. (2009) found that detention ponds can lengthen the window over which thermally polluted water is released, reducing the risk of thermal shock in sensitive ecosystems, but they can also increase the time over which temperatures remain elevated while possibly heating the water in stagnant pools, leading to a net increase in discharged water temperature and greater stress on sensitive ecosystems downstream. Although detention ponds may be ineffective in combating thermal pollution due to their own thermal contributions and elevated rates of methanogenesis, small bioretention structures designed to partially intercept runoff near their sources show more promise as TMPs. A study by Long and Dymond (2013), although limited in scale and scope, suggests that bioretention methods have potential in both reducing and cooling runoff. Small wetlands may have a similar impact on water temperatures as these bioretention structures. Wetlands are a broad group of related hydrogeomorphic features defined by frequent water inundation and distinct water tolerant vegetation. Artificial or anthropogenically altered wetlands are comparable to both detention ponds and bioretention structures (Shaffer et al., 1999), and existing research suggests that riparian wetlands can significantly cool stream temperatures during warm months and warm them during cool months due to both shading and surface-groundwater mixing (Dick et al., 2018). In addition, wetlands have been employed with success in cooling treatment plant water due to cooling associated with evapotranspiration (ET) in arid climates (Kadlec, 2006). Understanding how constructed wetlands in more temperature climates impact stream temperature is important if their efficacy as a TMP is to be understood.

The effect of stream incision on stream temperature regimes is poorly studied. Although research into channel restriction and narrowing measures suggests that these measures can improve stream habitability for thermally sensitive species, they are often observationally limited and reliant on models rather than observations (Loinaz at al., 2013; Justice et al., 2017). Groundwater inflow and hyporheic exchange can significantly influence stream temperatures. Hyporheic flow, the flow of water through sediments directly beneath the streambed, has been a topic of interest in understanding stream water temperatures. Although dependent on surface streamflow, hyporheic flow temperature is often restricted and lagged relative to surface temperatures, meaning diel temperature means are similar, although diel variation and times of temperature extremes are not (Arrigoni et al., 2008). Hyporheic flow is crucial in determining the thermal characteristics of many streams (Poole and Berman, 2001), and many existing models incorporate or consider the dependency of many streams thermally on hyporheic flow (Justice et al., 2017). Subsurface contributions due to groundwater and hyporheic flow have been used to explain why some streams show limited responses to air temperature variability in past research (Bogan et al., 2003; MacDonald et al., 2014). Given the dependence of stream temperatures on subsurface hydrology, the geomorphology of a stream has the potential to impact temperature by altering surface-subsurface water exchange. Stream incision, where a stream channel is deepened such that increasing volumes of water can be transported without exceeding bankfull flow, is symptomatic of erosion associated with runoff from urban and agricultural landscapes (Fig. 1). Restoration efforts to reverse incision are popular, but evidence is lacking that such efforts significantly improve stream biodiversity (Fanelli et al., 2019). If incision restricts stream temperatures, remediation efforts may lead to net biodiversity loss.

Figure 1: Incised stream at the University of Maryland Golf Course. Note how erosion associated with incision is undermining and felling nearby trees.

According to Bogan et al. (2003), research on the role of groundwater-surface interactions often focuses on identifying streams with low responsiveness to air temperatures, which is frequently inferred to be due to the influx of stable temperature groundwater. A stream that responds quickly to air temperatures will have a regression slope for stream versus equilibrium (air) temperatures close to 1 and an intercept close to 0 (Fig. 2) (Bogan et al., 2003). Bogan et al.

(2003) found that many stream temperature versus equilibrium temperature regression slopes are between 0.6-0.8. A minority of streams show little dependence thermally on atmospheric temperatures, with regression slopes of less than 0.6. In addition, the intercepts for these low dependence slopes are 8-12 °C, suggesting an inflow of cool water. Bogan et al. (2003) suggest that groundwater or factors such as snowmelt recharge may be responsible for maintaining low temperatures during warm seasons.

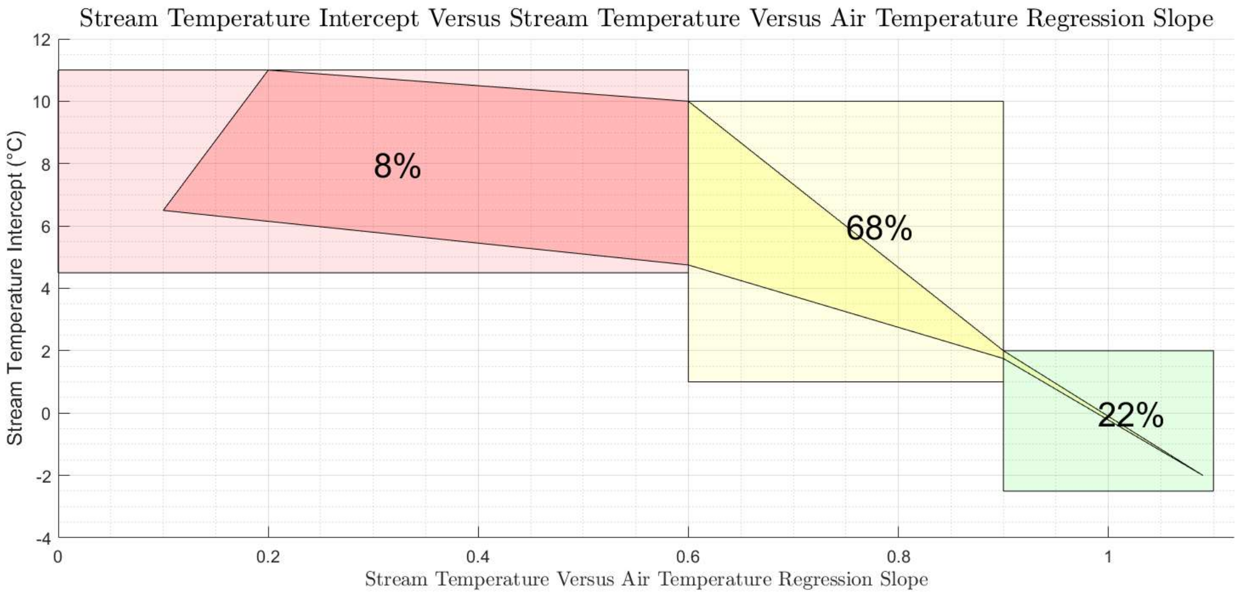

Figure 2: Simplified stream intercept temperature versus regression slope for stream temperature versus equilibrium temperature plot modified from Bogan et al. (2003). Streams are divided into three distinct regimes defined by equilibrium temperature dependence separated here by shaded boxes. Darker shaded boxes illustate trends within regimes. The percents correspond to the precent of streams belonging to the respective regime. Percents from original diagram do not add to 100%.

The apparent role of groundwater in regulating stream temperatures suggests that streams dependent on deep sources of groundwater may have restricted temperatures relative to the atmosphere, exhibiting less-pronounced seasonal or longitudinal variability. Stream incision leads to deeper stream channels, which may drain from deeper groundwater to supply baseflow. Therefore, incised streams may show a restricted thermal range relative to a shallow or non-incised streams of the same size, climate, and environment. If derived from groundwater sources, hyporheic exchanges may also mediate stream temperatures. Wetlands that facilitate groundwater and surface water exchanges could provide a mechanism for stream temperature mitigation and control, depending on the depth of groundwater flow paths.

HYPOTHESES

This study sought to investigate the relationship between geomorphological and hydrological watershed features and stream temperatures, testing two hypotheses:

1. An incised stream will exhibit a narrow range of water temperatures relative to a non-incised stream in the same region, leading to lower peak temperatures in warm months and restricted intramonthly water temperature variation.
2. A constructed wetland will have a narrow range of outlet water temperatures relative to surface inlet water temperatures, leading to lower peak temperatures in warm months and restricted intramonthly water temperature variation.

The corresponding null hypotheses follow:

1. There will be no statistically significant difference in seasonal temperatures or monthly temperature ranges between the non-incised and incised streams, with a p-value greater than 0.05.
2. There will be no statistically significant difference between seasonal surface output and input temperatures or monthly temperature ranges, with a p-value greater than 0.05.

These hypotheses were formulated with the assumption that surface-subsurface water interaction and exchange largely determine the degree of water temperature independence from air temperatures in small watersheds. For the incised stream, this is due to incision deepening the stream channel, allowing for the stream to be fed by deeper sources of groundwater. Deeper sources of groundwater should be more sheltered from the thermally variable atmosphere than shallower groundwater, leading to less thermal variation and greater lags in thermal response to temperature changes at the surface. A stream fed by these sources of groundwater should show less temperature dependence on air temperature than a source fed by shallower sources. Likewise, wetlands are characterized by the exchange of water between the surface and the soil. If constructed wetlands show a similar exchange, groundwater mixing should restrict water temperature ranges at the surface during warm months or runoff events due to the subsurface acting as a heatsink.

By focusing on temperature extremes, this research is tailored towards applicability for engineering design of TMPs. Reducing thermal shock during storm events and restricting peak warm season temperatures are the primary purposes of TMPs. Understanding how stream morphology and constructed wetlands affect stream temperatures can be useful in making informed policy decisions regarding effectively combating thermal pollution and approaching watershed restoration.

Figure 3: Defunct water system equipment, evidence of past groundwater exploitation, abandoned in the incised stream.

STUDY SITE

The hypotheses outlined above were tested at a watershed on the grounds of the University of Maryland Golf Course. The watershed is a branch of the larger Paint Branch watershed, which itself is part of the Anacostia watershed. Prior to being a golf course, the site was a dairy farm (United States Department of Agriculture, 1938. Signs of deliberate and undeliberate human intervention are present throughout the site, visible in the form of culverts, artificial ponds, and various debris and litter (Fig. 3).

The watershed contains two headwater streams for comparable flow magnitude: one incised (Fig. 4) and the other non-incised (Fig. 5-6). The downstream part of the incised stream extends onto the golf course, but most of the stream is located within a wooded portion of the northern part of the grounds, where it begins at a stormwater outflow culvert fed from a detention pond of the National Archives II. Although runoff from the National Archives II continues to erode and transport stream sediments, channel incision likely originated with gully during the agricultural era. For instance, streams within Greenbelt National Park have similar stream morphology despite a lack of exposure to urban runoff; however, thicker vegetation prevents significant erosion. Incision has lowered the bed of the incised stream 2-3 m beneath the adjacent stream terrace in its upstream portion. The degree of incision decreases downstream. The stream width is approximately 1.5 m for most of its length.

Figure 4: Incised stream at the University of Maryland Golf Course (Dr. Karen L. Prestegaard for scale).

The non-incised stream is located on the western side of the golf course and is near

Figure 5: Non-incised stream at the University of Maryland Golf Course (early autumn, looking downstream).

Figure 6: Non-incised stream at the University of Maryland Golf Course (late winter, looking downstream).

grassed areas for most of its length. Whereas the incised stream is wider and shaded by trees, the non-incised stream's cover varies seasonally. During summer, grasses near the channel are not cut, allowing them to grow tall and shade the channel. These grasses are cut or allowed to experience dieback in autumn, and the remaining short grasses provide little shading in the winter, exposing the channel to direct sunlight. Channel incision depth increases adjacent to culverts. The stream width is approximately 0.5 m for most of its length.

Figure 7: Wetlands at the University of Maryland Golf Course.

The wetland, situated in the approximate center of the course (Fig. 7), is fed by both streams. It occupies an area of approximately 1.7 hectares as measured with ArcGIS. It was originally a pond, but it drained in 2001 following a dam failure near the current wetland outlet, forming a wetland, according to historic satellite imagery from Google Earth.

Established gauge sites where temperature and water levels are recorded are located at eight locations within the watershed and are maintained by Dr. Karen L. Prestegaard's research group at the University of Maryland (Fig. 8). Both the incised and non-incised streams have two gauges each. These gauges are spaced such that the upper and lower portions of both streams are monitored. Three additional gauges monitor wetland groundwater level and temperature at approximately 1 m depth. A stream gauge is also located at the outlet of the wetland. All established gauges have at least one year of temperature and water level data with most having closer to five. The wetland portion of this network is also supplemented with three temporary temperature loggers monitoring shallow soil temperatures at 10 cm depths that were installed as part of this research.

EXPERIMENTAL DESIGN

The temperature sensors used for this research were of two types. The eight established stream and groundwater sites are instrumented with HOBO Water Level Loggers (U20L-04). The devices have a rated temperature resolution (precision) by the manufacturer of ± 0.10 °C at 25 °C and accuracy of ± 0.44 °C between 0 and 50 °C. Devices have a rated depth resolution of ± 0.0014 m and accuracy of ± 0.008 m. Each logger was set to record water temperature and level every five minutes. The soil temperatures were monitored with HOBO TidbiT Water Temperature Loggers (UTBI-001) recording soil temperature at 10 cm depth as well as one logger recording air temperature every five minutes. These TidbiT loggers have a finer resolution than the water level loggers at ± 0.02 °C and accuracy at ± 0.21°C from 0° to 50°C. The TidbiT loggers were calibrated together in the same water bath by Dr. Prestegaard and her team. The devices were submerged in ice water and slowly warmed together. The actual temperature was taken to be the average of the temperature recorded by the devices. Each device was then given a calibration adjustment to correct the temperature to the average temperature of all the sensors. Therefore, the measured water temperatures could be compared with one another, and the uncertainty would be close to the instrument precision. Given that this research is primarily concerned with relative temperatures, calibration of the sensors increased the reliability of these comparisons.

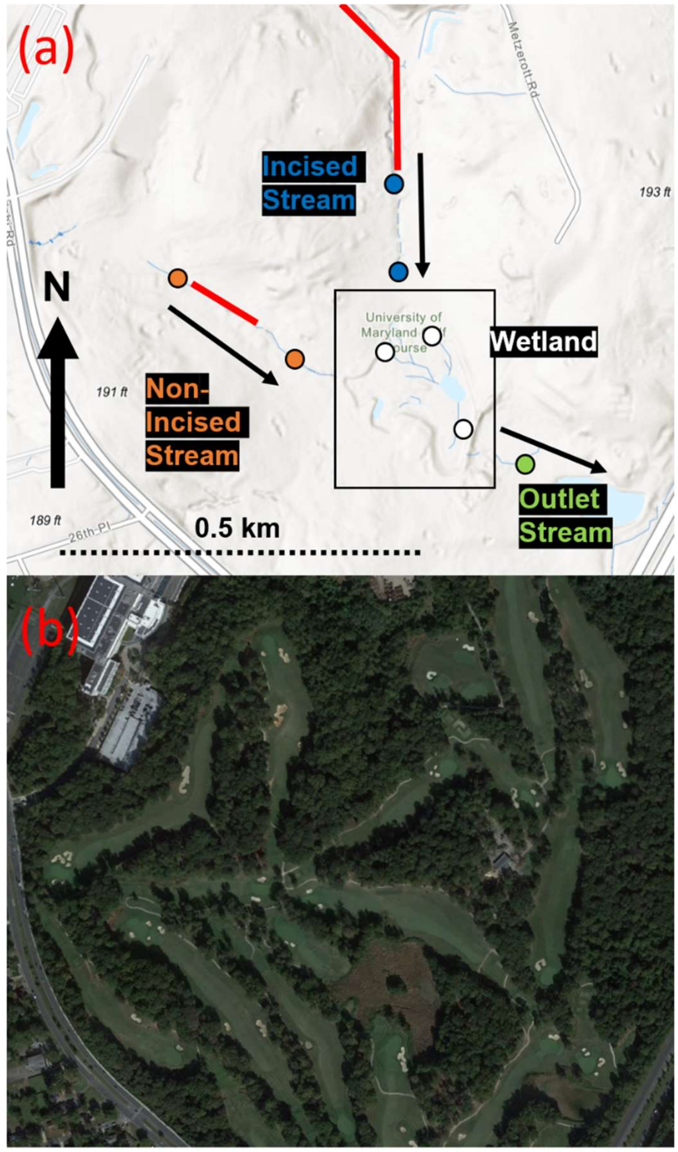

Figure 8: (a) ArcGIS terrane with labels (LiDAR) map for the University of Maryland Golf Course. Established gauge sites for the non-incised (orange), incised (blue), and outlet (green) streams and wetland wells (white) marked. Arrows denote flow direction, and red bars corresponds to longitudinally surveyed segments of the streams. (b) Satellite image of the University of Maryland Golf Course from Google Earth.

Longitudinal stream measurement methods

Although the preestablished gauge sites provided most of the data necessary to compare temperatures of the two inflow and one outflow streams, temperature data collected at closely spaced intervals along the lengths of both headwater streams provided information about the process and features that affect stream temperature. To obtain these data, short-term, longitudinal (spatial) thermal profiling of the incised and non-incised stream were conducted to observe whether temperature increases, decreases, or remains constant along the length of each stream (Fig. 8-9).

Two different permutations of longitudinal profiling were used: temporarily exposed and non-exposed. Temporarily exposed procedure involved attaching a TidbiT logger to a pole and submerging the logger to a few centimeters' depth at regular intervals along the streams for an interval of approximately one to two minutes. Temperatures at these intervals were recorded and distinguished by tape measures along the bankfull or high flow path. After the selected stream reach was logged, the

Figure 9: Laying the tap measure parallel to the incised stream's bankfull flow path as part of a longitudinal profile survey (Dr. Karen L. Prestegaard for scale).

temperature measurements were then matched to the distance along the stream via its timestamp. Non-exposed procedure utilized a watertight container for transporting the TidbiT logger between sites. This modification allowed the logger to remain within water for most of the profiling, lowering the risk of temperature rises due to the device being exposed to air. This profiling procedure was employed at the non-incised stream for spring profiling as well as the incised stream for both autumn profiling and spring profiling. The autumn spatial samplings were employed in the non-incised stream and incised stream on days where the air temperatures were consistently warmer than stream temperatures; therefore, the lowest temperature value recorded within the submersal interval time of a site was utilized for that site as the logger could only be cooled by water. Since site windows were only recorded to the minute for both permutations, some overlap in windows and temperature readings occurred. This inaccuracy was minimized by keeping the intervals small, under eight meters in the approximately 200 m non-incised stream profile and under twenty meters in the 400 meter incised profile. These intervals ensured a comparable sampling frequency as a function of longitudinal step versus stream width. While more frequent surveying could have improved resolution, diel variation could have become a factor due to the time window surveying would need to occur over. In spring, the difference between water temperatures and air temperatures were not as certain; therefore, the first timestamp for the minute the logger was removed from a stream was used.

These spatial profiles were plotted as temperature versus distance downstream, with the position of notable hydrological features, such as ponds and springs, identified in the field also noted. These graphs were also be organized to compare incised to non-incised streams. The primary value of these data is in determining stream temperature ranges within a profile. These ranges show the degree of spatial thermal variation and restriction with respect to distance downstream.

Temporal comparison of temperature regimes among established stream gauge sites

Monthly mean, median, and range data were computed for air temperature, the two inlet stream downstream sites, and the outlet stream site for a survey period between April 2021 and March 2022. Months with water temperature records spanning at least 50% of the month were then used for statistical analysis by Wilcoxon rank-sum test using the *ranksum* function in MATLAB. The Wilcoxon rank-sum test allows for the comparison of categories through quantitative data without a known distribution. The *ranksum* function allows for both direct computation of p-values (exact) or the computationally less intensive calculation using a normal approximation without assuming normal distribution to derive an intermediate Z-value (approximate). Data records for each month included all archived recorded data minus points immediately following a break persisting greater than five minutes within a single recording window. Mean comparisons were completed independently for warm month (June through August) and cool month (December through February) data, using all temperature data for the months considered. Given the number of data points, the calculation used the approximate method. These mean comparisons were completed for the incised stream relative to the non-incised stream and the outlet stream relative to both the incised and non-incised inlet streams. Median analysis was completed using monthly median values for the months with a sufficient temperature record span using the Wilcoxon rank-sum test using the exact method. Warm month and cool month median statistical analyses were completed for the incised stream relative to the non-incised stream and the outlet relative to the inlet streams. Monthly ranges were compared over the entire year-long window using the Wilcoxon rank-sum test for the incised stream relative to the non-incised stream and the outlet relative to the inlet streams using the exact method.

Cumulative probability analyses were also used to compare temperature variations among the sites for a warm month (August) and cool month (January) window. The temperature versus probability of temperature exceedance was plotted for air temperature, upstream non-incised stream water, downstream non-incised stream water, upstream incised stream water, downstream incised stream water, outlet stream water, 1 m deep groundwater at the inlet, and 1 m deep groundwater at the outlet. The 10 cm deep groundwater data was also available for the inlet and outlet for part of August and was included where possible. Differences in temperature versus probability of exceedance were also plotted for the downstream minus upstream temperatures for the non-incised and incised stream, 1 m minus 10 cm deep groundwater water temperatures, and 1m deep groundwater outlet minus inlet temperatures.

Temperature and groundwater level data were also obtained from data loggers in shallow wells installed to depths of 1 m in the wetland. These data were used to construct timeseries for water level and temperature. In addition, temperature versus gauge water level was plotted for both inlet and outlet wells for August and January.

Seasonal regressions were preformed using techniques adapted from Bogan et al. (2003) for comparing streams. By using monthly means from the months with sufficient data, a linear regression for stream temperature versus air temperature was calculated for the non-incised, incised, and outlet streams. The resulting regressions yielded intercept and slope data that, when plotted together, allowed for the classification of the streams into one of three dependence categories outlined in Bogan et al. (2003) which identify the degree of stream temperature dependence on air temperatures and likely the importance of groundwater contribution in regulating and restricting stream temperatures.

RESULTS

Longitudinal temperature profiles

Four longitudinal profiles were completed (Fig. 10-11): the non-incised stream on 20/10/2021, the incised stream on 22/10/2021, and a profile for both non-incised and incised streams on 04/04/2022. October data are for a period of low flow where ET rates were high whereas April data are for a period of high flow where ET rates were low. In addition, sheltering for the non-incised stream, which was provide almost exclusively by seasonal grasses, was significantly less during April than in October due to annual dieback.

The non-incised stream profile for October shows that much of the stream was dry, with flow sinking beneath the shallow streambed before reaching the wetland (Fig.10a). The resulting profile, therefore, is constricted in length due to a lack of surface water to thermally gauge. Even within the sampled stream length, there were dry spots which punctuated surface flow, leading to distinct pools of effectively stagnant water, although few of these pools were distinguishable by temperature. The stream initiated at the outflow of a culvert, and stream temperature was above the reach average. The pool below the culvert was the main location where the stream was exposed to the atmosphere and sunlight. This temperature spike continued after the first dry patch before falling again as cover became available through tall grasses over a meter tall shading the stream. No surface flow was feeding the stream; therefore, the cooling stream temperature, which were well below thermal equilibrium with the atmosphere, were likely fed by shallow, cool groundwater. Even as vegetative cover decreased, temperatures continued to drop steadily with distance down the stream before increasing rapidly at another exposed pool. The total thermal range was 4 °C with a generally cooling trend along the profile. The adjacent golf course fairways were watered with sprinklers shortly after the sampling period, suggesting that the watering schedule may have influenced shallow water temperatures in this otherwise dry period. Sprinklers were only active for a few minutes, and their distance from the stream were on the order of tens of meters.

The incised stream profile for October showed a more restricted thermal range over a longer distance, with a temperature range of less than 1 °C (Fig. 10b). Although the stream showed a slight positive trend in warming over the profiled length, there was little change throughout the length. Springs entering the stream did not coincide with either temperature increases or decreases; however, stream temperatures increased near culverts and decreased downstream of them. Shading was relatively consistent over the length of the profile, with the highest temperatures being achieved where canopy cover was thinnest.

The April non-incised longitudinal study followed a period of intense storm events within a week and sprinkler use within minutes to hours of surveying. While cover was reduced relative to October, water temperature variation was considerably less heterogenous, with a range of less than 2 °C (Fig. 11a). Flow was significantly higher than in October, and there were no dry spots over the length of the stream. While broader stagnant pools did appear, they did not alter temperatures considerably nor consistently. Overall, temperature trends were smoother near the upstream portion, with changes becoming increasingly sharp in the downstream portion.

Though occurring on the same day as the non-incised April study, the incised April study was sufficiently far enough from the greens as to not be immediately impacted by watering. Regardless, the stream was fed along its entire length by visible surface springs and seeping stream walls exposed by incision. Temperatures were considerably more heterogenous than both the August profiles, with a range exceeding 4.5 °C (Fig. 11b). Unlike for the non-incised stream, water temperature variation did correlate with incised stream features. A sharp trend of initial warming of approximately 4.5 °C in under 30 m occurred along a segment with high wall seeps roughly a meter above the stream. After transport through the first culvert and a sharp topographic drop, the water temperature dropped by approximate 3 °C in less than 10 m.

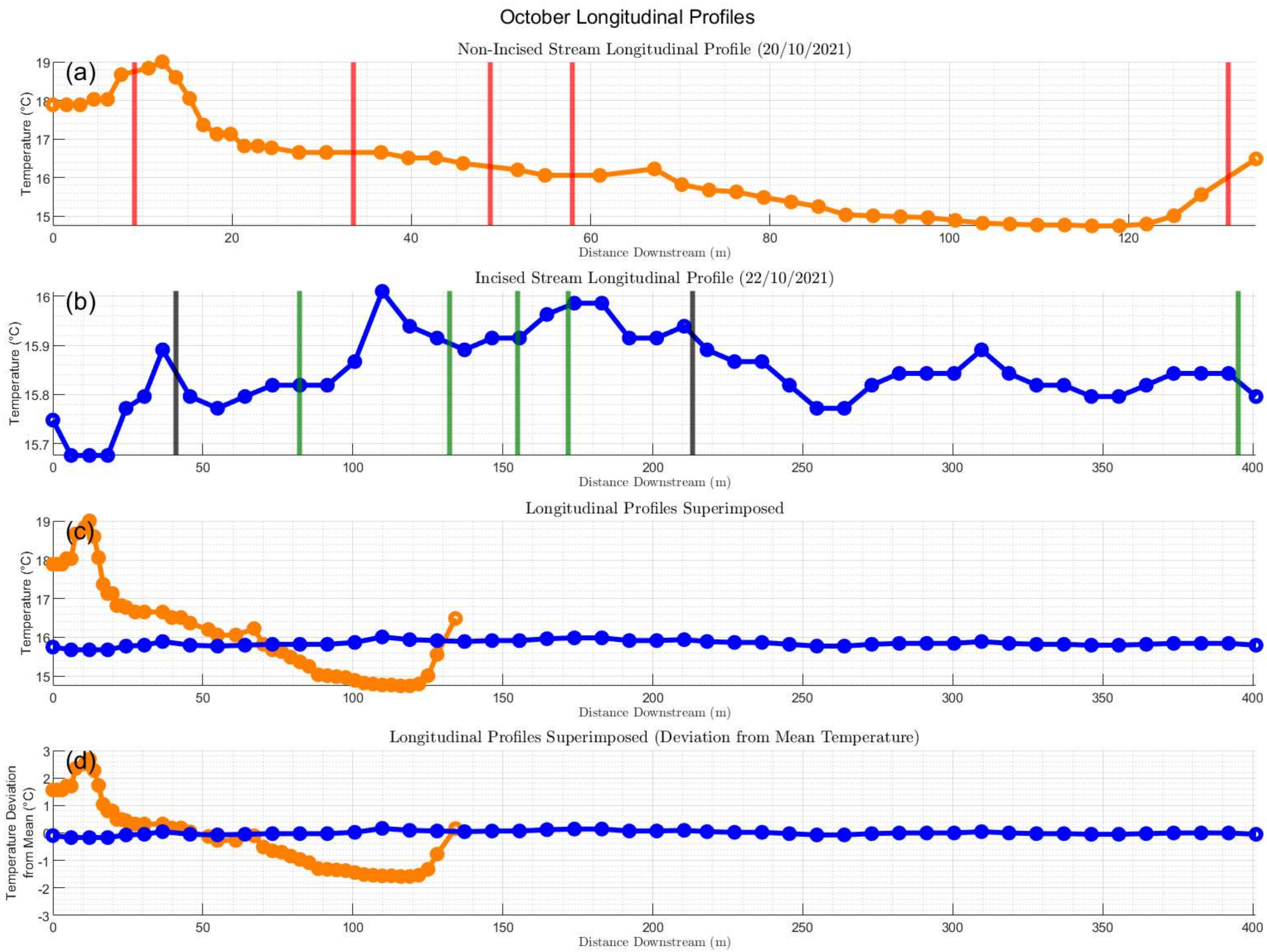

Figure 10: October longitudinal profile survey results for the non-incised (orange) and incised (blue) streams. Note the different dates and axis scales. The non-incised length surveyed is shorter than the incised length surveyed. Red denotes dry spots, black denotes culverts, and green denotes springs (dry). (a) October 2021 non-incised stream longitudinal profile. (b) October2021 incised stream longitudinal profile. (c) Both October 2021 longitudinal profiles superimposed over each other. (d) The deviation from mean longitudinal temperatures of both streams for October 2021 superimposed over each other. ε = ±0.21 °C

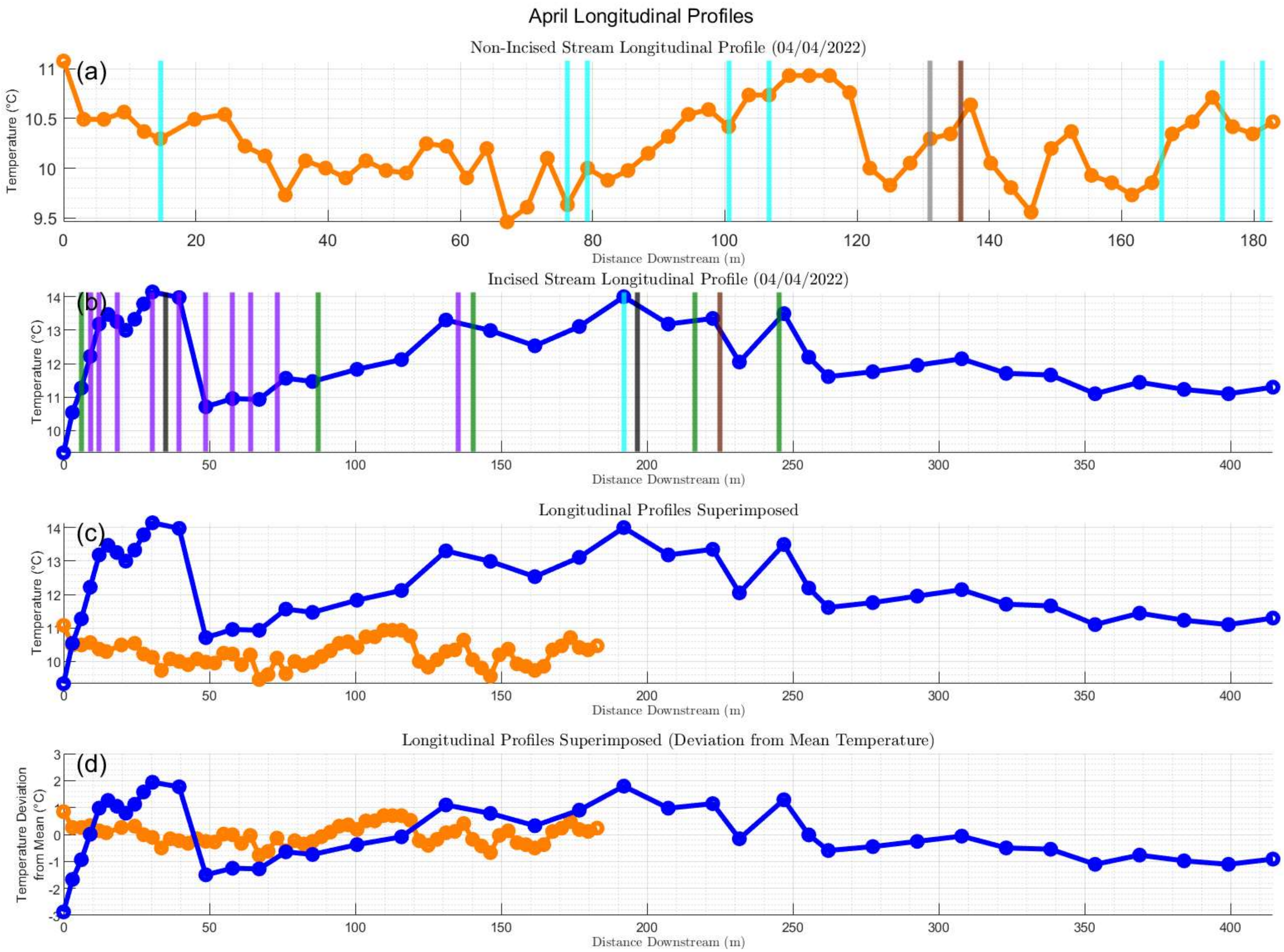

Figure 11: April longitudinal profile survey results for the non-incised (orange) and incised streams. Note the different axis scales. The non-incised length surveyed is shorter than the incised length surveyed. Cyan denotes pools of largely stagnant water, grey denotes fall-like features, brown denotes the rejoining of a fork in the stream, green denotes springs, purple denotes seeps, and black denotes culverts. Features may not correspond to a different location between Fig. 10 and Fig. 11 due to features not being points. (a) October 2021 non-incised stream longitudinal profile. (b) October2021 incised stream longitudinal profile. (c) Both October 2021 longitudinal profiles superimposed over each other. (d) The deviation from mean longitudinal temperatures of both streams for October 2021 superimposed over each other. ε = ±0.21 °C

Here, the degree of incision was much deeper, and seeps of approximately 1 m above the stream were again common. Water temperature climbed more slowly after this as incision diminished, reaching a peak near the second culvert. Unlike with the first culvert, water temperatures did not cool rapidly after passing through the second, but they did cool after a fork in the stream diverted around the culvert rejoined it downstream. Temperatures once again rose where a large spring fed the stream but cooled with length as incision rose without as many obvious seeps after. Figure 12 summarizes how the April surveys compared to the October profiles. While the range of temperatures in the incised stream were significantly restricted and generally cooler than those of the non-incised stream for the October surveys, the trend reversed in April, with the non-incised stream showing a restricted range of temperatures and general cooler water temperatures.

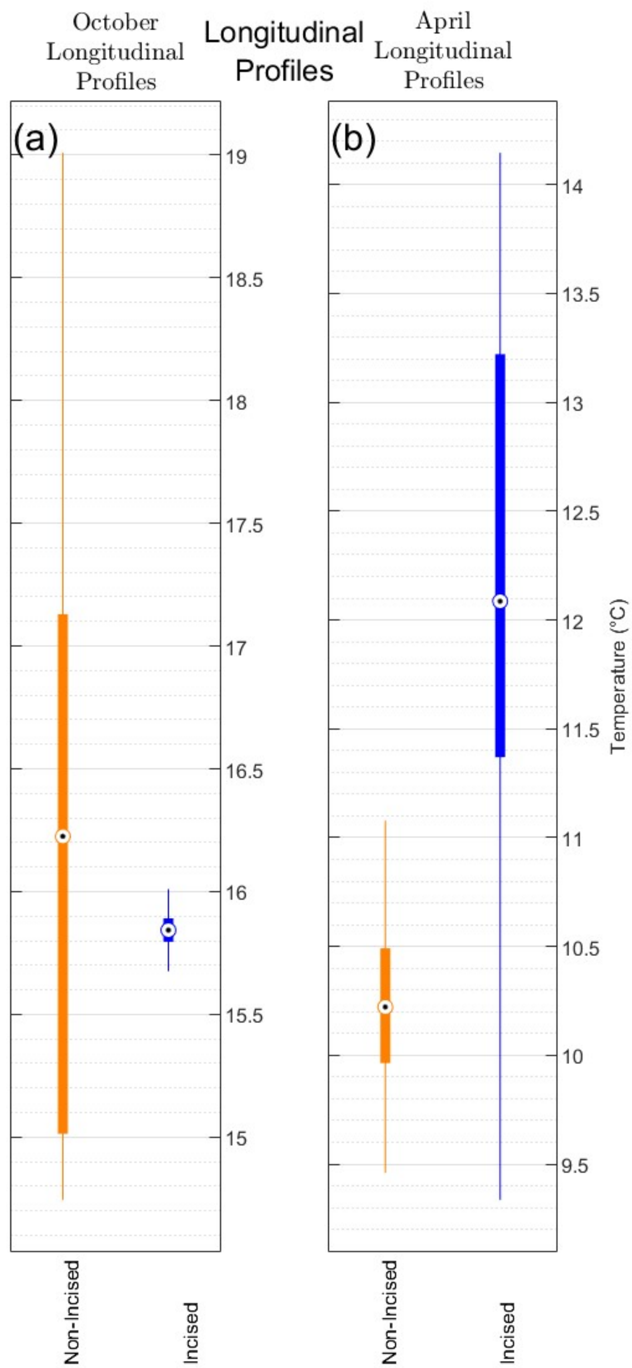

Figure 12: Longitudinal temperature ranges for both non-incised (orange) and incised (blue) stream profiles for (a) October 2021 and (b) April 2022, with black dots denoting median temperatures, solid box denoting 25th to 75th temperature ranges, and line representing full temperature range. Note the difference in axes. ε = ±0.21 °C

Monthly means, medians, and ranges and statistical analyses

Twelve months of temperature data spanning from April 2021 through March 2022 for four categories (air, non-incised stream, incised stream, and outlet stream) were compiled for a total of forty-eight study months (Fig. 13). Of those forty-eight cumulative months, a total of seven did not meet the 50% observed and recorded threshold to be utilized for statistical analysis due to device failure or insufficient water levels (April air, June outlet, July outlet, November air, November non-incised, November incised, and November outlet). Another four months met the 50% threshold but fell short of a 80% or more observed and recorded temperature threshold (October air, October non-incised, October incised, and October outlet).

The general trend for these data show a sinusoidal temperature variation across all categories, with peak medians in July and August and minima in December. Monthly means and medians were similar for most of the year, but medians were noticeably higher than means in October for stream temperatures.

Statistical analysis was completed using the Wilcoxon rank-sum test (Table 1). Incised stream temperatures were significantly cooler than non-incised stream temperatures for both warm and cool months. The outlet was statistically warmer than the incised and non-incised input streams during warm months and statistically cooler in cool months. There was no significant difference in monthly medians for warm months or cool months for either the incised stream relative to the non-incised stream or the outlet relative to the inlet. There was also no statistically significant difference in monthly temperature ranges between the incised and non-incised stream and the outlet and inlet streams across the entire year.

Warm and cool month timeseries

The timeseries for air, non-incised stream, incised stream, outlet stream, and groundwater temperatures show that the difference between stream and groundwater temperatures was the least pronounced during cool months and most pronounced during warm months (Fig. 14). Sinusoidal diurnal temperature variation was also less pronounced during cool months, with the cycle appearing noisier. During warm months, by contrast, the sinusoidal pattern was pronounced for all categories except 1m deep groundwater data, though it was present in the 10 cm deep groundwater and soil (Fig 14a). In addition, the response of streams and groundwater to air temperature change was more pronounced for the system during the cool months (Fig. 14b).

Timeseries for 1 m deep wetland well groundwater temperatures and gauge depth readings for August and January show that changes in temperature occurred largely independently of changes in water level (Fig. 15). While both seasons showed similar mean gauge depth for individual wells, temperature variation was higher in the winter while gauge depth variation was higher in the summer (Fig. 16). Inlet and outlet streams also showed weak temperature responses to storm events to within the range expected for diurnal variation, even for storm events where water depth increases by an order of magnitude (Fig. 17-18). While August storm events corresponded to greater changes in water level than January ones, August depth changes were less persistent, appearing as sharper spikes than January events on the timeseries (Fig. 17). While depth changes were greatest for the outlet and least for the incised inlet, changes were the most persistent for the non-incised stream. While most storm events and water level do not appear to have driven temperature changes outside of the diurnal range, they may have still impact temperature. Storm events throughout August corresponded to temperature drops, and diurnal ranges were sometimes restricted following these events (Fig. 17a). The magnitude of drops did not correspond to the magnitude of water level increases, and the air temperatures changes during the same times (Fig. 14a) could mean that air temperature changes associated with weather events dominated the stream temperature responses. An event on the 26th of August, however, corresponded to a water temperature response, especially in the incised stream, without a corresponding air temperature change. While diurnal variation was weak throughout January for all three streams, it may be worth noting that water levels were higher and that levels remained elevated for longer following storm events (Fig. 17b).

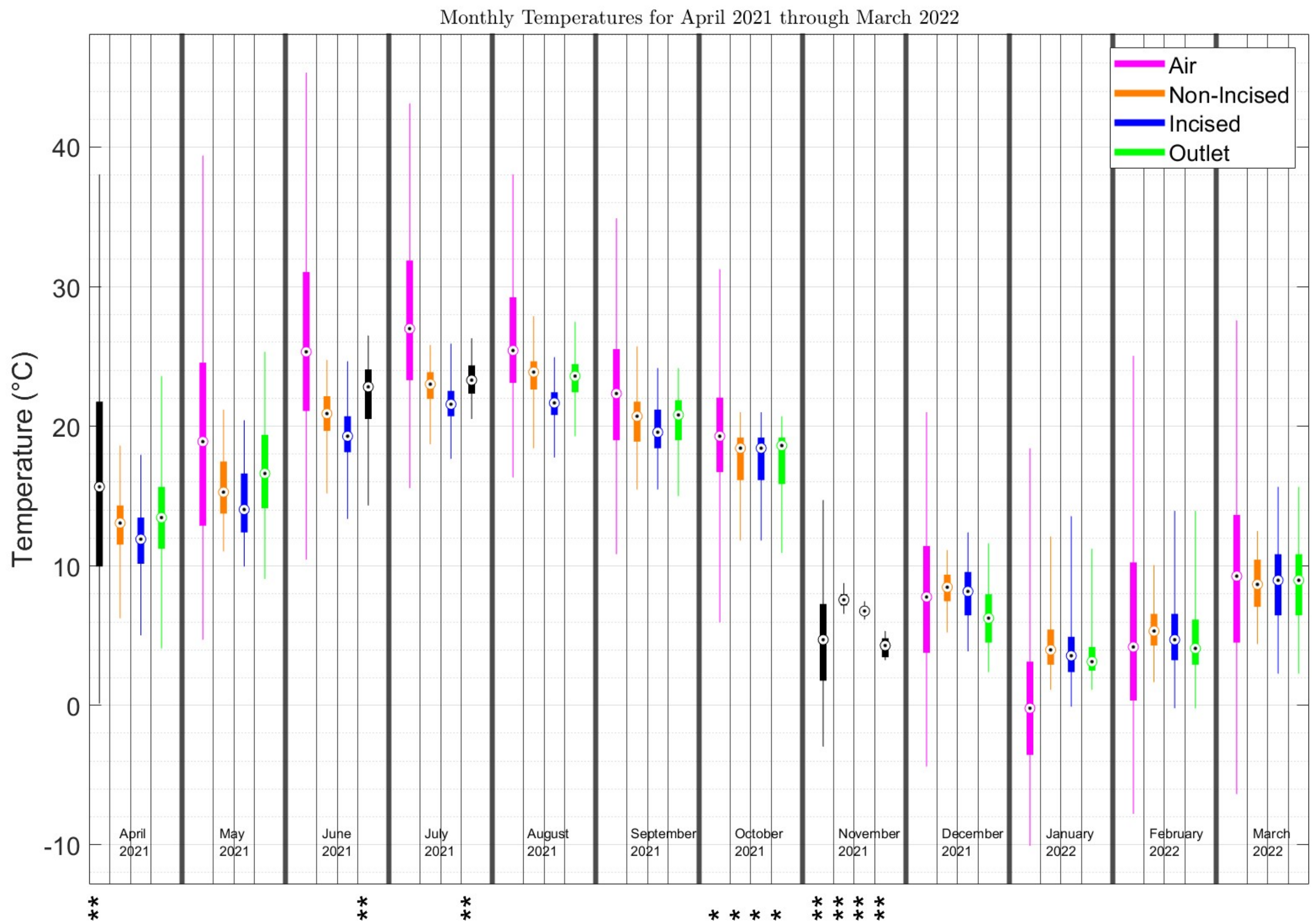

Figure 13: Boxplot for monthly temperatures for air (magenta), non-incised stream (orange), incised stream (blue), and outlet stream (green) temperature over a year-long observation window between April 2021 and March 2022. A single asterisk (*) denotes sample windows exceeding the 50% of monthly temperature values observed and recorded threshold but less than 80%. A double asterisk (**) denotes windows not meeting the 50% threshold for observed and recorded data and not considered for statistical analysis and inference (blacked out). Black dots represent median temperatures, solid boxes represent 25th to 75th percentile ranges, and colored lines represent full temperature ranges. ε (Air) = ±0.21 *°C and* ε (Else) = ±0.44 *°C*

	p value	Z value	h
Incised to non-incised medians (warm months)	0.4000	N/A	*0*
Incised to non-incised means (warm months)	<0.00005	-84.5322	*1*
Outlet to inlet medians (warm months)	0.7000	N/A	*0*
Outlet to inlet means (warm months)	<0.00005	-20.2449	*1*
Incised to non-incised medians (cool months)	0.5714	N/A	*0*
Incised to non-incised means (cool months)	<0.00005	<0.00005	*1*
Outlet to inlet medians (cool months)	0.5476	N/A	*0*
Outlet to inlet means (cool months)	<0.00005	-51.7048	*1*
Incised to non-incised ranges	0.1992	N/A	*0*
Outlet to inlet ranges	0.1700	N/A	*0*

Table 1: Wilcoxon ranked sum statistical analysis results for two-tailed test with a critical p-value of 0.05. Values calculated by exact or direct test for medians and ranges and approximate test for means. For approximate tests, Z-values are listed, showing direction of difference where significant. h value is 0 if null hypothesis is retained and 1 if it is rejected.

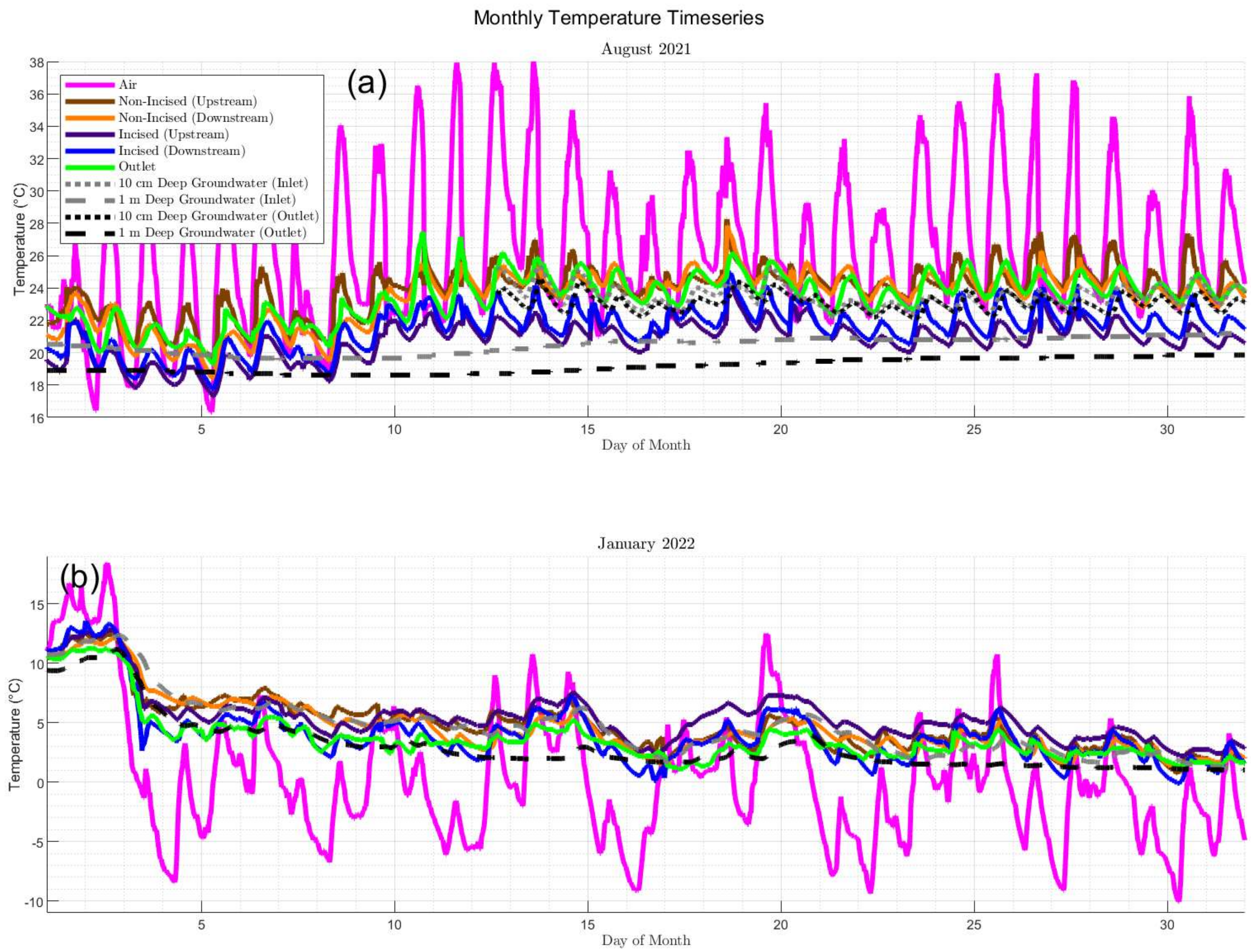

Figure 14: Monthly temperature timeseries for (a) August 2021 and (b) January 2022. Note that 10 cm deep groundwater temperature records are only available for part of August. Note the difference in axes. ε (Air, 10 cm Deep Groundwater) = ±0.21 *°C and* ε (Else) = ±0.44 *°C*

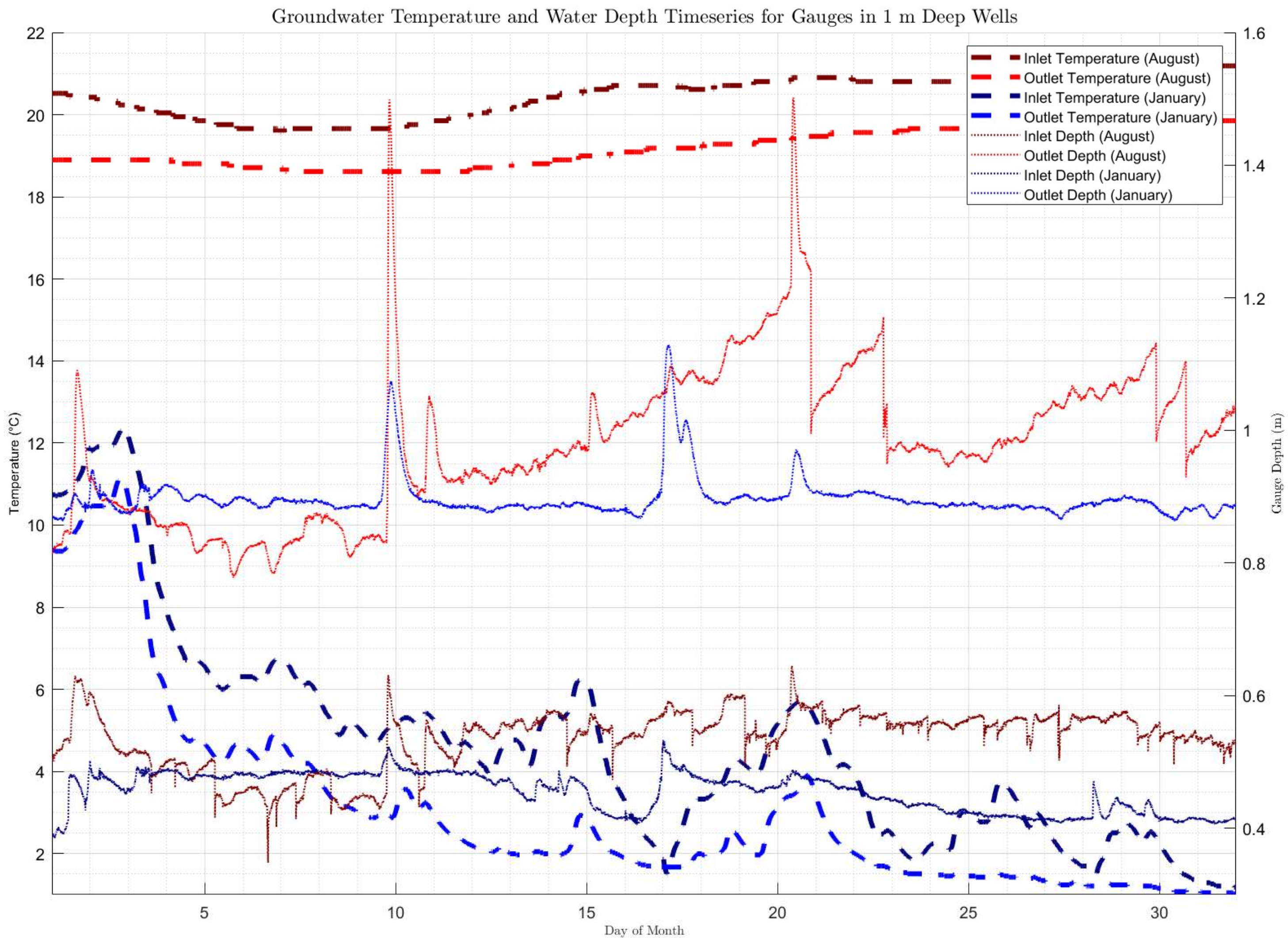

Figure 15: Groundwater temperature (broad dashed) and water depth (point dashed) monthly timeseries for the 1 m deep wetland inlet and outlet wells for August 2021 and January 2022. Month is distinguished by color, and well is distinguished by shade. Temperature is represented by the left y-axis, and gauge depth from the right y-axis. Gauge depths values greater than 1 m correspond to periods of water inundation at the surface. ε = ±0.44 °C, ±0.008 m

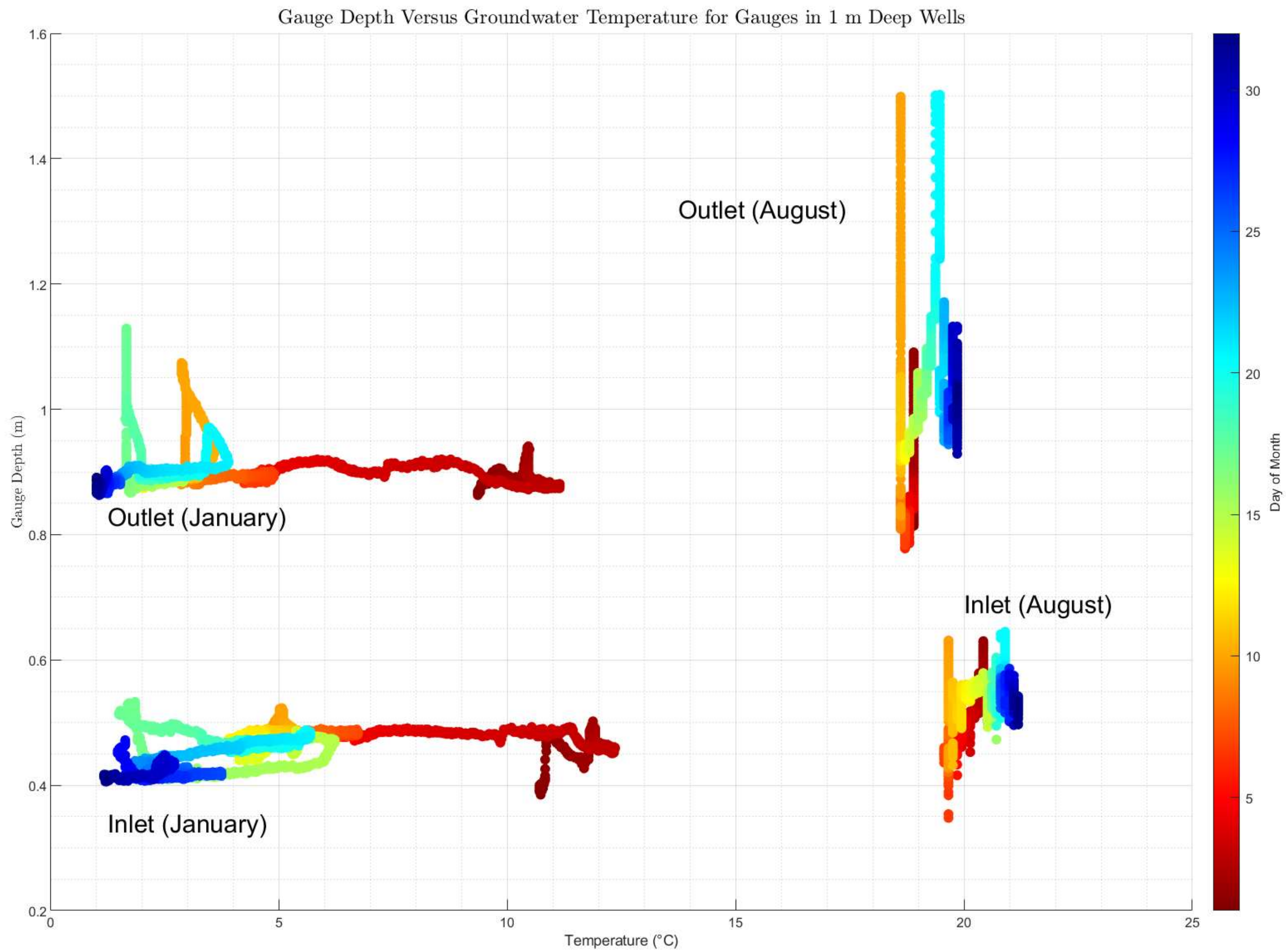

Figure 16: Gauge depth versus groundwater temperature for the 1 m deep inlet and outlet wells for August 2021 and January 2022. Variation with time is shown with the color bar. Gauge depths values greater than 1 m correspond to periods of water inundation at the surface. ε = ±0.44 °C, ±0.008 m

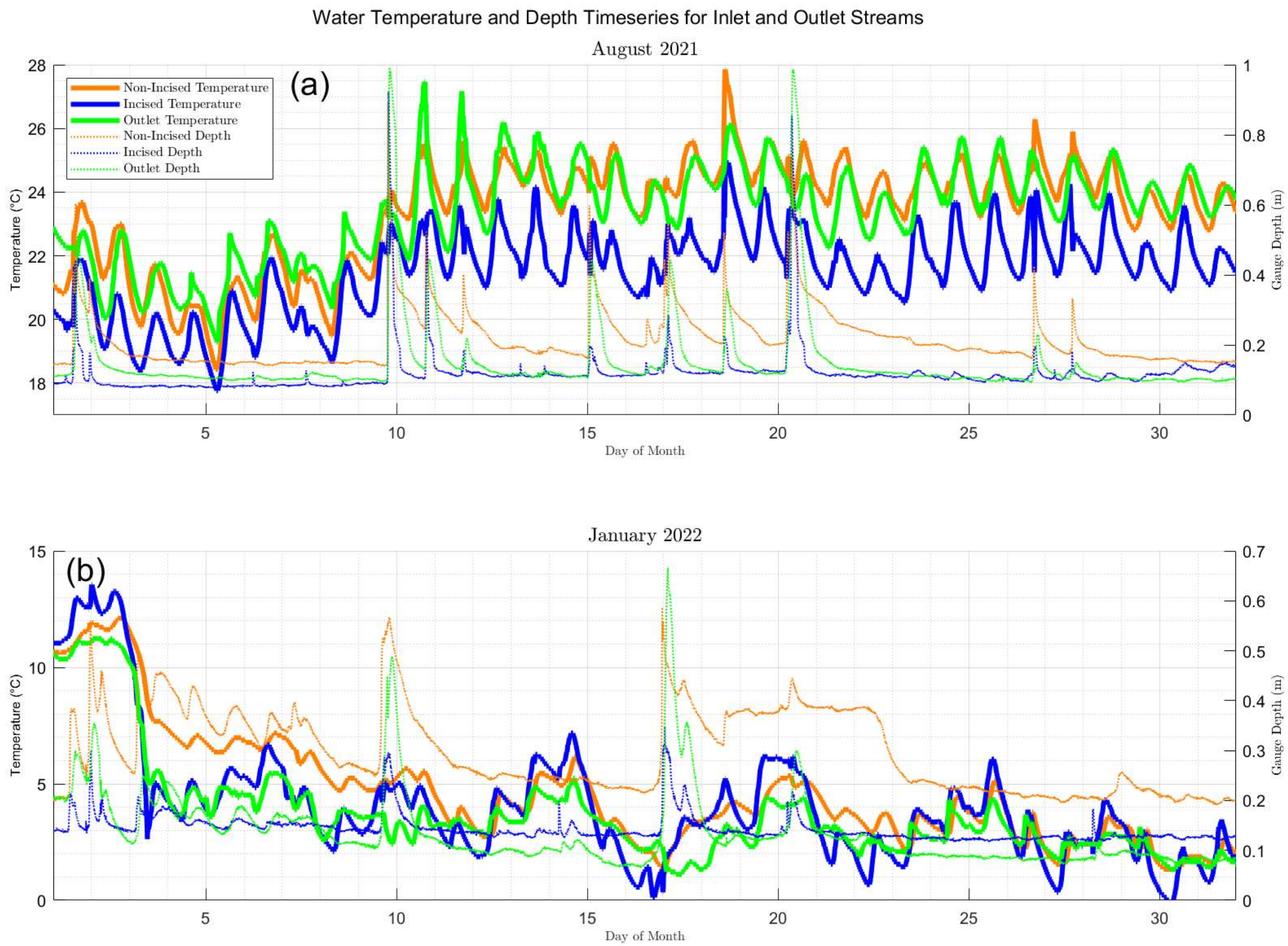

Figure 17: Non-incised (orange) and incised (blue) inlet and outlet (green) stream water temperatures (solid) and water depth (point dashed) monthly timeseries for August 2021 and January 2022. Temperature is represented by the left y-axis, and gauge depth from the right y-axis. Note the difference in axes. ε = ±0.44 °C, ±0.008 m

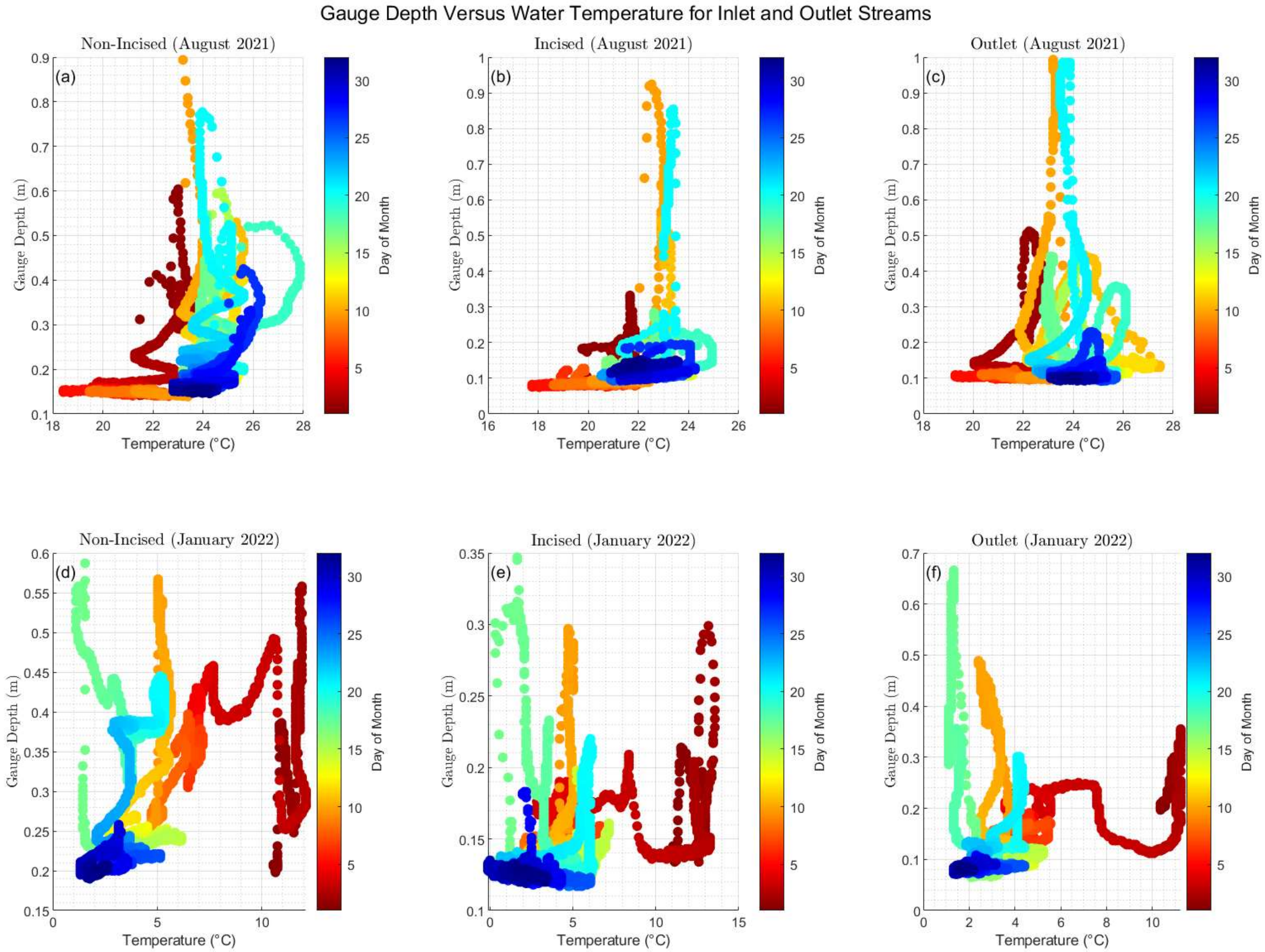

Figure 18: Gauge depth versus water temperature for the inlet and outlet streams for August 2021 and January 2022. Variation with time is shown with the color bar. Gauge depths values greater than 1 m correspond to periods of water inundation at the surface. Note the difference in axes. ε = ±0.44 °C, ±0.008 m

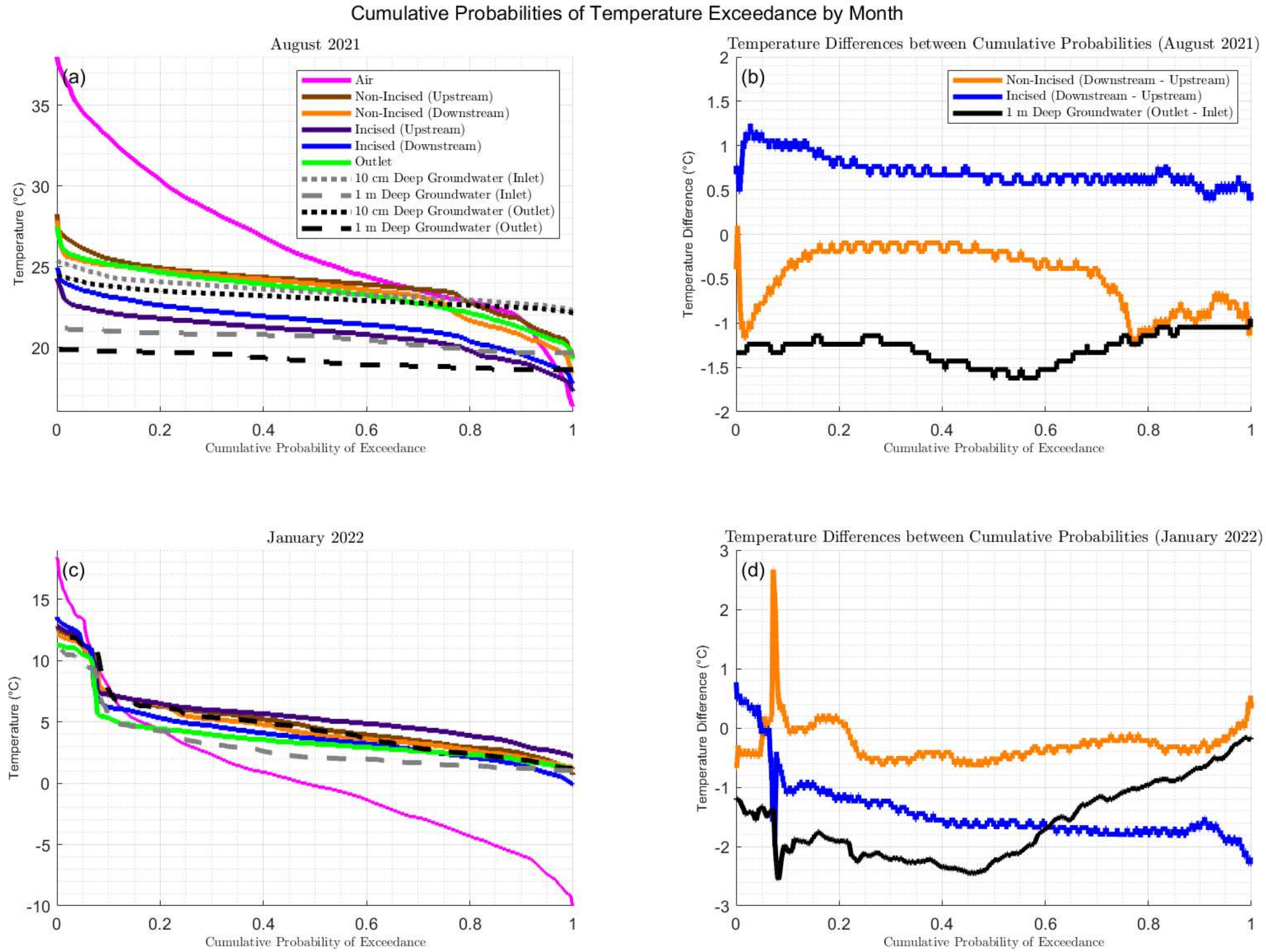

Figure 19: Cumulative probabilities for temperature exceedance for (a) August 2021 and (c) January 2022. Note that 10 cm deep groundwater temperature records are only available for part of August. Temperature differences between cumulative probabilities of exceedance for the downstream and upstream temperatures for the non-incised (blue) and incised (orange) streams and the inlet and outlet well temperatures for the 1 m deep groundwater (black) for (b) August 2021 and (d) January 2022. Note the difference in axes. ε (Air, 10 cm Deep Groundwater) = ±0.21 *°C,* ε (Differences) = ±0.62 *°C, and* ε (Else) = ±0.44 *°C*

Exceedance probabilities of stream temperature for warm and cool months

The cumulative probability of exceedance plots reinforce that water temperatures were more comparable between gauge sites in January than August (Fig. 19a, 19c). With the exception of the air temperature probability curve, it is difficult to distinguish between sites by the shape of the plots alone for January (Fig. 19c). Water temperatures were also shown to be more responsive to warm air temperatures than cooler ones. In contrast, the plots are easy to distinguish visually by shape for August, and responsiveness to air temperature was higher to cooler air temperatures (Fig. 19a). Surface water temperatures were comparable between a site's 20th and 95th percentiles, with temperatures differences between percentiles increasing below the 20th and especial the 5th percentile values and above the 95th percentile values. These sharp ends to the probability plots were less pronounced for the 10 cm groundwater temperatures and absent for the 1 m deep groundwater. This temperature stability meant that the shallow groundwater temperatures, which were close to surface water temperatures for most of August (Fig. 14a), remained warmer than air, surface, and 1 m deep groundwater below the 20th percentile for temperature. For temperatures above the 95th percentile, the upstream portion of the non-incised stream and the downstream portion of the incised stream show a smoother increase in temperature with increasing percentile than the non-incised downstream and incised upstream, leading to a convergence in maximum temperature for upstream and downstream portions. The outlet's curve closely followed that of the non-incised downstream, especially at higher temperatures.

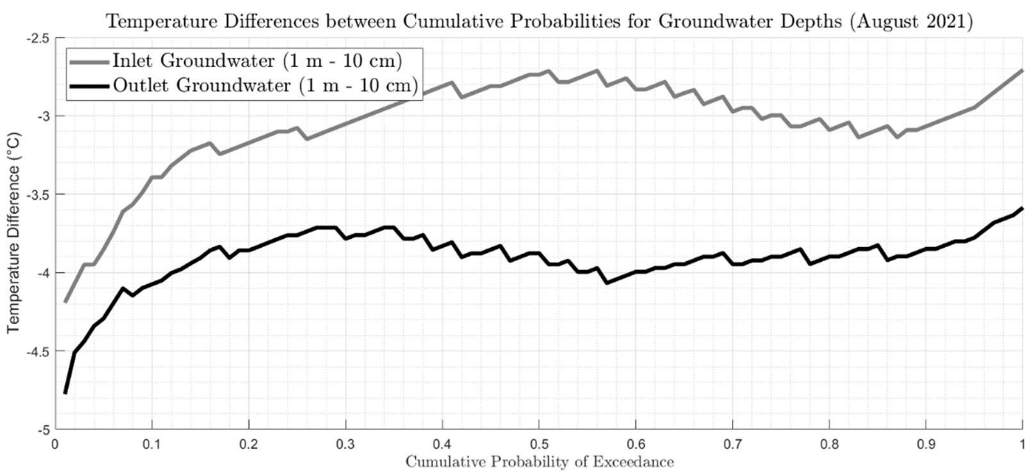

Figure 20: Temperature differences between cumulative probabilities of exceedance between 1 m deep and 10 cm deep groundwater for the inlet (grey) and outlet (black) wells for August 2021. Due to an incomplete record for 10 cm deep groundwater temperatures for the month, differences were calculated by matching percentiles than fractional probability. Error summed in quadrature. ε = ±0.49 *°C*

The plots also show that the incised stream cooled with length during the cool month and warmed with length during the warm month (Fig. 19b,19d). This pattern was only broken at the lowest probabilities of exceedance, where the stream warmed with distance downstream. In contrast, the non-incised stream remained largely constant in temperature with distance downstream during the cool month and cooled with distance downstream during the warm month. While the amplitude of the change for the non-incised stream was greater than for the incised stream, many of the features in the difference graph are inverted between the non-incised and incised streams. This results in a reflection-like pattern. For August, groundwater temperatures declined with depth between 10 cm and 1 m depths for both the inlet and outlet wells, with the gradient being steeper at the outlet well (Fig. 20). Gradients were closest between wells during the warmest periods, with a difference between well gradients of approximately 0.75 °C. This also corresponds to times when the gradients were steepest due to high surface temperatures and stable groundwater temperatures. Gradients were the most different in the near 50th percentile ranges, approaching 1.5 °C. At the lowest temperatures, gradient differences were near 1 °C and gradients were also the least steep.

Stream temperature regressions and Bogan classification

Liner regressions were performed for relationship between air temperature monthly means and monthly stream temperature means for the non-incised, incised, and outlet streams for months meeting the 50% observed and recorded threshold (Fig. 21a). When the resulting slopes and intercepts were plotted using the convention outlined by Bogan et al. (2003), all three streams appeared outside the normal boundaries for stream and river distributions, best corresponding to the middle cohort of streams, which account for 68% of streams or those streams with the usual water temperature dependence on air temperature and groundwater interactions (Fig. 21b). The incised stream had the highest intercept and lowest slope, suggesting more independence from air temperature than the other three streams. The outlet showed the strongest dependence on air temperature, given its high slope and low intercept.

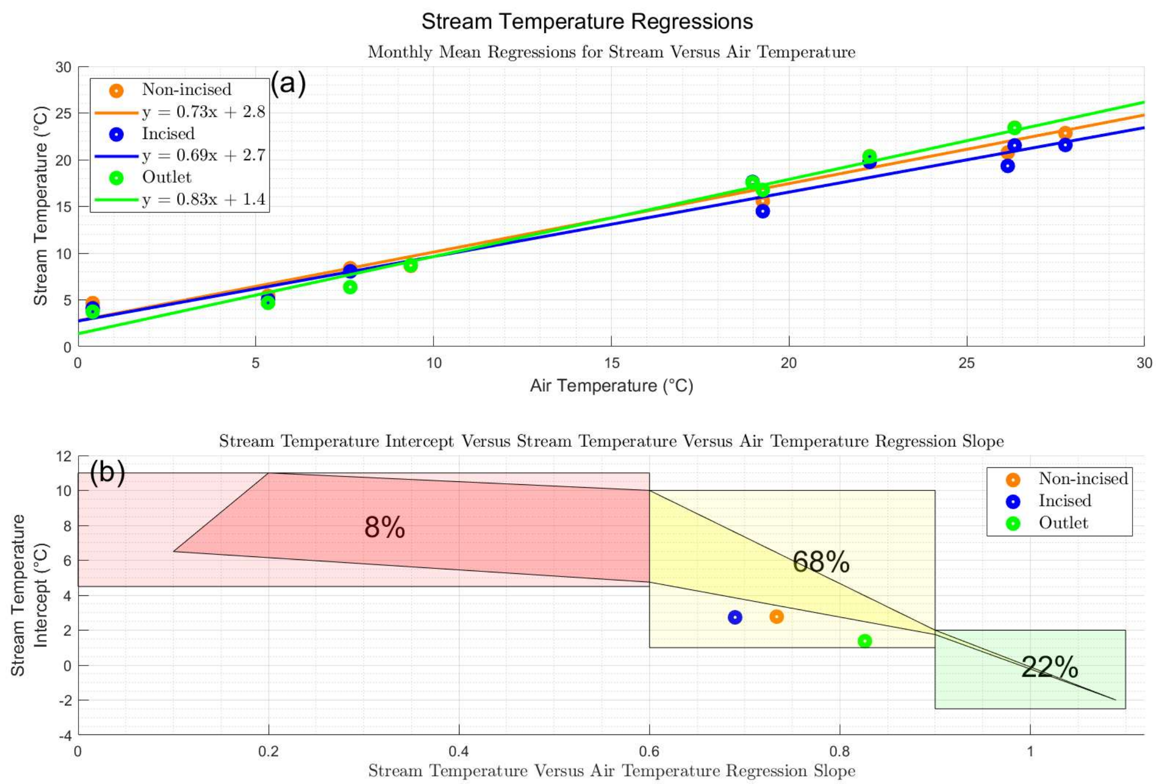

Figure 21: (a) Monthly mean stream temperature regressions for months exceeding the 50% observed threshold and (b) stream temperature versus stream temperature versus air temperature regression slope plot and corresponding classifications from Bogan et al. (2003).

DISCUSSION

The data collected in this study identified significant temperature differences between the incised and non-incised streams as well as distinct seasonal temperature regimes for the two streams. In October, the range for incised stream temperatures was a small fraction of that for the non-incised stream (Fig. 12a). In April, the trend largely reversed, though the thermal range of the non-incised stream relative to the incised stream was still greater than the incised stream relative to the non-incised in October (Fig. 12b). In October, persistent dry weather and dry patches meant the non-incised stream had to have been fed by groundwater for much of its length rather than overland flow. This also meant longitudinal flow rates were relatively slow; therefore, the degree of longitudinal water mixing and flow rates were low. Despite this, the stream cooled with length even when air temperatures were substantial higher than stream temperatures, suggesting that groundwater not only fed the stream for much of its length but also impacted temperatures substantially. For the incised stream, the water was significantly less stagnant and flow rates were greater. Water pooled little, resulting in significant longitudinal mixing and greater temperature homogeny. In addition, the non-incised profile demonstrated water was cool, resulting from largely cool water influx into the stream relative to air temperatures. If groundwater temperatures and discharge rates were homogenous or nearly homogenous along the stream's length, the incised stream would likely warm with distance downstream. Thinking of this in terms of heat budget, a parcel would begin with a temperature near that of the groundwater that would rise with length due to exposure to warmer air. This parcel is experiencing net warming. With regular distance intervals downstream, more parcels are added or near the original parcel's initial temperature. These parcels then warm with exposure to air as well. The original parcel would have warmed significantly more than the last parcels to be added, but the average parcel temperature with length increases even as new parcels are added.

In April, the non-incised stream flow rate was significantly higher, resulting in higher rates of longitudinal water mixing. This would more evenly distribute apparent cooling or warming from the groundwater as individual samples would be sampling several parcels, not just the exposed groundwater seep. The April trend, at least for the first 60 m, appears comparable in shape to the October profile but with a restricted temperature range (Fig 10a,10c-10d,11a,11c-11d). After this distance, the stream was too dry in October to record, making comparisons difficult. The April temperature ranges in the final segment, however, are greater than the incised stream in October. This can be interpreted as heterogenous groundwater temperatures or discharge being relatively common in this final stretch of surveyed stream. The incised stream had considerably more heterogenous temperatures in April than even the non-incised stream in October, but water influx was visually more heterogenous as well (Fig 10b,10c-10d,11b,11c-11d). Visually, the idea that incision would cut the stream deeper into the water table was confirmed by height of the seeps during conditions with a high water table. In addition, springs were feeding sizable amounts of water into the stream. Groundwater contribution in October had to have come from a deeper source, given the lack of wall seeps or wet springs. This deep source likely never ceased; shallow and surface sources were only added. This interpretation could explain why temperatures decreased at locations with high incision and with low seep and spring counts. While deeper sources of groundwater had been feeding the incised stream, additional shallow sources may have been feeding it as well. The obviousness of this heterogenous feeding on the longitudinal profile, however, shows that deeper sources of groundwater alone are not sufficient to mediate temperatures during higher flow events.

Looking at the warm and cool month timeseries and the corresponding cumulative probabilities of exceedance, the importance of groundwater interactions in controlling surface water temperatures is further emphasized (Fig. 14,19). When groundwater temperatures at depth were responsive to air temperature changes, the stream temperatures become increasingly difficult to distinguish from each other, and diurnal variability became less regular. The 1 m deep groundwater closely followed the trend of surface water temperature variation, dropping more than 5 °C within a week. During the summer, when stream temperatures were clearly stratified on the timeseries, 1 m deep groundwater temperatures varied by less than 2 °C over the duration of a month. Considering that both 1 m deep sites reached a low near 1 °C during the winter but began August with temperatures near 19 °C and 20.5 °C, there had to have been a point in the year where the groundwater mixing regime switched from liberal mixing to what appears to be stagnant stratification of the groundwater and isolation from the surface.

Shallow 10 cm deep groundwater showed distinct diel variations in August but with diminished amplitude and lagged peaks relative to surface water (Fig. 14a). For most of the shallow groundwater data, temperatures were cooler than the incised stream, but warmer than the incised stream (Fig. 14a, 19a). This suggests that the groundwater feeding the incised stream was of a deeper source with temperatures closer to the 1 m groundwater values than 10 cm values.

The significance of this change in groundwater behavior and its apparent seasonality suggests that ET controls the behavior of the groundwater in this watershed. Variables such as air temperature and precipitation alone do not appear to have a seasonally consistent impact on the mixing regime, and the only remaining variable with seasonal variation and a recognized impact on hydrology is ET. Assuming this is the case, vegetation has the potential to restrict the flow between groundwater and surface water, effectively leading to the seasonal segregation of the watershed into surface and subsurface components with limited opportunity for interaction.

Given that the deep groundwater temperatures fall to low temperatures in the winter and fail to mix effectively with surface water during the summer, the groundwater should have little temperature restricting effect on the wetland's temperature. In fact, the low winter groundwater temperatures may actually cool the wetland and, thus, outlet water.

While groundwater mixing may not have restricted temperatures in the wetland, it does appear to have had some quantifiable impact on the non-incised and incised stream temperatures (Fig. 14, 19). Considering the longitudinal profile data, incision could cool streams and restrict temperature with respect to longitudinal distance, but this efficacy was reduced during and following storm events when sources of water influx become increasingly varied (Fig. 10-12). Looking at the cumulative probabilities for August, the incised upstream temperatures appeared to have been closer to the shallow groundwater temperatures than the downstream portions, especially during peak temperatures. This trend was reversed for the non-incised stream, where the downstream temperatures more closely follow the temperature variability of the shallow groundwater, though not as closely as the incised upstream. During January, the non-incised downstream temperatures reflected the deep groundwater temperatures much more closely than in the summer, though neither upstream nor downstream water temperatures for the incised stream appeared to have a consistently stronger relationship to deep groundwater temperatures during the same period (Fig.19a,19c).

Between the 5th and 95th percentiles for temperatures, incision does ultimately appear to have had restricted temperature ranges, but thermal shock associated with the extremes of the temperature ranges appeared equally extreme with and without the impact of incision, leading to statistically insignificant range variation between incised and non-incised streams (Fig.19a,19c). In the incised stream during August, water tended to start upstream with temperatures more comparable to those of the groundwater and warm with exposure to air (Fig. 14a). Because the deep groundwater temperature variability in the summer was low, the upstream temperatures varied less than the downstream portion, which should have been exposed to more temperature forcing from the air. While the non-incised stream's temperature at the downstream gauge may have been more dependent on groundwater for temperature, less incision suggests that the groundwater feeding the stream was likely shallower and more responsive to air temperature variation. Prolonged intervals of stable, warm weather may have brought shallow groundwater temperatures near surface water temperatures. The diurnal temperature amplitude change was negligible in the deep groundwater; restricted in the incised upstream, non-incised downstream, and shallow groundwater; and comparable to the outlet, which is isolated from groundwater, in the incised downstream and non-incised upstream. This provides evidence that the non-incised and incised streams are inverted in terms of groundwater sensitivity such that the portions with the most incision have the most dependent on groundwater for temperature. While the ranges between non-incised and incised streams were comparable during the summer, the incised stream temperatures were largely that of a stable source of deep, cool groundwater entering a stream and being warmed gradually over its length by exposure to higher temperatures at the surface, and the non-incised stream was that of shallow groundwater responding gradually to changes in surface temperature (Fig. 22). Under this interpretation, both streams are defined by groundwater interactions, but the groundwater responsible is different between streams.

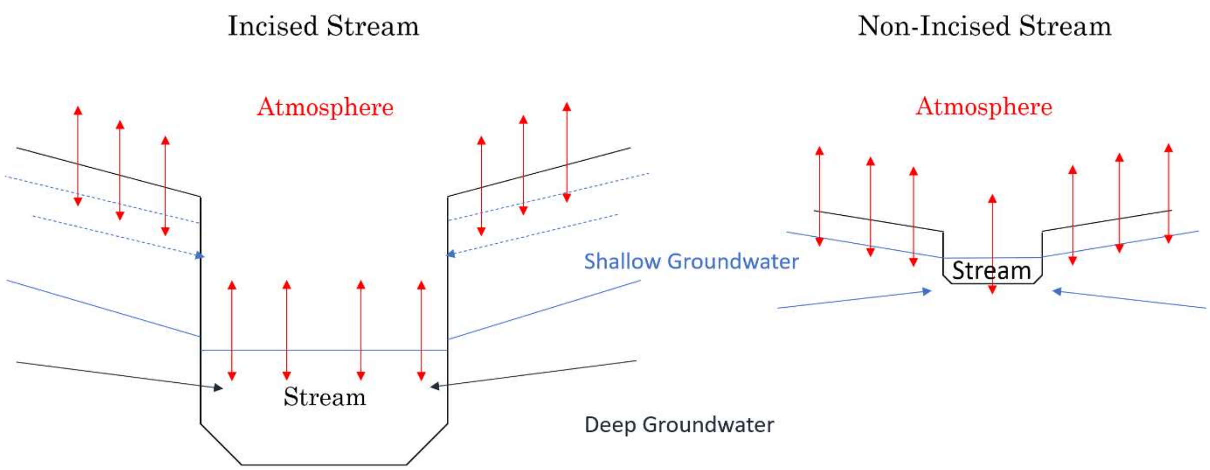

Figure 22: Conceptual model of the different groundwater influx regimes interpreted for the incised and non-incised streams. During low flow conditions, the incised stream is fed by deep groundwater sheltered from the atmosphere and with a stable temperature. Diurnal variation results from the gradual forcing of the stream along its length by exposure to air over a large surface. The shallow stream is small, and thermal inertia is low. Even small groundwater seeps alter temperatures rapidly and result in heterogenous temperature with longitudinal length. Diurnal variations persist due to the groundwater being shallow and responsive to changes in air temperature. During high flow conditions, the incised stream is fed partially by shallow groundwater seeps. These seeps contribute a substantial amount of responsive shallow groundwater to the stream at irregular intervals, resulting in heterogenous temperature with longitudinal length. High flow increase seep counts in the shallow stream until groundwater discharge is relatively consistent. This, combined with greater longitudinal mixing due to higher flow rates, leads to reduced temperature heterogeneity longitudinally. Since the diurnal variation for the shallow groundwater is less than exposed surface water, diurnal variation during high flow may be restricted without vanishing completely.

During January, the groundwater mixed with surface water more readily, both increasing the distance over and the degree to which groundwater mixing was occurring in both streams but also diminishing its effects due to the groundwater's temperature more closely reflecting surface temperatures (Fig. 14b). This led to high thermal ranges for the non-incised stream but little temperature change with length and weak diurnal amplitude cyclicity. The incised stream already had groundwater mixing over its entire length; therefore, changes in diurnal cyclicity were weaker than in the non-incised stream, though the change was stronger in the less incised downstream portion of the incised stream than the upstream portion. What did change was thermal range, especially in the upstream portion. The 25th to 75th temperature percentile range was much larger during the cool month, and this reflects a greater range in groundwater temperature. However, this groundwater still showed significantly less thermal variability than the air temperature, remaining warmer for most of the month. Under this interpretation, upstream water temperatures at the incised stream started relatively warm and cooled with length.

Regarding the statistical analyses, the monthly temperature ranges (Fig. 13) were not significantly different between the incised and non-incised stream and the outlet and the inlet streams due to incision controlling means, medians, longitudinal ranges, and inner quartile ranges, not extremes (Table 1)**.** Returning to the exceedance probabilities (Fig. 14), forcing brought about by events that drove temperatures outside the 5th to 95th percentile ranges during warm months appear to have overwhelmed mitigating factors in streams, especially for high temperatures. In the non-incised stream, this led to longitudinal temperature homogenization. In contrast, this led to heterogenization in the incised stream. During cool months, a longitudinal temperature gradient may have existed, but mitigating factors were weakened. The result was similar downstream monthly temperature ranges. The outlet is effectively an unmitigated stream, meaning extremes should be comparable to the inlet streams even if interquartile ranges are not.

The means and medians are a more complex story. The incised stream temperature medians were not significantly different from the outlet stream temperature medians, and the outlet temperature medians were not significantly different for either warm or cool months (Table 1). Temperatures, however, were significant between incised and non-incised and between outlet and inlet for both seasons. This was likely due to the amount of data considered. Medians were calculated for each month whereas temperature means used all data for threshold-exceeding months for the interval being considered, resulting in three orders of magnitude more data points for temperature versus median analyses. While means and medians are not identical, the null hypothesis of identical temperature can be rejected.

Arguably the most interesting results of the statistical analyses are the direction in which the temperature differences are significant. The seasonal thermal ranges for the outlet were greater than the inlet streams, meaning it is warmer during warm months and cooler during cool months than the inputs to the wetland (Table 1). These are closer to those expected for a detention pond as described by Herb et al. (2009) than for bioretention structures (Long and Dymond, 2013) or previously studied natural (Dick et al., 2018) and constructed (Kadlec, 2006) wetlands. The incised stream, in contrast, was cooler than the non-incised stream during warm months and cool months. Whereas the results of the outlet stream can be explained as a lack of the predicted groundwater mixing, the relative coolness of the incised stream is more difficult to explain and contradicts the range restriction originally predicted. Considering that deeper sources of groundwater were than the surface water throughout most of the year, it is possible that the incised stream starts cooler during both times of year and either warms lightly or cools slightly with length, depending on the air temperature (Fig. 19a, 19c). The shallower groundwater feeding the non-incised downstream starts warmer, even during cool months. If the water measured at the non-incised downstream site is relatively fresh from the groundwater, it should be warmer than cool groundwater further cooled by air exposure in the incised stream.

Interpreting the regression results with these interpretations in mind, the incised stream and non-incised streams are comparable in terms of air temperature and groundwater temperature dependences, with the incised stream remaining slightly less responsive to changes in air temperature. Groundwater still impacts the outlet stream, but the seasonality of groundwater contribution leads to an overall greater dependence on air temperatures for stream temperatures.

While this interpretation may explain seasonal differences in stream and groundwater temperatures within the watershed, it does not explain why surface and groundwater temperatures were influenced relatively little by storm events outside of what may be explainable by air temperature change accompanying events (Fig. 15-18). While there was some evidence for limited changes in surface water temperature with storm events and elevated water levels (Fig. 17-18), 1 m deep groundwater temperatures were effectively independent of these storm events and water level increases, even during January when the 1 m deep groundwater temperatures were relatively variable (Fig. 15-16). While ET may have been responsible for surface water levels returning to baseflow conditions in August faster than in January, it could not have been responsible for mitigating temperatures throughout the year. This surface impact of ET on lowering water levels did not manifest consistently throughout the watershed since the 1 m deep outlet well depth only rose considerably and with persistence during the warm month period (Fig. 15-16). Most runoff and subsurface flow that reached the streams, then, could have been approaching equilibrium defined within or near the diurnal variation from an interaction with the soil. The soil and shallow groundwater should have been close to equilibrium, and runoff flowing across it or permeating into it should have approached its temperature. Much of the runoff and subsurface reaching the streams first would have been thermally mediated by this effect. Since subsurface flow could have persisted for days after a storm event, it may have been responsible for restricting diurnal ranges following storm events (Fig. 17). If air temperatures continued to change following the storm event without giving the shallow groundwater enough time to re-equilibrate, the shallow groundwater could become a source for thermal heterogenies, especially if seeps and springs were spaced irregularly along the streams. This could explain the April longitudinal survey for the incised stream (Fig. 11b). Only exceptionally large amounts of precipitation or rapid air temperature changes could overwhelm the thermal mitigating properties of the soil to create the sharp extremes seen at the fringes of the cumulative probability plots for August (Fig. 19a) Since there was much more soil to mediating infiltrating water temperatures for the groundwater than surface water, the amount of precipitation necessary to alter temperatures without liberal surface-subsurface water mixing and exchange was likely too high to impact 1 m deep groundwater temperatures with any degree of significance.

It is important to note that, if the mechanisms proposed here accurately describe the processes occurring in the study site, these findings may still not be universally applicable to all urban streams. While the study site received urban runoff, the total amount was small. Results may be different for larger watersheds, watersheds with a greater portion of their water budgets originating as urban runoff, or watersheds with more impermeable surface cover, these findings may not apply well. However, these results do show how historically incised streams and constructed wetlands may contribute to water temperature heterogeneities within urban watersheds.

CONCLUSIONS

While the null hypotheses were rejected, the grounds for rejection also conflict with the results expected for the alternative hypotheses. The following were concluded:

1. Seasonal temperature ranges were statistically different between the incised and non-incised streams, with incised stream temperatures remaining cooler than the non-incised stream during both warm and cool months.

2. Monthly temperature ranges were not statistically different between the incised and non-incised streams.

3. Seasonal temperature ranges were statistically different between the outlet and both incised and non-incised inlet streams, with outlet stream temperatures remaining warmer during warm months and cooler during cool months than the inlet streams.

4. Monthly temperature ranges were not statistically different between the outlet and inlet streams.

Ultimately, the experimental results imply that the motivating sentiment behind the original alternative hypotheses, that geomorphology impacts how and what groundwater interacts with surface features such that stream water temperatures are affected, has bearing on surface hydrology. However, how geomorphology and groundwater relate is different than originally predicted.

The magnitude of mitigation brought by having a stream fed by deeper sources of groundwater may be sufficient to control and restrict temperatures during temperatures between the 5^{th} to 95^{th} percentile for a given month, but events which exceed these boundaries likely occur with a magnitude of forcing which overwhelms the mitigative influences of factors such as incision. Considering range is determined by extremes and incision controls means, ranges are not restricted. This limits the efficacy of incision as a TMP in controlling thermal shock, but it suggests promise in depressing annual stream temperatures.

In winter, surface-subsurface interactions increase in intensity such that there are signs of mixing in even non-incised segments, but ranges are not seriously impacted since the groundwater temperatures are also more variable, closely following surface water temperature trends. While groundwater may cool more of the streams, the temperature gradient between steams and groundwater would be weaker.

The dramatic shift in seasonal groundwater behavior may be evidence of an ‘ET Switch,’ where groundwater mixing is most significant when ET rates are low and decline once trees begin to transpire. Sources such as the constructed wetland lose the benefits of thermal mitigation from groundwater interactions as temperatures warm, leading to a lack of mitigating effect during the season where thermal pollution has the most potential to harm biodiversity.

If increased rates of spring and summer ET rates limit interaction and mixing between the surface and subsurface, incision could act as an open window that allows for thermal mitigation from groundwater even when deeper sources of groundwater are seasonally isolated.

Ultimately, the efficacy of incision in mitigating thermal pollution was only effective at depressing warm season means without providing significant protection from thermal shock. The constructed wetland, by contrast, did little to mitigate temperature and demonstrated the potential for certain wetlands to adversely increase summer stream temperatures.

ACKNOWLEDGEMENTS

I would like to thank Dr. Karen L. Prestegaard for her guidance and patience throughout not only my time completing my senior thesis but also my entire experience as a student at the University of Maryland. It is thanks to her support and instruction that I can finally claim to have truly participated in the scientific community, and, for this, I am eternally grateful.

I would also like to thank Samantha Volz for her assistance throughout this process. She is responsible for most of the maintenance and upkeep of the gauge network at the golf course, and she also helped considerably with conducting the longitudinal stream surveys. Without her efforts, I would not have had the data necessary to even approach this topic.

Finally, I would like to thank Dr. Phillip M. Piccoli for coordinating the senior thesis program. He has consistently encouraged me to perform my best throughout these last two semesters, and I could not imagine having to undertake this journey without someone as positive and enthusiastic as him setting the tone. I had fun!

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