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Effect of upstream ponds on stream temperature

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Abstract Many tributaries feeding streams are connected to ponds that heat up during summer months; however, the influence of these ponds on receiving stream temperature was not known. Stream temperature affects microfauna and fish habitats in aquatic ecosystems. Three tributaries with headwater ponds exposed to sunlight and one tributary unassociated with a large, upstream pond were selected for study within the Pennypack Creek watershed in the Philadelphia Metropolitan Area. Temperature loggers were installed in the pond (when applicable), associated tributary, and in the Pennypack Creek up and downstream of its confluence with the tributary. Although diurnal temperature fluctuations were apparent, the study showed no significant differences in temperature up and downstream of tributary discharge to Pennypack Creek. Pond water temperatures were up to 4°C warmer than the Pennypack Creek; however, temperatures downstream and upstream of the tributaries leading out of the ponds were within 1°C of each other.

Keywords Aquatic habitat · Headwater ponds · Loggers · Shading · Streams · Water temperature · Urban hydrology · Pennsylvania

Introduction

Importance of temperature in streams

Stream temperature affects microfauna survival, fish reproduction, and aquatic metabolism rates. Nearly every species is temperature sensitive. In terms of survival, cold water fishes tend to be limited to water below 25°C, and trout prefer water less than 20°C. Sponseller et al. (2001) found that macroinvertebrate taxa richness, diversity, and evenness decrease as maximum stream temperature increases. Although other physical habitat and ecosystem-level factors may play important roles in determining success and ultimate standing crop of aquatic organisms (Allan 1995), temperature has a fundamental effect on seasonal timing of life cycles and survival of stream microfauna and fish. Headwater streams seem to be particularly sensitive to temperature changes (Allan 1995).

Warm temperature is a commonly cited habitat threat in urban streams because runoff is typically warmer than natural discharge to streams from groundwater (Paul and Meyer 2001; Wang and Kanehl 2003). Deforestation and reduction in baseflow often accompany increases in impervious land cover due to urbanization, and these factors may also result in increased stream temperature. Typically, in a non-urban stream, the source water is cool groundwater and temperatures increase along a downstream gradient as the surface water is exposed to solar radiation. Theurer et al. (1984) listed sources of heat flux in flowing streams as atmospheric radiation, direct solar radiation, topographic and riparian vegetation radiation, air circulation (convection), streambed conduction, evaporation, fluid friction, and water reflection and back-radiation.

Inverted temperature gradients (downstream cooling) have been observed where clear cutting exposed headwater ponds and streams (Beschta and Taylor 1988; Mellina et al. 2002) or retention ponds (Kieser et al. 2003). Wetlands can reduce the influence of headwater ponds by increasing infiltration and shading (Kieser et al. 2003). Downstream shading can also result in cooling (e.g., shading from riparian buffers). In an experiment using artificial cover, Johnson (2004) found shading reduced maximum temperatures, but had less influence on mean temperature. Changes in diurnal patterns in stream temperature, particularly an increase in the amplitude of diurnal temperature fluctuations, is a sign of anthropogenic inputs and/or modifications (dams, deforestation, etc.; Poole and Berman 2001). Borman and Larson (2003) found that air temperature was a more important factor in changes to stream temperature regime than crop type in an agricultural setting.

Modeling (i.e., computer simulation) can be an important tool to predict stream temperature because it involves heat budgets, and is less dependent on variability of measurements (Bartholow 1989; Johnson 2004). Models have helped compare the influence of different factors (LeBlanc et al. 1997), predict cooling distances (Sridhar et al. 2004), and improve understanding of anthropogenic inputs (Bogan et al. 2004).

In summary, a number of factors influence stream temperature, including: air temperature, shading and vegetation, substrate, and physical characteristics of the stream (Johnson 2004; Poole and Berman 2001; Bogan et al. 2003). This study presents data on one factor, upstream ponds which have been warmed.

Site description

The Pennypack Creek watershed in southeastern Pennsylvania has undergone cycles of urbanization over the past centuries. The headwaters of Pennypack Creek are in suburbs that have seen marked increases in land development in the past three decades, (i.e., urban sprawl). The watershed has a 23 ha catchment and impervious cover is estimated at 42% of land area.

In 2002, Pennypack Creek Watershed was listed by the Pennsylvania Department of Environmental Protection (PA DEP) as impaired owing to habitat and flow modifications. Sources of impairment were cited as small residential/urban runoff and storm sewers. Philadelphia Water Department (PWD) completed a baseline assessment of Pennypack Creek watershed in 2002, conducting biological, chemical, and physical habitat monitoring to assess conditions within the watershed and identify stressors and sources of impairment (PWD 2003). Benthic macroinvertebrate sampling revealed that 50% of sites within Pennypack Creek watershed were ‘‘severely impaired’’ and 95% were ‘‘moderately impaired’’. Based on stream reach in km, approximately 80% were impaired. Impairment is based on finding dominantly tolerant macroinvertebrate taxa and few pollution sensitive taxa. Though sensitive taxa were present at a small number of sites assessed, they were only found in low densities.

Similarly, results of ichthyofaunal (fish) sampling characterized fish communities of Pennypack Creek watershed as dominated by a tolerant, generalist feeding taxa. Three species contributed 80% of total fish biomass. Although chemical assessments conducted by the PWD identified nutrient enrichment as a major concern with the watershed, the observed biological impairment was attributed mainly to physical stressors affecting habitat quality in the watershed, including hydrologic extremes, physical obstructions, erosion, and sedimentation.

The PWD report further identified 30 or more small man-made landscape and farm ponds within the central region of the watershed as potential physical stressors to the Pennypack Creek due to temperature change (PWD 2003). As these ponds heat up during the summer months, they may discharge warmer water into tributaries that they feed. The influence of these ponds on downstream temperature was unknown, and a study was designed to begin to address this question.

Materials and methods

Temperature loggers were installed in ponds, tributaries associated with the ponds, and in the main stem of Pennypack Creek up and down stream of study tributaries (Fig. 1). Data logging temperature sensors (Onset Computer Corp., Bourne, MA) were programmed to collect data at 30-min intervals from mid-May to early October 2004. Data were downloaded every 2–3 weeks. Some gaps in logging occurred due to a leaky case, battery failure, and loss of logger (presumably during storm events).

Three man-made ponds and one tributary with no significant sized pond were selected for study (Fig. 1). Cairnrun Pond is approximately 0.6 ha, and discharges to a tributary approximately 300 m from the confluence with Pennypack Creek. Loggers were placed in Cairnrun Pond, in the tributary immediately downstream of the pond outfall, and upstream and downstream of the tributary's confluence with the main stem of Pennypack Creek. Silverbrook Pond is approximately 1 ha. Silverbrook Pond is a widening of a tributary by the same name, which then discharges to Pennypack Creek approximately 740 m downstream. A logger was placed in the tributary at the discharge end of the pond before it

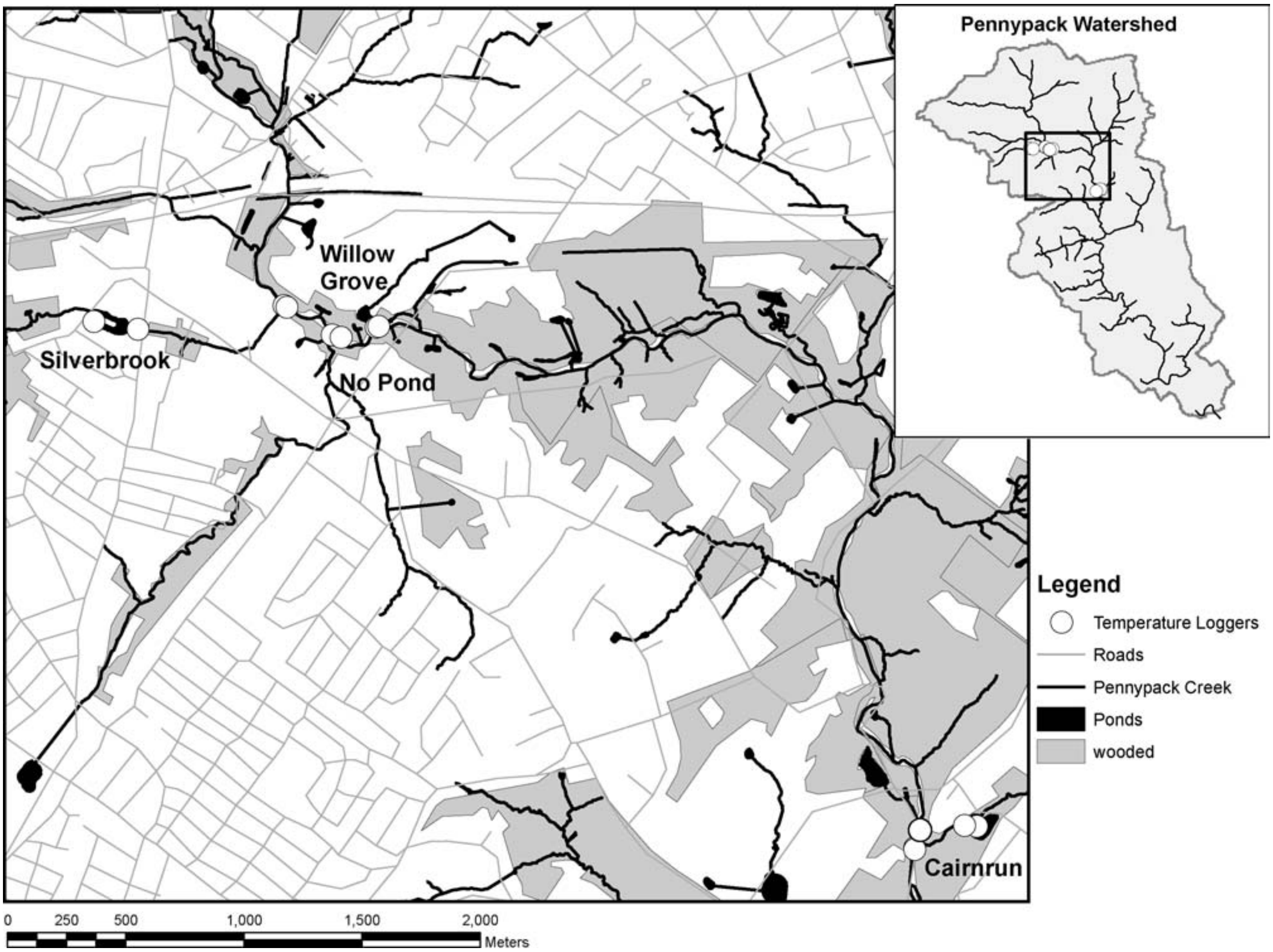

Fig. 1 Location map showing study sites and wooded areas around the streams

enters a culvert, then upstream and downstream on Pennypack Creek. Willow Grove Day Camp Pond (0.4 ha) discharges directly to Pennypack Creek. The pond was not monitored because owner permission was not granted. Pennypack Creek was accessible upstream and downstream of this pond, so loggers were placed only in the Creek.

A tributary with no headwater pond was also selected based on a 1983 US Geological Survey map. However, subsequent examination of a digital orthophotograph created in 2003 indicated there was some ponding on this tributary. One pond was present a considerable distance from the tributary's confluence with Pennypack Creek, discharging to a reach that is buried below ground for about 330 m. Total distance from this pond to the confluence was 2,754 m, which greatly exceeds the modeled range of influence of temperature inputs (1,800 m) suggested by Sridhar et al. (2004). A second, very small pond was observed to the side of this tributary closer to the confluence (165 m upstream). This pond is only 0.3 ha, and the pond water discharges into a small, shaded wetland area before entering the tributary. It was visually estimated that this side branch contributed less than 20% of the tributary outflow at the Pennypack, but discharge measurements were not available for comparison. It may be difficult to find a tributary with no ponding, but the selected tributary was assumed to be unaffected by ponding.

The ponds selected were open from tree cover for most of their area, and thus susceptible to heating from direct sunlight. Temperature loggers were placed approximately 0.33 m below the pond water surface. Temperature loggers placed in the creek and tributaries were carefully placed such that they were sheltered by trees or rocks where they would not receive direct sunlight, but were exposed to flowing water (not pools). The downstream logger was placed to receive the flow from the tributary. Typical stream depth was 0.05–0.2 m.

Nonetheless, it is known that temperature results were influenced by placement of the loggers. Because only one logger was placed at each site, the natural variability of temperature could not be assessed in this initial study. Sensitivity of the temperature loggers was ±0.1°C, but environmental variability (from placement of the loggers) was likely greater. Based on the variation in mean temperature along the stream reach with no headwater pond, estimated differences of less than about 1°C between sites could be attributed to natural variability.

In addition to variability in temperature due to placement, temperature data from all sites exhibited diurnal fluctuation in temperature, and were influenced by climatic factors (i.e., local weather, cloud cover, and storm events), which could either cool or warm the water. The influence of rainfall was not taken into account when calculating the range in temperatures, but it does not affect the range in values based on examination of specific storm events. Furthermore, the sites are in close proximity and subject to the same weather.

Although discharge of the tributaries was not measured at the sampling sites, a similar tributary (Hatboro USGS Site ID 1467085) on the Pennypack watershed monitored by the US Geological Survey (http://www.nwis.waterdata.usgs) contributed about 5–10% of the baseflow discharge on the main stem (Rhawn St USGS Site ID 1467048). While a single tributary might not affect baseflow temperature significantly, this study addressed the hypothesis that the combined affect of multiple tributaries with ponds could affect temperature. Furthermore, the downstream loggers were placed in the discharge from the tributary to capture a localized effect. If temperature was not significantly different near the mouth of the tributary, the overall effect on the stream would not be significant either.

Data were plotted and compared within and between sites. Mean values over the course of the study and by month were calculated, in addition to maximum and minimum values for each month. Further statistical analysis was not conducted because of the limited number of loggers and occasional gaps in the data.

Results

In this setting, there were no significant differences in mean temperature between the sites with and without ponds or between temperatures in Pennypack Creek upstream and downstream of tributaries (Table 1). Furthermore, the site with no pond showed little difference from the other two nearby ponded tributaries. Details are provided below for the mean temperatures observed and the ranges in temperature observed (Table 2). The ranges in temperature reflect diurnal temperature variation within tributaries. Pronounced temperature fluctuations can also affect microfauna fish habitat through regulation of metabolism and percent saturation of dissolved oxygen. The diurnal fluctuation in temperature varied from 3 to 12°C from month to month, but was similar in upstream and downstream loggers.

Table 1 Summary of mean temperatures (°C) recorded, June–Sept 2004

Site	Pond	Pond tributary	Upstream on Pennypack	Downstream on Pennypack
Cairnrun Pond[1]	24.25	20	20.1	20
Silverbrook Pond	22.8	23.5	22.7	22.45 (June and Sept only)
Willow Grove Day Camp Pond	Not accessible	Direct to Pennypack	22.2	22.4
No pond	Not applicable	Not applicable	21.8	22.25

[1]Includes data starting May 19

Mean temperatures in ponds and tributaries

At the beginning of the summer, the Cairnrun Pond was 4°C higher than the tributaries. By the end of the summer it was about 6°C higher. Data for some time intervals at this pond were missing because the casing for this logger flooded several times. Pond effluent seemed to dissipate most of its heat by the time it reached the temperature logger within the receiving tributary, where the mean temperature was 20°C (compared to a mean pond temperature of 24.5°C). Mean temperature in Pennypack Creek where the tributary discharges was also about 20°C (cooler at the beginning and end of the season). Although the upstream site had slightly warmer mean temperatures, data from upstream and downstream temperature sensors at this location were similar except at the end of the summer when upstream was 1.3–1.5°C warmer (Table 2). Because this variation is in the opposite direction from predicted if the ponds warmed the stream water, it is assumed the variability is due to placement of the loggers.

The Willow Grove Day Camp pond was not monitored (permission not granted). However, the pond discharged directly to the Pennypack at an accessible point, so the main stem of the creek was monitored. The upstream and downstream sensors were nearly identical throughout the summer. Mean temperature over the course of the season was around 22°C for both sensors.

Silverbrook Pond and water within its outfall culvert had warmer temperatures than Pennypack Creek during July (1–2°C, Table 2) but had mean

Table 2 Variation in temperatures (°C) by month

	May			June			July			August			September		
	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
Cairnrun Pond	23.9	28.3	20.5	23.8	27.1	20.2	25.5	29.4	23.2	26.2	30.7	22.4	23.0	27.9	19
Cairnrun tributary	19.4	24.4	14.9	19.7	24.1	15.9	21.7	25.1	18.8	20.3	24.8	15.3	18.5	22.6	13.2
Cairnrun upstream outlet	18.7	21.5	14.4	19.2	23.2	15.4	21.1	23.9	18.1	21.3	24.9	17.0	19.4	23.5	14.9
Cairnrun downstream outlet	18.7	24.5	13.9	18.8	23.1	15.2	20.8	25.7	17.9	19.8	23.1	15.8	18.1	22.1	12.7
Silverbrook Pond				22.5	24.9	19.3	23.6	30.7	19.8	22.6	25.8	17.7	22.2	24.3	19.6
Silverbrook tributary				23.3	25.7	21.1	24.5	29.5	18.4	23.7	30.8	18.9	22.3	25.4	20
Silverbrook upstream outlet				22.1	23.0	20.3	22.6	24.2	21.0	22.8	25.4	20.2	22.9	24.7	21.7
Silverbrook downstream outlet				22.0	23.7	20.3							22.7	24.3	20.7
Willow Grove Day camp upstream outlet				21.7	23.7	19.3	22.3	24.8	19.9	22.2	25.3	18.0	22.1	23.7	19.8
Willow Grove Day camp downstream outlet				21.8	24.0	19.5	22.5	25.6	20.0	22.6	25.6	18.4	22.3	24.2	19.9
No pond tributary upstream outlet				21.3	23.1	19.2	22.1	24.5	20.0	21.6	24.5	17.9			
No pond tributary downstream outlet				21.8	23.6	19.6	22.4	24.8	20.1	22.3	25.3	18.1	22.3	24.1	19.9

temperatures similar to the Pennypack site the remainder of the season. This pond was about 1.5°C cooler than Cairnrun Pond on average. Probably the placement of the logger on the south side of the pond provided extra shading from the pond wall. Interpretation of Pennypack Creek data at this site was limited because the downstream temperature logger was lost in July and August (replaced in September). For the limited monitoring period, mean temperatures at the upstream and downstream Pennypack sites were similar (22.7 and 22.4°C, respectively).

At the tributary site lacking pond discharge, mean temperatures were 21.8 and 22.2°C in the upstream and downstream temperature, respectively (Table 1). The upstream and downstream sensors were very similar to other Pennypack Creek sites, so no significant distinction can be made between the influence of this tributary and those with large upstream ponds.

Temperature variation

Diurnal variation in temperature due to the changes in incident solar radiation was observed at all sites (Table 2). Although this temperature variation is natural and predictable, severe changes in temperature are a symptom of anthropogenic influence and can be stressful to aquatic species. For example, temperature shifts of more than 1°C (ca. 2°F) per hour due to heated discharge from permitted activities are considered in violation of water quality criteria for a trout stocking fishery (designation of Pennypack Creek) by the Pennsylvania Department of Environmental Protection. The Department also has established maximum temperature criteria for waters of the Commonwealth based on designated uses. The maximum temperature permitted in Trout Stocking Fisheries in summer varies from 21°C (70°F) in June 1–15 to 30°C (87°F) in August 16–30.

The highest temperatures observed in the study area (29–30°C) were in the two ponds and in the Silverbrook tributary, which was an unshaded reach. The temperatures in Pennypack Creek were the same or lower than the source areas depending on the time of year. The maximum temperature criterion was exceeded in June but not later in the study period.

The diurnal cycle created temperature shifts of 3–12°C at all sites (Table 2). The degree of fluctuation was similar between sites for a given time period (Fig. 2), reflecting the consistency of weather across the locations. The temperature variation in the ponds varied between 5 and 10°C, more typically the lower end. The diurnal variations in upstream and downstream sites on Pennypack Creek were similar to each other at each site, with variations between 3 and 8°C.

Somewhat surprisingly, the largest differences between maximum and minimum temperatures were not observed in the ponds, but in the tributaries leading from the ponds. The ponds were open rather than shaded, but the pond sensors were placed on the edge of the pond and in deeper water; in contrast, the stream water was shallow where the sensors were placed possibly leading to more temperature variation. The highest difference between maximum and minimum temperature was between 10 and 12°C, and was observed in the tributaries from Cairnrun Pond and Silverbrook Pond in August. The latter is unshaded.

Hourly variations close to the 1°C limit were observed in the ponds and greater than 1°C in the Silverbrook tributary. Variation was lower than 1°C in the Pennypack Creek with the exception of some erratic

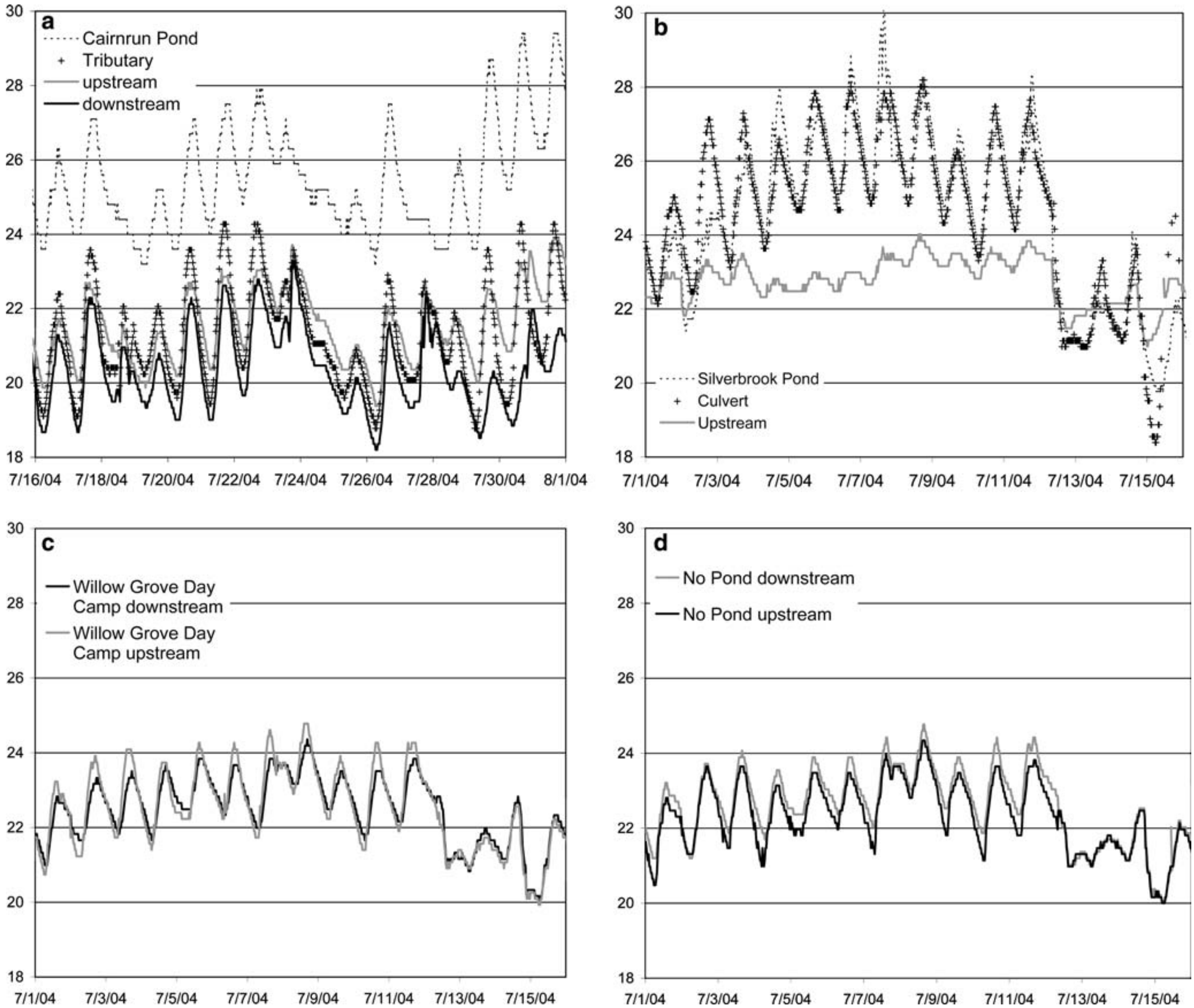

Fig. 2 Example temperature log from July showing diurnal variation at each site. Diurnal variations are similar upstream and downstream, and from site to site except for the larger variation in the pond and tributary at Silverbrook. The downstream logger was missing from Silverbrook in July

readings in the upstream logger at the site with no pond before it was lost in a storm.

Discussion

The warmth of the ponds seems to dissipate rapidly downstream in this study area. There was no obvious variation in temperature or diurnal cycles caused by the discharge of the pond tributaries to the Pennypack Creek. There are likely two factors that lead to the dissipation of temperature and rather uniform temperatures observed along the Pennypack Creek, both a function of the particular setting which is a suburban watershed.

First, shading has been observed to cool stream temperatures. All of the tributaries in this study had shading although the ponds were open (Fig. 1). Even the short drainage from the Willow Grove Day Camp pond was shaded. Furthermore, Cairnrun Pond and Silverbrook Pond had long drainage paths before reaching the Pennypack which can dissipate temperature.

A second factor is sources of water. If overland flow contributes significantly to the runoff, temperature will be more uniform in the basin, rather than influenced by a single discharge site such as a pond. Because of the large degree of impervious surface (42%) and the rapid response to storm events observed in the watershed, overland flow is likely to be an important contribution to the stream budget. Another influence on stream temperatures is the location of a water treatment plant near the Silverbrook, Willow Grove Day Camp, and no pond sites. The water treatment plant is estimated to discharge between 25 and 50% of baseflow in the stream, depending on the time of year. Water temperature was measured upstream and downstream of the treatment plant as part of another study. The water downstream of the water treatment plant was about 2°C warmer than upstream. This is the temperature difference between mean observed at the sites near the water treatment plant and the Cairnrun Pond site (5,365 m downstream). However, if the water treatment plant was the only factor determining stream temperature, there would be a gradual cooling from the Silverbrook tributary which is closest to the treatment plant, to the tributary with no significant pond, and then to the Willow Grove Day Camp pond discharge point. There is no such progressive cooling. In addition, the temperature in Silverbrook Pond and its tributary is similar to the Pennypack Creek temperature even though the pond is not receiving any water from the treatment plant.

In summary, water temperatures in Pennypack Creek are somewhat elevated over preferred temperatures for a cold water trout stream. While upstream ponds may be one contributing factor, overland flow, the water treatment plant, and diurnal variations in solar radiation also have important impacts on stream temperature. Furthermore, the extensive shading in buffer zones helps mitigate the warming effects. Therefore, the temperature impact of ponds alone does not likely have a significant effect on the biodiversity of microfauna and fish in urban streams.

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