PUTTING STREAM TEMPERATURE DATA TO WORK

Delaware River Basin Policy and Practice Workgroup

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***Preface:** This document for stream temperature, and those for stream depth, stream specific conductivity, and municipal engagement elsewhere, were developed by the Delaware River Basin Policy and Practice Workgroup. The intent of the workgroup has been to provide foundational science references for environmental advocates who are collecting stream data and who wish to communicate results to local government officials. The target readership for this document is the stream monitoring community in the DRB, however the workgroup hopes others may benefit as well.*

*The workgroup strongly believes that environmental advocates must have a **clear** understanding of the science and the issues under discussion. This and the other documents are therefore written with sufficient detail and rigor to enable advocates to engage in confident and informed dialogue.*

The document is lengthy. Please feel free to select sections of interest – while sections follow a logical sequence, they were developed to be largely independent of each other.

Delaware River Basin Policy and Practice Workgroup members are associated with the following organizations:

- *Berks Nature*
- *Brodhead Watershed Association*
- *Charlestown Township Environmental Advisory Committee*
- *Chester-Ridley-Crum Watersheds Association*
- *Darby Creek Valley Association*
- *Green Valleys Watershed Association*
- *Lopatcong Creek Initiative*
- *Musconetcong Watershed Association*
- *New Jersey Highlands Coalition*
- *Pennsylvania Organization for Watersheds and Rivers, Inc.*
- *Penn State University Extension Master Watershed Stewards*
- *Stroud Water Research Center*
- *Tulpehocken Creek Watershed Association*
- *Valley Creek Restoration Partnership*
- *Westtown Township Environmental Advisory Council*

Comments are most welcome at bit.ly/engageforfreshwater.

Executive Summary

Most aquatic organisms lack sophisticated means of regulating internal temperature and are consequently highly sensitive to changes in the temperature of the environment in which they exist. The intent of this document is to provide individuals who collect stream temperature data (and interested others) the ability to engage in the process by which decisions that impact stream quality, and temperature in particular, are made at a municipal level. It comprises four themes.

•***Determinants of stream temperature.*** Stream temperature is determined by a combination of factors: *i*) the temperature of the groundwater from which the stream originates and is otherwise connected; *ii*) the temperature of the air to which the stream is exposed; *iii*) solar radiation that strikes the stream directly; *iv*) cooling by means of evaporation; *v*) precipitation, including stormwater runoff; and *vi*) stream mixing.

•***Temperature thresholds of aquatic organisms.*** Temperature thresholds exist below or above which some aspect of performance required for survival cannot take place. In terms of stream warming, for example, cellular heat stress responses for coldwater fish initiate at approximately 20 °C, and severe compromises to survival begin at 24 °C. Published thresholds exist, and are reported here, for both coldwater and warmwater fish and for benthic macroinvertebrates. *Of utmost importance*, the understanding of temperature and fish survival is intermediated by the spatial scale of fish use of habitats and thermal refugia, which are easily fragmented.

•***Land use and development of concern.*** The types of land use and development of greatest concern to stream temperature are *i*) deforestation, which removes vegetation that protects the stream from solar radiation; *ii*) impervious surfaces, which absorb solar radiation and transfer that energy to air, groundwater, and stormwater runoff ; *iii*) impoundments, for example ponds, dams and stormwater retention basins that hold water long enough to warm; *iv*) discharge of heated effluents produced through municipal or industrial processes; and *v*) groundwater depletion through water withdrawals or drought.

•***Municipal engagement prompted by stream temperature data.*** The prospect that stream temperature will exceed thresholds for aquatic life is determined by documenting trends from historical data and/or recognizing imminent threat from proposed land development. The receptivity of a community toward galvanizing against a perceived threat to stream health is keyed to: *i*) whether any part of the economy is based on recreational fishing; *ii*) the degree to which community sentiment toward environmental issues exists, and *iii*) the view of stream temperature by the community as a proxy for other temperature-related issues.

GLOSSARY

Albedo: A non-dimensional, unitless quantity that represents the amount of sunlight reflected by a surface, ranging from 1 (total reflection) to 0 (absorbing all incoming light). For example, snow has a very high albedo, and asphalt and concrete have very low albedo.

Connectivity (see fish connectivity): Aquatic connectivity refers to physically linked pathways through which energy, matter, and organisms move from one part of the stream to another, both upstream and downstream, within a water column, and of the main body of water and the floodplain; connectivity of aquatic habitats are crucial for fish genetic diversity.

CT_{min}: critical thermal minimum; the temperature below which some aspect of performance, typically equilibrium or locomotion, cannot occur, predisposing the animal to death.

CT_{max}: critical thermal maximum; the temperature above which some aspect of performance, typically equilibrium or locomotion, cannot occur, predisposing the animal to death.

CTM: critical thermal maximum; another term for $CT_{max.}$

Diel: denoting a period of 24 hours.

Heat: energy transferred from one system to another because of a difference in temperature; the term is used as well in this document, less formally, to refer to thermal energy alone.

NDVI: Normalized Difference Vegetation Index; based on Landsat reflectance, NDVI is a metric having values ranging from -1 (ocean) through 0 (no vegetation) to 1 (fully vegetated) that quantify vegetation greenness, hence plant density and health.

Phenology: the study of the timing of recurring biological phases, the causes of their timing with regard to biotic and abiotic forces, and interrelation among phases of the same or different species

Specific heat capacity: describes how much energy, generally as heat, is required to change one kilogram of a substance by 1 °C.

Solar radiation: electromagnetic radiation emitted by the sun.

Temperature: measure of the average kinetic energy of molecules in a system.

Thermal conduction: transfer of heat between two materials in direct contact in response to a temperature gradient; the transfer is mediated by atomic or molecular collisions.

Thermal radiation: electromagnetic radiation generated by the conversion of heat attributable to the movement of charged particles in a substance into electromagnetic waves.

Thermal refuge/ia: Thermal refuges are thermally distinct riverscape features used by aquatic organisms during unfavorable thermal conditions. They are used primarily by organisms that cannot regulate their own body temperature for protection from thermal extremes prevalent throughout the system. Key features of refuges are that they are thermally distinct, spatially distributed, and vary through time.

Troposphere: The lowest layer of the atmosphere of Earth, which we breathe and where most of our weather phenomena are.

UILT: Upper Incipient Lethal Temperature; the temperature tolerated by some percentage of organisms, generally 50%, for various times of exposure, with mortality as the endpoint.

ULT: Upper Lethal Temperature; sometimes used in place of UILT, but the precise definition depends on the study.

ABBREVIATIONS

CTD: Conductivity, temperature, and depth, usually in reference to stream parameters measured by sensor monitors
EPA: United States Environmental Protection Agency
DRB: Delaware River Basin

INTRODUCTION

Every aspect of aquatic ecology, indeed of all life, is intimately tied to temperature. The reason is simple: temperature governs the rate at which chemical reactions occur, including those relating to biosynthesis, metabolism, and neurotransmission, *i.e.*, all the functions of a living organism. In this sense, we humans are lucky. We have mechanisms for maintaining a constant body temperature upon which the thousands of chemical reactions important to us proceed at constant and carefully orchestrated rates. Most aquatic organisms do not possess such sophisticated mechanisms of temperature regulation, hence their body temperature is much closer to that of the environment in which they exist. Temperature thresholds for these organisms exist below which reactions cannot proceed and above which they become so dysregulated life cannot be sustained.

Land and water use and climate change have prompted a focus on increases in temperature for a variety of habitats. Such increases are often viewed from the perspective of harm, whether harm caused by the increase in temperature alone or harm by substances (for example, chloride) whose toxicity increases as temperature increases. However, the more important impact – at least from an ecological standpoint – is the potential for change in the distribution and abundance of organisms across natural settings. The change can occur through multiple mechanisms, such as *i*) effects on growth, development, and reproduction of a species, *ii*) reductions in oxygen solubility, *iii*) production and consumption of oxygen linked to photosynthesis; and *iv*) changes in the distribution of plants and other animals that comprise the food chain or, alternatively, that compete for similar resources.

As noted in the preface, this document – Putting Stream Temperature Data to Work – is intended to provide individuals who collect stream temperature data, or others similarly interested in such data, the ability to engage meaningfully in the process by which decisions that impact stream quality are made at a municipal level. The document is divided into five sections: 1) Determinants of Stream Water Temperature, 2) Temperature Thresholds for Aquatic Organisms, 3) Land Use and Development of Concern, and *4*) Municipal Engagement Prompted by Stream Temperature Data.

1. DETERMINANTS OF STREAM WATER TEMPERATURE

Any understanding of stream temperature, and of the human events that influence it, requires an understanding of how energy is transferred as heat to and from a stream. Sources of heat – the sun, air, and precipitation, to name a few – are depicted in Figure 1.

Thermal conduction is the flow of energy between two materials in direct contact with each other in response to a difference in temperature. It accounts for the transfer of heat between a stream and the groundwater with which it is connected, a stream and the air above it, a stream and the underlying bed, and a stream and water in the form of precipitation, directly or as runoff. Conduction is a two-way process: heat is transferred *to* or *from* the stream, depending on the stream's temperature relative to that of the material with which it is in contact.

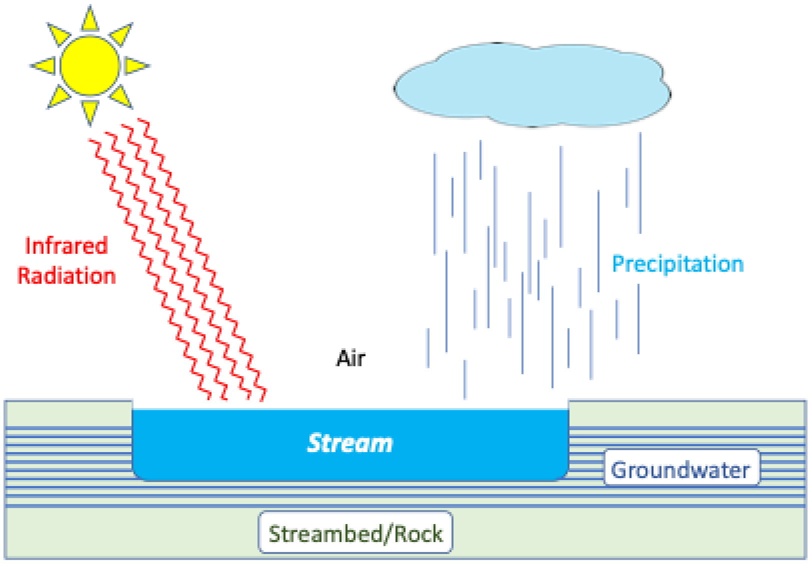

Figure 1. ***Sources of heat relevant to stream water.*** The transfer of heat to the stream from the air, precipitation, streambed, and groundwater, and *vice versa*, occurs through conduction. The transfer of heat from the sun to the stream occurs through radiation, specifically that of infrared waves.

Thermal radiation accounts for the transfer of heat by electromagnetic radiation. Unlike conduction, it does not require contact between materials. The most important form of thermal radiation in relation to stream temperature is *solar radiation*, and especially that in the infrared part of the spectrum. Infrared waves from the sun that manage to penetrate the atmosphere can penetrate stream water as well, to some extent, and in so doing heat it. By way of analogy, solar radiation is the reason we feel so much hotter in direct sunlight than in shade, or that the interior of a car, also in direct sunlight, can become so hot.

One more term related to heat requires discussion, and that is *'specific heat capacity'*. Not to get overly technical, but… the specific heat capacity of water is 1 kilocalorie, meaning that one kilocalorie of heat is required to raise the temperature of 1 kg of water by 1° C. Know that this value is quite a bit higher than that for air (0.24 kilocalories) or rock (for example granite, 0.19 kilocalories). Consequently – ***and this is the important part!*** – the temperature of water is slower to rise or decline in relation to that of adjacent air or rock, a stabilizing property relevant to differences in diel and seasonal variation in water versus air temperature.

A. Groundwater

An important determinant of stream temperature is the groundwater from which the stream originates and is otherwise in contact. A survey of 1424 streams across the country (stream sizes 1st to 9th order; median 3rd order) demonstrates that about 40% of streams exhibit a 'groundwater signature', meaning that groundwater contributes substantially, if not almost entirely, to stream temperature (Hare *et al.*, 2021). These streams divide evenly into those with shallow groundwater signatures and those with deep groundwater signatures.

Shallow groundwater, typically defined to be within 6–15 m (20–50 ft) of the surface, is sensitive to surface temperature. However, changes in the temperature of shallow groundwater – for example in response to the change of seasons – lag and are attenuated relative to surface temperature changes. This is due to the insulating properties of vegetation, the mass of soil and rock, and the heat capacity of the groundwater. For this reason, shallow groundwater can be cooler or warmer than the air, topsoil, and the stream it feeds depending on the season and other factors relating to heat exchange. For the Delaware River Basin (DRB), average shallow groundwater temperature is 8–14° C (47–57° F) ("Average shallow groundwater temperatures", n.d.). Shallow groundwater is commonly cited to be within 1 °C of the annual mean air temperature (for example, see Vannote and Sweeney, 1980).

Groundwater deeper than 6–15 m is essentially decoupled from the surface, maintaining an almost constant temperature. Deep groundwater can be cooler or warmer, too, than the stream it feeds, but these differences aren't complicated by the (slight) time-shifted oscillations exhibited by shallow groundwater (Hare *et al.*, 2021). Groundwater can extend to great depths. It is sometimes useful to know that the temperature of groundwater increases by about 25° C (77° F) for every kilometer in depth, owing to the earth's interior temperature.

For shallow and deep groundwater alike, the conduction of heat to or from whatever source depends on surrounding geology, as different types of rocks exhibit different thermal conductivities. Also important is the degree of surface and subsurface porosity. Surface porosity determines the rate of recharge of groundwater from precipitation. Subsurface porosity determines the rate of heat exchange between rock and groundwater as a function of surface area.

The average Pennsylvania stream is cited to get about two-thirds of its flow from groundwater ("A Quick Guide to Groundwater in Pennsylvania", 2022). The term 'average' implies, of course, variation about a mean. Groundwater that forms a stream's baseflow is also cited to take a year – and sometimes much more – to make the underground journey to the stream.

Groundwater, while subject to set-points and variations in temperature of natural cause, is also subject to changes in temperature owing to human activity. Such activity includes removal of tree cover (deforestation), expansion of impervious surfaces, pumping and artificial recharge, and the myriad phenomena that underlie climate change. The effects of deforestation, impervious surface, and groundwater depletion are discussed in detail in the third section of this document '*Land Use and Development of Concern*'.

B. Air and streambed

Other determinants of stream temperature include ambient air and the ground as heat sources or sinks, both operating through conductive heat transfer. Taking ambient air as an example, heat is transferred from air to the stream if the air is warmer, and from the stream to the air if the air is cooler. The rate of transfer is defined by the surface area between the two, the amounts of the air and water (formally, their masses), and differences in temperature. Ambient air temperature oscillates on a diel and seasonal basis, but – remembering that water has a relatively high specific heat – the change in stream temperature lags from that of the air. Moreover, the maximum and minimum temperatures of the stream are modulated relative to those of air, that is, they range less widely (Figure 2). This is reminiscent of the discussion above for shallow groundwater, however stream water is less insulated than shallow groundwater and therefore responds more rapidly and with less modulation. Note that solar radiation striking water – discussed below – can also contribute to the diel pattern of stream temperature, and at times quite substantially.

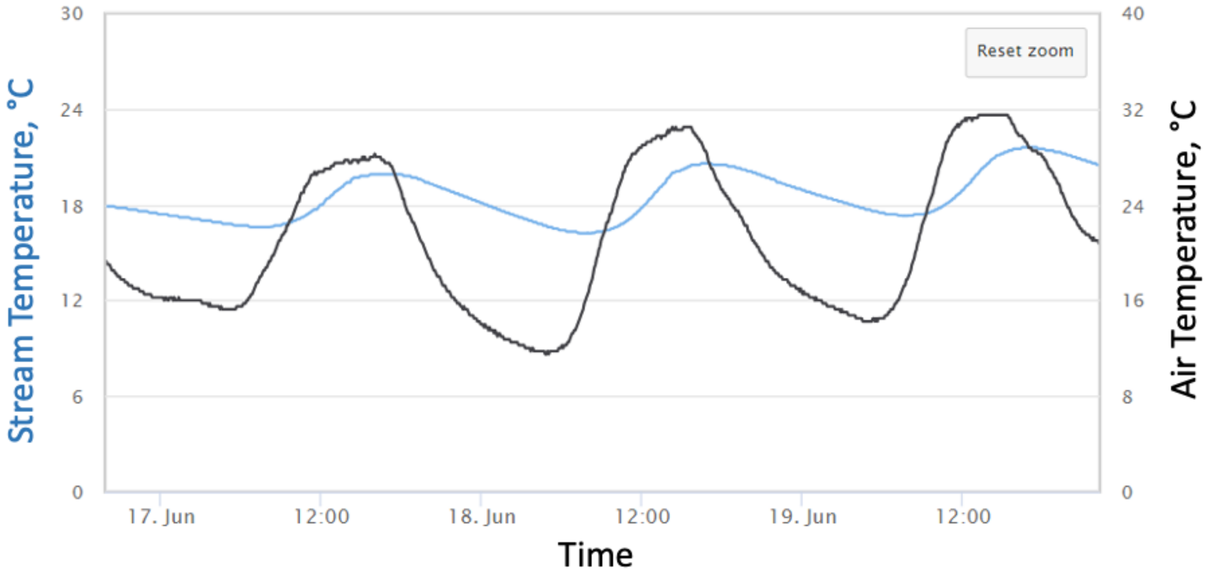

Figure 2. ***Diel variations in stream and air temperatures.*** A 3-day recording of temperatures on Crum Creek in Chester County, PA, was made by an EnviroDIY station. Stream temperature (blue) was measured with a CTD probe. Air temperature (black) was measured indirectly in the Pelican box holding the Mayfly data logger. Note the delay and attenuation of stream temperature relative to air temperature. The diel pattern of stream temperature can reflect not only conductive heat transfer from air but heat transfer from solar radiation; stream temperature is offset in time from both.

It is useful to remember that air contains molecules of water in gas, or vapor, phase. We measure this as humidity. The greater the humidity, the greater the mass of air. This is a consideration in heat transfer, as the transfer depends on relative masses. The greater the humidity, too, the less evaporation from a stream.

With all this in mind, we can return to the concept of ‘signatures’. We noted above that 40% of streams in the continental United States have a groundwater signature. The remainder have an atmospheric signature (Hare *et al*., 2021). The atmospheric signature is stated by the authors to largely correlate to air temperature, the subject of this particular subsection. But remember that air temperature and solar radiation are correlated. Therefore, an atmospheric signature in fact relates to the contributions of both air temperature and solar radiation, the latter to be discussed in the next subsection.

As a matter of perspective, this is a good place to point out that, notwithstanding the power of the terms 'signatures', the temperature of most streams is not decided *uniquely* by groundwater or air temperature/solar radiation, but by some combination of these and other factors, however much one might predominate. Vannote and Sweeney (1980) point out, partly using the tributaries of White Clay Creek in southeastern Pennsylvania as an example, that seasonal and diel variances in temperature increase with river order up to intermediate-sized (order 4–5) rivers (Figures 3 and 4). The increase presumably relates to the transition from small streams that are fed almost solely by groundwater seeps at constant temperature to larger streams more removed from groundwater and therefore more subject to the fluctuations of air temperature and solar radiation. The authors relate the decrease in seasonal and diel variability in the still larger tributaries to the combined effect of the large volume and high specific heat of water.

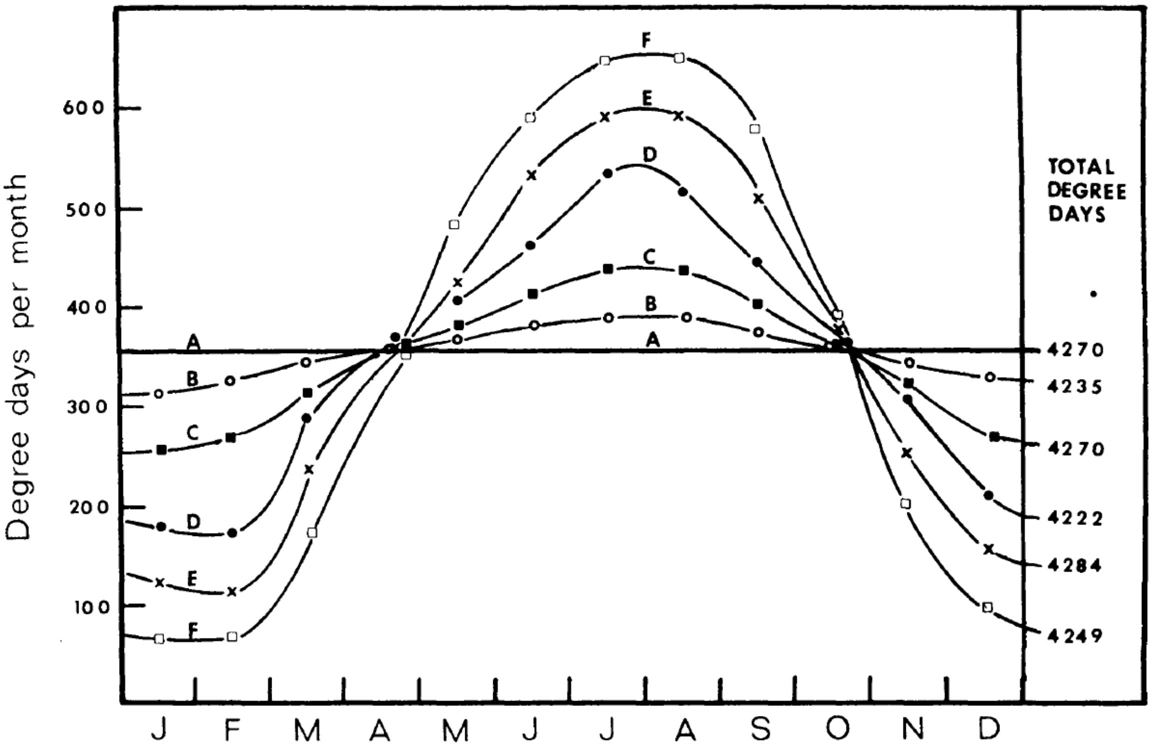

Figure 3. **Distribution of monthly degree-day accumulations at various recording stations along White Clay Creek.** *A*, outflow of groundwater; *B*, woodland spring seeps; *C*, first order spring brooks; *D*, second order streams; *E*, third order stream (upstream segment); *F*, third order stream (downstream segment). From Vannote and Sweeney, 1980.

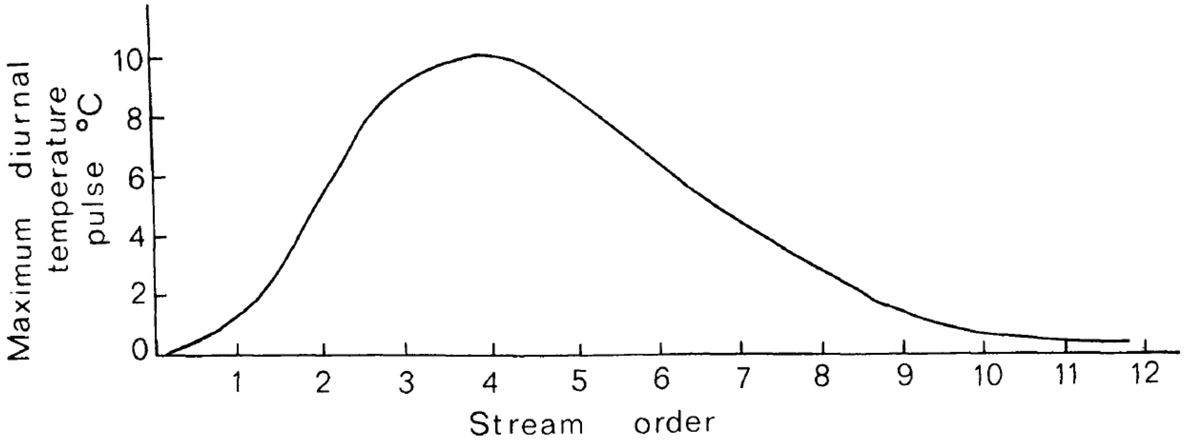

Figure 4. **Maximum diurnal change in temperature as a function of stream order in temperate North America.** Data are from unpublished White Clay Creek studies and water resource reports of the United States Geological Survey. From Vannote and Sweeney, 1980.

If we're thinking in terms of human activity, the overriding concern with regard to air temperature as it relates to stream temperature are the increases in air temperature with heat-absorbing surfaces and deforestation, whose extremes in fact constitute an 'urban *heat island* effect' – and with climate change. These issues are discussed in the third section of this document '*Land Use and Development of Concern*'.

C. Solar radiation

Solar radiation is everything to the temperature of the earth's surface. It heats the molecules of our atmosphere, those of soil and rock, and those (mostly H_2O, of course) of streams, lakes, and oceans. Without solar radiation, the temperature of the earth would drop eventually to a few degrees above absolute zero, sustained only by the internal decay of radioactive isotopes and the heat achieved with the planet's formation. So, in the subsections above, which covered conduction in relation to groundwater and air, and below, which cover conduction in other contexts, we should realize that solar radiation is the original source of heat. Here, in this subsection, we discuss the effects of solar radiation on the water it strikes directly.

On a cloudless day at noon in summer, solar radiation can account for an increase in water temperature by about 0.7 °C per cubic meter of water per hour assuming no conduction to surrounding objects or heat loss due to long-wave radiation.[1] This is considerable. In fact,

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[1] The amount of solar energy arriving at the earth's surface at midday is about 1000 watts per square meter (this agrees with what we measure in summer in the DRB). Not all that energy is absorbed by the water, as 20% or so is reflected, leaving about 800 watts per square meter. We assume only the top of the cubic meter of water is illuminated. A watt corresponds to one Joule per second, therefore heat delivery to the water is 800 Joules per second, or not quite 3 million Joules per hour. The formula for change in temperatures is heat energy (in Joules) divided by the mass of water (in grams, so one million grams) and then divided by the specific heat capacity of

solar radiation can be of greater significance than overlying air in terms of heat transfer to water. However, the value of solar radiation is less in seasons other than summer and at times other than noon, as the angle of the sun relative to the stream – and hence the intensity of radiation per surface area – is less. And, of course, solar radiation is of no (direct) consequence to a stream in continuous shade. The most important type of solar radiation pertaining to water temperature is that in the infrared range of the spectrum ("Solar Radiation and Photosynthetically Active Radiation", n.d.).

Warming of water directly by solar radiation does not occur at depths greater than about 1 m due to lack of infrared penetration ("Light in the Ocean", n.d.). This is especially worth noting in standing water: while some of the heat imparted by solar radiation to the upper layer of water would be transferred to deeper layers by conduction, the fact that warm water is less dense than cool water sets up a stratification of warm (top) to cool (bottom) layers. Stream water, while nonetheless heated by solar radiation, is able to achieve a relatively uniform temperature, as it is subject to mixing as it courses over rocks and soil and rebounds off streambanks. Local hot spots and cool-water stratification, however, can still be found in streams and rivers.

An important exception to uniformity in streams are potholes in the stream's bed. Water here is protected from solar radiation and does not mix with water coursing above. Colder water, furthermore, settles to the bottom of the pothole, subject largely only to the temperature of surrounding rock at that level. The cooler temperature and absence of current is ideal for coldwater fish. Another important exception to uniformity are cold water seeps from groundwater, which are similarly attractive to coldwater fish.

One might ask whether the upper surface of a standing body of water or a stream can give back to the atmosphere some of the heat attained through solar radiation, and the answer is yes. Part of the return can be through conduction should the stream be warmer than the air above it. However, because the water contains heat, the water is a radiant body, too, emitting certain forms of infrared radiation. These forms are much less energetic than those of the sun.

With regard to human activity, the warming caused by solar radiation is especially notable, and often deleterious, in situations where streams lack tree cover or impoundments exist, especially streams with slow moving water. Impoundments are bodies of standing water created along streams by dams or adjacent to streams as basins, such as water retention basins. The effect of deforestation and impoundments is discussed in the third section of this document '*Land Use and Development of Concern*'.

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water (4.18 Joules/g·°C). This comes out to be about 0.7 °C per hour for the cubic meter of water used in the example.

D. Evaporation

Evaporation is a process by which surface water molecules gain enough kinetic energy through collision with neighboring molecules to vaporize into the air, a so-called liquid-to-gas phase transition. Because the molecule removes energy, the water from which it departs cools. The kinetic energy required for evaporation is supplied by conductive and/or radiative heat. The process of evaporation is inhibited by humidity, due primarily to the fact that water molecules in gas phase in the immediate vicinity of the stream suppress evaporation owing to phase equilibrium. The process of evaporation is facilitated, on the other hand, by wind, which exposes more water to the surface of the stream, but more importantly sweeps away recently volatilized molecules.

Evapotranspiration is the collective term for the above-described process of evaporation and for ‘transpiration’, the process by which water evaporates from the stomata of plant leaves. Transpiration in relation to stream properties can be quite a significant process. It is not unknown for stream depths as measured by EnviroDIY monitors to vary in a diel fashion in summer due to the amount of water sucked up from the stream by roots and eliminated through transpiration during daylight. Might transpiration – by cooling the air above or near the stream – cool the stream itself? The answer is not clear, as transpiration may cause loss of shallow groundwater, whose flow into streams is (in summer) cooling (Condon *et al*., 2020).

E. Precipitation

Precipitation, for instance in the form of rain, can fall on the stream directly. It can also be carried to the stream over or through the upper layers of the ground, or by means of storm sewers, as runoff. A more circuitous route of delivery can occur through groundwater recharge. The extent to which precipitation can change stream temperature, however it is delivered, will depend on the difference in temperature between the two, and the volume of the stream relative to the volume (intensity and duration) of the precipitation event.

The temperature of rain is difficult to predict given the different thermal strata in the atmosphere through which it might fall. In the case of precipitation falling on the stream directly, heat would be exchanged between the two through conductive transfer. Water flowing over or through the upper layers of the ground would exchange heat at least partly with the ground prior to entering the stream, again through conductive transfer. Rain entering groundwater would exchange heat through the rock through which it infiltrates and the groundwater itself, again by conduction.

In virtually all cases the effects of precipitation on stream temperature are transient. One might be tempted to say, then, that precipitation effects on stream velocity and/or sediment due to erosion are more meaningful. But that ignores temperature transients in which precipitation has fallen on hot surfaces such as asphalt before running into nearby streams or has flushed warm water from stormwater ponds. The graph shown as Figure 5 depicts such transients. Some of those shown touch or exceed the point (20 °C) at which thermal stress responses are initiated for coldwater fish. This is discussed further in the second section of this document, *Temperature Thresholds for Aquatic Organisms*, and the third section, *Land Use and Development of Concern*.

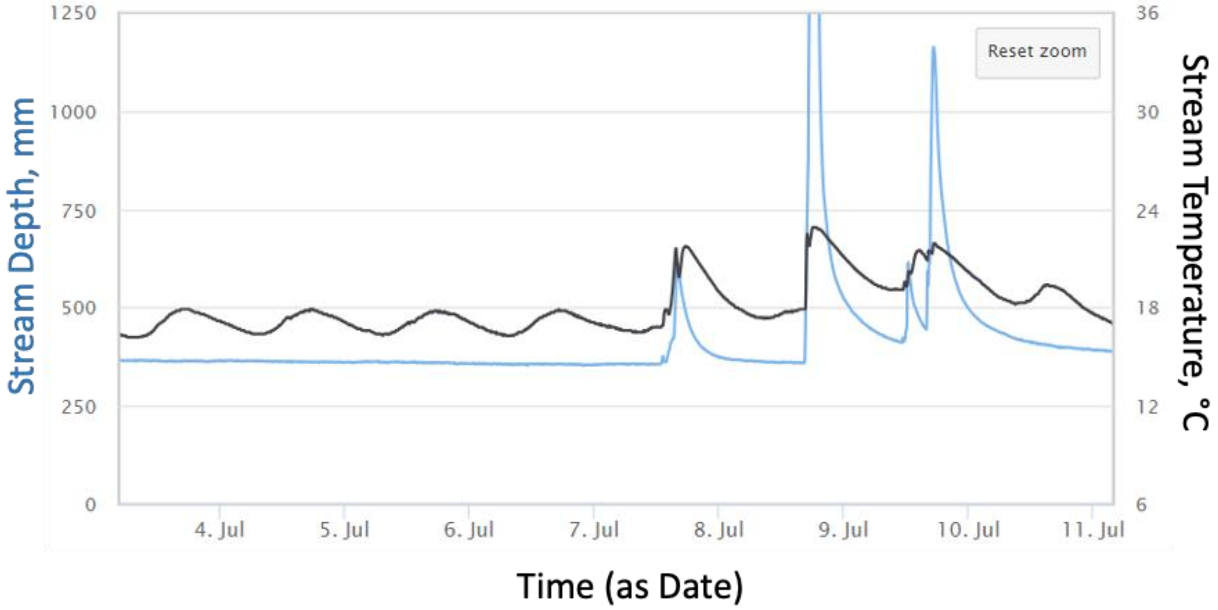

Figure 5. ***Increases in stream temperature with precipitation.*** Depicted are depth (blue) and temperature (black) tracings over 8 days in July for Valley Creek in Chester County, PA. Increases in depth and temperature July 7–9 are related to 4 distinct precipitation events.

F. Stream Morphology

As implied in some of the discussion above regarding heat exchange, the shape of a stream can be quite important. A wide, shallow stream will exchange heat with air, for example, much more quickly than a narrow, deep stream owing to the surface area available for conduction. A wide, shallow stream is also much more sensitive to heating achieved through solar radiation, again owing to the increased surface area to volume ratio. The effects of stream shape, including those on daily variations in stream temperature, are discussed in detail by Caissie (2006).

G. Stream mixing

Many temperature monitors are situated in 2nd- and 3rd-order streams. The measured temperatures therefore 'begin' with the weighted average temperature of water delivered by upstream tributaries. The temperature of these tributaries, in turn, reflect the transferred conductive and radiative energies described above in relation to myriad catchments. As streams get larger, they tend to get warmer – a growing stream receives proportionally more water from tributaries than groundwater and it widens, exposing the water to more sunlight. In some cases, streams can recover from the warmth due to shading of downstream sections or through substantive inflow of additional groundwater. The Lopatcong Creek in northern New

Jersey, while starting cold, warms due to deforestation and urban development, but then cools further downstream due to limestone spring (groundwater) inputs.

Relevant to the concept of stream mixing are the contributions of municipal and industrial effluents. Effluents include those from the treatment of human and industrial wastes. These are discussed in the third section of this document '*Land use and Development of Concern'*. It is also important to mention that many urban streams are no longer streams in the traditional sense but rather are enclosed within underground pipe networks. In some cases the water may be cooler than that of streams in summer, as the water is not exposed to ambient air and sunlight and may be conveyed deeply in the ground, so that as the pipes discharge into open streams there is a cooling effect. This is not always the case, however. We discuss later that underground stormwater conveyances in cities may be warmed by proximity to man-made structures.

2. TEMPERATURE THRESHOLDS FOR AQUATIC ORGANISMS

All aquatic species require specific ranges of temperatures in order to exist if not thrive. The requirement is, at a basic level, that of the organisms' metabolism and overarching physiology. Both comprise complex sets of chemical and cellular activities that are temperature-dependent. It is these activities that control, among other things, reproduction, development, and behaviors that relate to migration, predation, and feeding.

Responses of an organism, when plotted against temperature, generally conform to bell-shaped curves (Figure 6, next page). What the response is depends on the investigation. It can be something as molecular as the expression of a particular gene or as macroscopic and fundamental as survival. The terms 'CT_{min}' and 'CT_{max}' , which are abbreviations for 'critical thermal minimum' and 'critical thermal maximum', are particularly important. These are the temperatures below (CT_{min}) or above (CT_{max}) which some aspect of performance required for survival – in an experimental context usually equilibrium or locomotion – cannot take place. Some organisms can function at a wide range of temperatures – *i.e.*, the bell-shaped curve for something like growth or activity is wide. These organisms are referred to as *eurytherms*. Others can tolerate only a much more restricted range, *i.e.*, the curve is narrow. These are *stenotherms*.

While many responses conform to a bell-shaped curve, how the analysis is conducted bears consideration. A great many studies are performed in the laboratory, which provides a controlled environment but often lacks the complexity of an ecosystem. Others are performed in the field, which provides an ecological context but for which the environment is neither precisely defined nor controlled. Additionally, responses are sometimes evaluated in relation to a slow ramping of temperature, whereas others are related to *sudden* changes, so-called temperature shocks. Acclimation, too, must be considered. Acclimation is the adaptation of an organism to an existing temperature, whatever that temperature might be, before a change is induced. The organisms' adaptations are internal changes, via epigenetics, selection, and other biological changes. All this is important in understanding any study that surfaces as a publication.

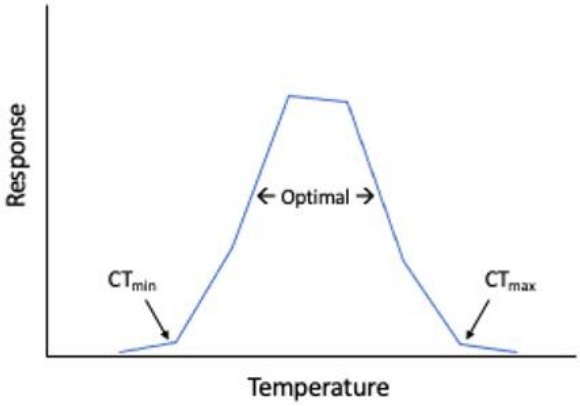

Figure 6. ***'Response' of an aquatic organism to temperature.*** The response can be any of a number of biological parameters that an investigator chooses to measure. Here, the response is related to some aspect of performance having a direct impact on survival, for example locomotion, as CT_{min} and CT_{max} are indicated. The response curve resembles a bell, hence the term 'bell-shaped'.

While CT_{max} is the most often reported term relating to heat stress, two other terms are common as well. 'CTM', referring to Critical Thermal Maximum, is an alternative expression for CT_{max}. 'UILT', or Upper Incipient Lethal Temperature, is a bit different. UILT is the temperature tolerated by 50% of the organisms for various times of exposure, such as 4–7 days, with mortality as the endpoint ("Thermal Toxicity Literature Evaluation", 2011). The terminology is cumbersome, to be sure, but you'll find these expressions in many sources.

While temperature may have a straightforward impact on organisms in controlled laboratory settings, its effect on organisms in natural settings is mediated through complex spatial, chemical, and ecological pathways. We need to recognize these complexities. First is the heterogeneity in stream architecture that creates spatial differences in temperature, differences that are not necessarily reflected in monitoring data. We'll discuss these differences below in terms of thermal refugia, but they include the aforementioned potholes and groundwater seeps. Second is the fact that chemical events within water apart from those of organisms' metabolism and physiology are keyed to temperature as well. Most important in this regard is oxygen solubility, as oxygen is less soluble in water – and therefore less available to aquatic life – as water warms. Third are the effects of temperature on the food chain. Temperature has a profound effect on unicellular organisms and other microorganisms – those that operate at the base of the food chain – not to mention effects on plant growth and photosynthesis. Differential effects on predation as a function of temperature must be considered as well.

A. Temperature thresholds for fish

Real time, continuous-measurement stream monitors show temperature increasing in many streams, both locally and worldwide, affecting not only average summer water temperature and increasing the number of days that exceed toxicity thresholds for native fish (Pederson et al., 2010), but also changing the dynamics of when temperatures increase or cool at other times of year (Isaak et al., 2012, Nelson &Palmer, 2007).

Management of fisheries is one factor that impacts coldwater salmonid fish survival and mortality that interacts with stream temperature. Catch-and-release itself has shown to decrease survival in some fish and/or studies, not only on the survival of the caught fish but on the number of its progeny (for a review and references, see Hodge, B: An Annotated Bibliography on the Science on Catch and Release Angling of Salmonids). But it has been long known that the risk of mortality from catch-and-release is greater under conditions of increased temperatures based on cardiac, respiratory, and stress physiology, in both in vivo and in situ studies (Wilkie et al., 1997, Anderson et al., 1998, Boyd et al., 2010, van Leeuwen et al., 2020, Meyers et al., 2022). However, Meyers et al. (2022) noted that if fishing restrictions are warranted, it would be helpful to address both warm and cool conditions.

Studies indicate that the understanding of temperature and fish survival is intermediated by the spatial scale of fish use of habitats and the presence of thermal refugia (areas of lower probability of heat stress). Sullivan and colleagues (2021) discuss the complex ways in which thermal refugia are used by fish, the interaction of hydrologic and landscape features influencing refugia, and the need to map their locations in a watershed in order to maximize their conservation potential (e.g., locations of groundwater pumping and impacts on refugia). Predictions of species vulnerability to increasing global heating, especially for obligate coldwater species (Comte et al., 2013, Muhlfeld et al., 2018), may be informed by the locations and number of thermal refugia (White, et al., 2019). Prominent coldwater species in the Delaware River Basin are Brook Trout, Brown Trout, and Rainbow Trout (Stauffer *et al.*, 2016).

Brook Trout spawn in waters that are between 4 °C and 10 °C and grow optimally between 13 °C and 16 °C. Cellular heat stress responses initiate at approximately 20 °C (Chadwick et al., 2015, Chadwick & McCormick, 2017). UILT for Brook Trout is around 24 °C, and CTM is 29–30 °C (Stauffer *et al.*, 2016; "Thermal Toxicity Literature Evaluation", 2011). These values for spawning, optimal growth, UILT, and CTM are quite close to those exhibited by Brown Trout and Rainbow Trout, or are relatively small when compared to those for non-salmonids. There is concern that loss of thermal refuge habitats is one of the most significant threats to stream fish communities and could lead to extirpation of coldwater fish populations (Isaak and Rieman, 2013, Isaak et al., 2017).

Warmwater fish in the Delaware River Basin include American Shad, Black Crappie, Chain Pickerel, Golden Shiner, Pumpkinseed, Striped Bass, and Yellow Perch (Stauffer *et al.*, 2016). As the classification implies, warmwater fish have a greater tolerance to elevated stream temperatures. Optimal growth of Yellow Perch, for example, occurs at 26–30 °C ("Thermal

Toxicity Literature Evaluation", 2011). The UILT for Yellow Perch, depending on prior acclimatization, is 30-32 °C. UILTs for Striped Bass, Smallmouth Bass, Largemouth Bass, and Black Crappie are similar.

High stream temperature can affect fish behavior and change behavior differentially among individual fish depending on a number of variables including individual attributes such as size, resource needs, personality, and dominance (White *et al*., 2019). These individual attributes may interact with the time spent and competitiveness for high quality foraging and seeking thermal refugia. White's 2019 in vivo study showed that increased stream temperature decreased aggression interactions across members of a stream trout population, and that the larger and more exploratory fish, typically more aggressive, initiated fewer aggressive interactions at high temperatures. As temperatures approached a critical maximum, fish increased the time in thermal refugia and also spent less time in forage patches where food was available. The authors posited that reduced aggression at higher temperature may explain why thermal refugia are often occupied by higher densities of fish. Population survival during stressfully high temperature may be influenced by how close refugia are to foraging locations within their larger habitat. Better temporal and spatial observational and analytic techniques have been developed in the past 10 years, and a review of the gains made in understanding the shifts that occur in river temperature, in thermal refugia, and in food availability can be found in Steel et al., 2017. Restoring connectivity of streams or restorative management of temperature water releases from a reservoir, could restore migratory pathways that allow fish access to more diverse thermal regimes. The authors point out the importance of efforts to support "the natural pathways of water, wood, and sediment from tributaries to mainstem reaches will simultaneously create thermal diversity, surface-water and groundwater connections, and natural patterns of daily and seasonal temperature fluctuations" (Steel et al., 2017), and recognizes the need for thermal diversity and stream connectivity - a "spatial mosaic" of water temperatures.

TEMPERATURE RANGES

Coldwater fish (trout)

Spawning: 4-10°C (39.2-50°F)
Optimal growth: 13–16°C (55.4-60.80°F)
Stress responses initiated: 20°C (68°F)
Upper Incipient Lethal Temperature: 24°C (75.2°F)

Warmwater fish

Optimal growth: 26–30°C (78.8-86°F)
Upper Incipient Lethal Temperature: 30–32°C (86°F-89.6°F)

Survival, reproduction, and growth rates of trout are strongly dependent on their ability to adapt through movement within the spatial and temporal variability in their local ecosystems, the phenology of the emergence timing of aquatic insects, and on their tactics for regulating heat exposures (Petty et al., 2012). The impact of increasing stream temperature on trout also differs in main-stem (warmer and often more productive foraging habitats) and tributary (colder, lower forage) streams. With different cost:benefit tradeoffs (like energy expenditure and predator risk), trout move among both main-stem and tributaries at different times through the year for spawning, location of refugia, and greater forage opportunity. Trout mobility increases as stream temperature increases to the lethal temperature for brook trout of about 25 °C. Thus, Petty and colleagues found that trout mobility (and immigration and emigration) is greater in a main-stem or creek with higher temperatures, than for trout in tributaries where temperatures may never come close to 25 °C. The main-stem trout sought thermal refugia in the main-stem that can come from coldwater seeps, tributary confluences, and groundwater upwellings or seeps. Yet, temperature affects the appetite of trout, with appetite loss specifically at 24°C for brook trout, and at 26°C for brown trout (Taniguchi et al., 2011). Petty and colleagues concluded that management actions are needed to protect and facilitate the movements of mobile fish within the watershed so that thermal refugia, foraging/food sources, and reproductive habitat are enabled by stream connectivity. Furthermore, better management of connectivity allows fish to respond to catastrophic events, dispersal barriers that prevent movements between the main-stem and tributaries, and over-harvesting, which could cause extirpation of populations.

As touched on in the introduction, one problem of increasing stream temperature is the corresponding decrease in the solubility of oxygen and thus oxygen levels in water or sediment, which causes respiratory stress, changes in behavior, and greater mortality in aquatic life. Biological effects also include large fish dying before small fish, species that need higher dissolved oxygen (DO) dying first, fish gulping air, and macroinvertebrates that are sensitive to dissolved oxygen being replaced by fly larvae and worms that are more tolerant of low oxygen conditions(“Dissolved Oxygen”, 2023). Water temperature rises can also play a role in acute oxygen supersaturation when aquatic plants are abundant and conditions are ideal for photosynthesis. Oxygen supersaturation can lead to fish mortality from gas bubble disease.

DO concentrations are greater in colder than in warmer regions, and in colder stream temperature, as water temperature is inversely related to DO, and the DO pattern generally follows the temperature gradient (Zhi et al., 2023). In dry seasons, water levels decrease and stream flows decline resulting in warmer water, which as described, is the predominant control of daily DO. Stream conditions that straighten the stream channel or reduce the water volume in a stream can contribute to temperature increases. Urban areas as heat islands might intuitively be thought to cause more deoxygenation, but they are second to the deoxygenation associated with agricultural lands. In urban areas, high DO is associated with vegetated areas, and low DO in areas with larger percentages of impervious surfaces (Zhi et al., 2023).

B. Temperature thresholds for macroinvertebrates

The taxonomic order of macroinvertebrates garnering the most attention in relation to water temperature is that representing mayflies (Ephemeroptera). Orders representing dragonflies and damselflies (Odonata), flies (Diptera), caddisflies (Trichoptera), and stoneflies (Plecoptera) – like mayflies, all within the Insecta class – are close behind (Bonacina *et al.*, 2023).

A great many species of mayflies exist in the Delaware River Basin. One of these – *Neocloeon triangulifer*, isolated from White Clay Creek in southeastern Pennsylvania – has proven especially conducive to experimentation. *N. triangulifer* larvae reared at 20 °C, when challenged with an acute ramping rate of 0.75 °C/hr, do not survive past 40 °C (Kim *et al.*, 2017). The value of 40 °C was defined by the investigators as an 'acute' CT_{max}. Of more interest, however, is the CT_{max} when determined for *N. triangulifer* larvae in 'life cycle rearing' studies. Here, survival is measured as attainment of the subimago state for first instar larvae reared at constant temperatures from 14 °C to 30 °C. The subimago state is a state between larvae and the adult in which the insect emerges with wings but is still sexually immature. No larvae attain the subimago state when reared at 30 °C. A precipitous decline in attainment was found to occur between 26 °C and 28 °C. The CT_{max} of 27–30 °C in this experiment – which reflects long-term thermal limits for successful metamorphosis – is considerably less than the acute CT_{max} above.

With regard to aquatic macroinvertebrates in general, Chown *et al.* (2015) provide a database for upper lethal temperature (ULT) values and other variants of CT_{max}. ULT is defined as loss of "potential for survival"; the values provide only a rough frame of reference, and it's important to note that none of the values refer specifically to studies conducted in northeastern United States. Families of interest to us in the DRB are, however, represented in the data elsewhere for the United States. For mayflies, ULTs range from 21 – 27°C, with one or two outliers on either side. For caddisflies and stoneflies, the ranges are 21–30°C, again with outliers.

Tomczyk *et al.* (2022) utilized two extensive databases – the Freshwater BioTraits database maintained by the EPA and the freshwaterecology.info (European) database described by Schmidt-Kloiber and Hering (2015) – to provide a summary of temperature preferences for a vast number of aquatic insect taxa, according to taxa specifically (albeit restricted to the European database) and grouped according to feeding groups (both databases). Preferred temperatures in the European database, based on "summer stream temperatures and macroinvertebrate occurrence," for Ephemeroptera, Odonata, Diptera, and Trichoptera are 13–21 °C, depending on the specific taxon. This would seem to confirm Chown *et al.* above that most benthic macroinvertebrates prefer cool water.

The data utilizing the EPA-maintained database did not classify organisms by taxa but rather by 'functional feeding groups' – *i.e.*, as collector-gatherers, predators, shredders, herbivores, filterers, and generalists. Optimal stream temperatures for these groups (U.S. data) were generally 13–23 °C, strengthening the assertion of a preference by aquatic invertebrates for cool water. The maximum temperature at which all groupings were found in the field was almost always 25 °C; filterers were the exception at 30 °C.

TEMPERATURE RANGES

Aquatic macroinvertebrates

Optimal growth: **13–16 °C**
Upper Lethal Temperature: **21–30 °C**

Given the importance of aquatic invertebrates to food chains, it is worthwhile to consider changes in temperature as they relate to phenology. Phenology is the study of periodic events in nature and how they integrate in an ecological setting. Those who fish for trout are well aware that invertebrate hatches occur in an ordered sequence beginning in January, for example with midges, proceeding to the Little Black Stonefly in February and March, then (among others) the Little Blue Winged Olive in March through May, etc., well into the summer. Predators for benthic invertebrates themselves are fish, amphibians, crustaceans, and other invertebrates. Predators for benthic invertebrates that undergo transition to flying insects are birds, bats, reptiles, and other insects. As streams warm, what might become of the ordered metamorphic events that relate to aquatic invertebrates? Would the time-frame for these compress? Would there be a reordering of them? And how would a compression or reordering synchronize with the feeding habits of other animals? What, specifically, would be the consequence of dysregulation in terms of ecosystem health? Woods *et al.* (2022) provide a review of literature on freshwater phenology that, among other topics, deals with aquatic macroinvertebrates.

3. LAND USE AND DEVELOPMENT OF CONCERN

The types of land use and development of greatest concern in relation to increases in stream water temperature are *i*) deforestation, *ii*) impervious surfaces, *iii*) impoundments, *iv*) discharge of heated effluents, and *v*) streamflow depletion through groundwater pumping of surface water withdrawals. The reader will already have noted that our focus in this document is on increases in stream temperature, not decreases. Development and climate change have made increases in stream temperature, particularly in summer, the primary threat to aquatic life. The reader is referred to Caissie (2006) for an additional treatment of some of these topics.

A. Deforestation

Vegetation that shades the stream, especially that consisting of trees with large, deep canopies, helps prevent stream warming. The protection of the stream is due not only to the interception of solar radiation that would heat the stream directly but to that which would heat the land over which runoff takes place. Vegetation therefore has a protective impact on stream temperature on both a day-by-day basis and in relation to precipitation events. Clearing the vegetation – a consideration for many types of land development without protective measures, but as well for windthrow, fire, and arboreal disease – would eliminate these protective effects.

The degree of protection offered by forestation is appreciable. A study of first- and second-order headwater streams in West Virginia (summer) found for streams that were 90% deforested an increase in the maximum daily water temperature of 0.79 °C/100 m over the stream course of 400 m, or about 3.2 °C total (Studinski *et al.*, 2012). Another study – similarly a headwater stream in summer, however in New Hampshire – found for a quite small stream increases in the maximum daily water temperature of 3–5 °C within 25 m following removal of riparian vegetation (Burton & Likens, 1973). In a study of Amazonian streams, which was the first to evaluate organismal responses specifically to deforestation-driven warming, deforested streams were up to 6 °C warmer (mid-afternoon) than forest streams, with fish on average 36% smaller (Ilha *et al.*, 2018).

The degree of protection corresponds to the degree of forestation. One study (Sponseller *et al.*, 2001) found the maximum daily water temperature for eight 2nd- and 3rd-order streams in the Upper Roanoke River Basin to be strongly related to the *percentage* of non-forested land along the riparian corridor, even (and especially) at a 200-m scale. This is consistent with another finding of the Sudinski *et al.* study cited above, in which temperature rise for streams that were 50% deforested was 0.72° over the course of 400 m, versus the 3.2 °C for 90% deforested.

At a more general level, a study of 5 watersheds in the Piedmont region of Maryland demonstrated that daily average stream temperature was correlated with land use, with special attention given deforestation in a watershed, although not precluding an impact of impervious surface (Nelson and Palmer, 2007). High runoff events associated with rainstorms caused surges in stream temperatures that averaged about 3.5 °C, dissipating over about 3 hours. The surges occurred most frequently at urbanized sites and could increase temperature by >7 °C.

A question of interest, particularly in relation to municipal decision making, is how much riparian buffer *width* is required to protect stream temperatures. Sweeney and Newbold (2014) review a large number of studies that investigate this from the perspective of shade and temperature effects per se. Their conclusion is that buffer widths of 10–30 m are often, but not always, fully effective in preventing temperature increases; full protection is assured only by a buffer width greater than 30 m. Cited variables include stream size and orientation, local topography, and the type, height, and density of vegetation.

B. Impervious surfaces

A clear scientific consensus exists that impervious surface cover is linked stream ecosystem impairment. The U.S. EPA ("Watershed Percent Impervious Cover", 2011) reports that the percentage of impervious area at which degradation of water quality begins is about 5%. Impairment of a stream ecosystem, and loss of wetland plant and amphibian communities, is substantive with regard to sensitive aquatic species at about 10% (*e.g.*, Schueler 1994, Caraco et al., 1998, Kaplan and Ayers 2000). A threshold of 25% leads to unsustainability dynamics (Schueler 1994). The U.S. EPA ("Watershed Percent Impervious Cover", 2011) states that the harm caused by impervious cover is due in part to increased stream temperatures.

Impervious surfaces are surfaces that impede or prevent the infiltration of water into the ground. They include streets, parking lots, roofs, driveways, and walkways. We tend to think of impervious surfaces principally in the context of stormwater management, and particularly in relation to stream volume and discharge during precipitation, but impervious surfaces can have a significant impact on stream temperature as well. Most impervious surfaces, notably those without tree cover, absorb solar radiation effectively and transfer considerable heat to streams through overlying air, stormwater runoff, and shallow groundwater.

Surface temperatures attained by unshaded impervious surfaces depend on the reflectivity of the surface (often referred to as 'albedo'), angle of incidence of solar radiation (highest at solar noon at summer solstice), humidity, and wind. The reflectivity of asphalt used for roadways and that of roofing shingle made from asphalt is 0.04 – 0.16 ("Pavement Thermal Performance", 2021; "Roof Albedo", n.d.; Kaarsberg and Akbari, 2006), meaning that 84–96% of solar radiation is absorbed as heat. Surface temperatures for asphalt pavement in the northeast can attain 140 °F in summer (Kallas, n.d); temperatures for roofing shingles are cited to be up to 70 °F greater than those of air ("High-albedo Materials for Reducing Building Cooling Use", 1992). The rapid rise in stream water temperature often noted with precipitation in summer represents at least in part the transfer through stormwater runoff of the heat stored in the asphalt of roadways, parking lots, and roofing shingles.

Concrete also represents an important impermeable surface. Its reflectivity is higher than that of asphalt (albedo = 0.18–0.35; "Pavement Thermal Performance", 2021), so it absorbs less heat for transfer to stormwater. The reflectivity of rocks is about that of concrete, but differences exist of course between light and dark rocks ("What is Reflectance Spectroscopy?", n.d.). Soil (apart from dry, sandy soil) and grass have an albedo of 0.05–0.30 ("Albedo", n.d.). Soil and grass represent permeable surfaces, however, so while they absorb significant heat from solar radiation, their contribution to runoff is less than that of impermeable surfaces. Grasses also moderate the impact of solar radiation on soil temperature by shading the soil – meadow grasses are far more beneficial than mowed (manicured) lawns (Lybarger, 2023).

At the risk of too much detail – although we think it important – we dissect below the impact of impervious surfaces on stream temperature at the level of groundwater, stormwater runoff, and ambient air.

i. Impact through groundwater

Groundwater is a principal determinant of temperature for many streams. Impervious surfaces affect groundwater in two ways that impact on stream temperature. First, impervious surfaces limit penetration of precipitation into the ground and thus limit recharge and reduce baseflow. Second, impervious surfaces transmit stored heat, primarily that conveyed by radiant energy, to shallow groundwater. The impact of these effects is expressed almost constantly.

Diminished infiltration leads to a reduction in groundwater recharge. This, in turn, results in a reduction of stream base flow (*i.e.*, water volume) for most streams. As reduced base flows are correlated with increases in stream temperature in summer (see Wang *et al.*, 2003, for example, and references therein), it is easy – and correct – to link such increases to reductions in colder groundwater entering the stream: the less groundwater inflow, the warmer the stream. The reverse would be true in winter, in which groundwater tends to warm the streams it serves.

That said, there can be other factors contributing to increases in stream temperature with reduced base flow. These include a greater surface to volume ratio that is more affected by ambient air temperatures and/or solar radiation. In many cases where impervious surfaces are prevalent there is also reduced riparian cover and shade, resulting in increased sun exposure of the stream channel and resultant higher water temperatures, especially in the summer.

Impervious surfaces at ground-level – for example streets and parking lots – can affect not only recharge but the temperature itself of shallow groundwater. As noted previously, shallow groundwater is generally defined as having a depth ≤ 15 m. The warming of shallow groundwater occurs by conduction of heat through rock underlying the impervious surface. The above-noted reduction in groundwater volume can render the groundwater more sensitive to changes in temperature.

The transfer of heat from impervious surfaces has been studied almost solely in relation to 'urbanization' and – in the extreme – urban heat islands. A study of groundwater in the Virginia Beach area in December shows the warmest temperatures (≥ 18 °C) to be in wells adjacent to large parking lots and the coolest temperatures (15.5 °C) to be in wells in rural areas (Eggleston and McCoy, 2015). Groundwater for the Nuremberg area ranges between 9 and 17 °C, with the highest temperatures noted in the city center and the lowest temperatures in rural areas (Schweighofer e*t al.*, 2021). An analysis of 3 plains in Japan demonstrates an increase in shallow groundwater warming with a decrease in vegetation associated with urbanization, formally a 0.5–0.7 °C warming for a 0.12 difference in the Landsat Normalized Difference Vegetation Index (NDVI, Gunawardhana and Kazama, 2012; NDVI is used to quantify vegetation greenness and is useful in understanding vegetation density and assessing changes in plant health by using aerial observations). These data should be viewed with caution, as urbanization involves not only an increase in impervious surfaces, but an increase in subsurface structures, for example basements and electrical transmission infrastructure, which radiate heat.

Of note – and beyond effects on stream temperature *per se* – increases in the temperature of groundwater has attracted attention in relation to mineral dissolution (hence, increases in conductivity), oxygen tension, desorption of organic matter and pollutants from soil and sediment, and changes in microbial community structure ("Temperature and Water", 2018; Riedel, 2019, and references therein).

ii. Impact through runoff

Runoff from impervious surfaces is conveyed directly to streams over land and through storm sewers. The temperature of rainwater may or may not be that of surface air, depending on atmospheric conditions such as air strata and humidity. Any change in temperature of the rainwater upon contact with asphalt will depend on the mass of asphalt (a function of its thickness), the rate and intensity of precipitation, and the rate of runoff. In one study, in which asphalt surface temperatures averaged 44 °C, or 20 °C more than the corresponding average sod surface temperatures, the average initial asphalt runoff temperature during a 24 °C rainfall simulation was 35 °C (Thompson *et al.*, 2008, conducted in Wisconsin); over the course of an hour it decreased to 28 °C, still well above that from sod, as the rain cooled the asphalt surface. One might be tempted to discount the effect of solar radiation as the cloud cover preceding precipitation moves in, but the mass of an asphalt surface can be quite significant, carrying heat from previous days' exposures.

The change in stream temperature due to runoff from an impervious surface will depend on many factors, including: the distance of the stream from the impervious surface, the vegetation, temperature, and permeability of intervening land, ambient air temperature, and the volume of the runoff relative to that of the stream. In all but the shortest distances, the stream temperature change will be dictated principally by the properties of the intervening land, ambient temperature, and volume of water that comes into contact with the stream. Should the intervening land be highly permeable, one may need to consider the push of underlying groundwater into the stream as part of the mix. Few if any studies have taken all the above factors into consideration. Moreover, increases in impermeable surface often occur with deforestation, a confounding factor in the analysis.

There are fewer variables in dealing with precipitation conveyed from an impermeable surface to a stream through storm sewers. In the abstract, one is dealing simply with relative volumes of water and the loss or gain of heat to the walls of the sewer by conductance, a function of velocity and distance. Because the sewers lie beneath the surface of the ground, they may be cooler than the surface and the precipitation itself, in which case the water draining from the sewers into the stream may have a cooling effect in summer, not unlike that of groundwater (but see below).

The effects of runoff on stream temperature can be especially profound in the case of urban heat islands. Here, the runoff that occurs above ground may be on large stretches of pavement alone, unbroken by any form of permeable, vegetated land. Storm sewers beneath the ground are likely to be more easily warmed by the transfer of heat from these extensive surfaces or from subsurface structures related to buildings, conveyances for electrical conduit, and underground transportation.

Rooftops as impermeable surfaces should be included in discussions of artificial conveyance. How many times have we seen – quite often in conflict with code – drain pipes on a property extended across or under the ground empty directly to streams? Local municipal stormwater ordinances often have a section titled "Roof Drains" which dictates the design of the system including acceptable discharge locations. Also, stormwater ordinances may have a section titled "Prohibitive Discharges" that restricts draining into surface waters.

iii. Impact through ambient air

Impervious surfaces also transfer heat absorbed through solar radiation to overlying air. Whether a nearby stream might be warmed by that air depends largely on the distance of the stream from the impervious surface. Other factors are the mass of the air, which is proportional to the area of the impervious surface, the extent of its warming, and precise atmospheric conditions, which include the degree of humidity and air movement. Urban heat islands are, of course, an extreme wherein increases in air temperature of 10 °C in relation to surrounding rural areas have been noted. Like the effects of impervious surfaces on groundwater, the impact of impervious surfaces on ambient air, especially surfaces of urban heat islands, are in constant.

C. Impoundments

Impoundments as they relate to streams are defined as human-made structures that obstruct the flow of a stream and thereby create an accumulation (a ponding) of slower-moving or standing water. Dams are the most common form of impoundments, but other impoundments include weirs, and culverts (if impeding flow). One might also think in terms of natural ponds directly linked to streams.

The principal effect of impoundments on stream temperature is related to thermal stratification. The surface of very slow-moving or standing water is warmed by solar radiation. The warm water remains at the surface, as the mixing of water no longer occurs as it would in a running stream, and it continues to be warmed by radiation. The retention of the water at the surface is supported by the buoyancy of warm water relative to cooler water. The coolest water is the least buoyant and therefore the deepest. Heat conduction supports a more or less smooth transition of temperature from warmer to cooler as a function of depth.

The precise degree of warming and stratification depends on many factors, including the geometry of the water (*i.e.*, depth, volume, and surface area), residence time, and forest cover. For relatively small ponds, there is also a seasonal element to consider. The increase in temperature of the surface relative to the deeper portions of smaller ponds occurs principally in the summer, as solar radiation becomes a less relevant factor than ambient air and ground temperatures in fall through spring.

The stratification of water according to temperature has an obvious impact on the biota of the accumulated water. But – importantly – stratification can also have an impact downstream of the impoundment. The water that supports downstream flow from small ponds (dam heights less than 15 meters) is often drawn off the top by spillover. For small ponds in the mid-Atlantic states in summer in which flow is supported by spillover, the difference in water temperature immediately downstream of the impoundment can range up to 7° C greater than that upstream of the impoundment.

Yet, a study of a large number of impoundments in Massachusetts underscores the large number of variables that exist with regard to differences between temperatures downstream and upstream of small surface-release dams (Zaidel et al, 2020). While most dams (67%) warmed downstream temperatures, with August mean temperatures 0.25– 5.25° C higher than upstream, not all did. Predictors of an increase in downstream temperature were dam height, impoundment volume, impoundment widening, impoundment residence time, impoundment:watershed area, and watershed forest cover. Predictors of no change were average upstream August temperature, watershed impervious cover, watershed size, and watershed sand and gravel.

It is worth noting that water retention basins used in stormwater management can form the equivalent of small impoundments should they be poorly engineered or maintained. Water that is stored for any length of time in these basins, that is, if these basins drain poorly, will be heated by solar radiation. This will have a gradual impact on groundwater temperature. Should subsequent precipitation push water levels to that of the banks or overflow conduits, warming of adjacent stream water will occur directly.

The water supporting downstream flow can be drawn from other depths or as a mix of depths depending on the sophistication of the impounding structure. This is particularly true of large dams. If the water is drawn solely from the deepest depth of the impoundment, water temperature may be lower downstream relative to upstream. This, too, would tend to support biota different from that upstream, one conditioned to cooler water. Most modern structures, however, will draw a mix of water through the temperature strata to replicate upstream temperatures.

D. Discharge of heated effluents

Water is used in power plants both as a source of steam and as a coolant. Water is also used in a variety of industrial processes – with petroleum refineries, chemical plants, steel plants, and smelters often cited – to cool machinery and end- or intermediate products. It is used for irrigation and crop cooling in an agricultural setting. Perhaps most importantly in an urban or suburban setting, it is used in the treatment of waste. "Methods to Reduce or Avoid Thermal Impacts to Surface Water" (2007) and Kinouchi, *et al.* (2007) provide perspectives on waste water management.

Once-through cooling systems in coal plants, for example, can significantly heat the cooling water. The extent of temperature increase depends on the design and efficiency of the cooling system, ambient conditions, and the specific characteristics of the coal plant. The temperature rise of the cooling water in once-through systems can vary. In some cases, the temperature of the discharged water can be tens of degrees Celsius higher than the intake water temperature.

Besides the impact due to the increased discharge water temperature, there can also be significant environmental consequences if these systems are quickly shut down and the rapid change in temperature impacts the aquatic life.

E. Groundwater depletion

Because groundwater contributes significantly to the flow and temperature of many streams, the depletion of groundwater by pumping – for example for agricultural or industrial needs – can be a concern. The concern is related to the transition of groundwater depletion into streamflow depletion, *i.e.*, the diminishment in stream baseflow. The time of onset of streamflow depletion with the initiation of pumping will depend principally on the distance of the pump from the stream and the 'hydraulic diffusivity' of the aquifer, albeit other factors exist. The reader is referred to Barlow and Leake, 2012, for a detailed discussion of such factors. Of importance, aquifers are generally treated as steady-state systems, so that streamflow depletion will eventually approximate the rate of groundwater depletion, *i.e.*, the decrease in stream baseflow will be more or less equivalent to the rate at which the groundwater is withdrawn by the pump absent any infiltration.

The impact is two-fold. First, as noted throughout this document, the temperature of groundwater is an important determinant of the temperature for many streams. The decrease of groundwater as an input would translate into higher stream temperatures in summer and lower stream temperatures in winter. Temperature thresholds for aquatic organisms at either extreme would become more of a concern. Second, the reduction in stream volume with a decrease in groundwater discharge will almost always increase the surface area relative to the volume of the stream, the degree of which will depend on the architecture of the stream bed. This will increase the rate of conductive heat exchange with overlying air and the degree of radiative heating. Hence, the effects of volume depletion per se in summer would be an increase in stream temperatures. The effects in winter would be mixed.

Evaluating the specifics of how pumping translates into streamflow depletion is a complicated business, generally devolving to sophisticated forms of field measurements and modeling. These are discussed, as well, in Barlow and Leake, 2012.

4. MUNICIPAL ENGAGEMENT PROMPTED BY STREAM TEMPERATURE DATA

Methods for communicating data to municipalities with the aim of influencing decisions that impact stream health are covered in detail in the document 'Engaging Municipalities', also developed by the Delaware River Basin Policy and Practice Workgroup. Readers will find considerable advice relating to research and preparation, relationships, strategies, and effective communication. Accordingly, the section here will deal only with forms of engagement prompted by stream temperature data.

It will surprise no one that thermal impacts on municipal water resources have received increasing, and substantial, attention in recent years from environmental advisory councils, fishing associations such as Trout Unlimited, both small and large watershed organizations, and many other governmental and private organizations. The attention is due partly to increases in temperature – now documented over many years – for a large number of streams and how these and predicted increases translate into risks for aquatic life and the health of stream-based ecosystems in general. Any temperature-based risk to aquatic life is made worse by the increasing fragmentation of waterways caused by roads and highways, at a basic level limiting fish access to habitat connectivity (Sadler et al., 2023) and refugia.

Increases in stream temperatures are not occurring in isolation. Rather, they are a critical part of increases occurring in other water bodies, land forms, and the troposphere. The interconnectedness of these systems cannot be overemphasized. Increasing temperatures are challenging the adaptability and productivity of all species of plants and animals and are being felt in very real ways at the level of ecological phenology ("Climate Change Impacts on Forests", 2023).

A. When to begin thinking about approaching a municipality

Let's begin with the most important question: What would be the prompt – in terms of stream temperature data – to begin thinking about approaching a municipality? One prompt might be that a stream is already exceeding state or federal standards and/or biological thresholds. Another might be that a stream is currently holding its own in terms of standards or thresholds but faces imminent threat at either level. In both cases, one is seeking action from the municipality so as to reverse current, or lessen future, impacts. A third prompt might be that a stream is meeting temperature criteria and is otherwise of high quality, and for this reason merits protection.

i. A stream already exceeds state or federal standards and/or biological thresholds

Preventing problems is always preferable to having to deal with them, however we begin from the sharply defined vantage that problematic temperatures already exist. If one can show with whatever data that streams are already exceeding state standards and/or biological thresholds, or that certain discrete landscape features already have measurable impacts on stream temperature, municipalities may be more cognizant of the actual threats in making future land use planning decisions. They may also be open to remediation.

The key, then, is to understand state standards, inclusive of temperature thresholds. Toward this end, all states are mandated by the Clean Water Act to have water quality standards, which include as key components designated uses, water quality criteria, and antidegradation policies. Designated uses almost always relate to drinking water, recreation, and – importantly, from our perspective – aquatic life.

Appendix A.1 provides classifications by designated uses of freshwater bodies and corresponding temperature criteria for states in the Delaware River Basin. All such classifications refer to support of aquatic life, and all distinguish between cold and warm water habitats. Note that the classifications are protective in nature. Temperature criteria almost always refer to temperature limits in relation to point source discharges. But this is useful information. Should a stream designated as cold water (or otherwise supporting trout in some manner) surpass the maximum allowable temperature, whatever the state has determined, one is justified in approaching the relevant municipalities and/or county or state governments, certainly to inform future development but also to seek remediation.

ii. A stream faces potential threat

Arguing effectively for the *prospect* that a stream's temperature will – at some point – exceed state standards or biological thresholds is sometimes a tough bar to clear. The prospect of threat, however, becomes quite real when stream temperatures are already close to exceeding such standards or thresholds. This goes without saying for streams that are designated by governmental (usually state) agencies as 'high quality' or 'exceptional value', or those that are striving for reclassification as such. This is not to leave out warmwater streams, especially those for which trout have been observed. All streams need advocates.

a. Trends from historical data

One might have access to stream temperature data that span a number of years. The idea, then, would be to evaluate these data to determine whether a problematic trend exists, including seasonal trends. Be forewarned, however: this is not a simple process. Given year-to-year variations in ambient temperatures, rainfall, and wind for any particular month or season, trends can be difficult to discern. Trends must also be evaluated statistically in order to be compelling. One challenge, therefore, is having or finding statistical expertise. Another is having a sufficient number of years to achieve statistical significance. EnviroDIY stations and HOBO monitors have burgeoned in popularity only recently and may therefore not provide the requisite time span. One might be able to use data from USGS stream monitors, albeit placement of these, at least in the DRB, are less common than those of EnviroDIY stations.

'Controls' can be quite useful to a statistical story. If you believe, for example, that the temperature of your stream has increased over the years due to land development within its watershed, there's nothing like a comparison to a stream in an adjacent watershed not subject to development. The second stream is a 'control'.

b. Threat from land development

Section 3 of this document discusses land use and development of concern, with a particular emphasis on deforestation and impervious surfaces. Calculating the exact contribution to stream temperature of a certain amount of deforestation or a given area of impervious surface is a sophisticated endeavor usually requiring expertise in civil engineering. While you *might* be able to interpret such calculations, developers are rarely pressed into providing them, and there is always the question of accuracy and bias.

This is, however, precisely a situation in which your temperature-centric expertise is valuable. You know the stream better than anyone. You know all the predictable and idiosyncratic features of its temperature. You have the real-time data! You are there to assert the importance of temperature (hence this document), should anyone decide to side-step it.

iii. Proactive education

If one can show a municipality through collected data where streams are meeting temperature criteria and are otherwise of high quality, the municipality may be more likely to entertain protective measures like increased setbacks or reclassification petitions. This sort of education could happen before the appearance of any contentious development project, so that the municipality is open to and experienced with potential temperature concerns.

C. What's in it for the municipality?

i. Economy

You may be in a position to help your municipality or other stream-related organizations consider the impact of increasing stream temperatures or fragmentation on recreational fishing. Recreational fishing and related recreational activities in Pennsylvania, for example, added $14 billion to Pennsylvania's gross domestic product according to the U.S. Bureau of Economic Analysis for 2021 (PA Dept. of Cons and Nat Res: https://www.dcnr.pa.gov/GoodNatured/pages/Article.aspx?post=227). You will certainly have many invested allies in this endeavor.

The recreational fishing capacity of your watershed could be presented to a municipality through presentations that help others to understand how streams are impacted by increases in temperature caused by land development.

The Alliance for Aquatic Resource Monitoring gives a helpful series of steps for a strategy to find the 'story' in the data collected for a presentation. These have been elaborated and augmented here based on experience in site-specific studies. Important questions to ask regarding temperature are:

1. How healthy is the site(s)? Are any water quality criteria being violated such as how long each summer (spring and fall) temperatures exceed those for a healthy reproductive fish habitat or even for fish toxicity? Are there any outlier data points and why did they occur?

2. Seasonal differences can impact the study data and outcomes and obscure or distort findings if not considered. For example, what seasonal patterns in temperature exist, including not only increases in summer and lower winter stream temperatures, but are water temperatures above ideal conditions for trout reproduction being delayed by warmer stream temperatures going into the fall, or beginning earlier in the spring? Are there deviations from those patterns, or changes in them over time?

3. The patterns of temperature could also be considered in relation to other stream measurements such as oxygen, macroinvertebrate species counts and richness, conductivity, and periods and accumulation of precipitation. Are there times of the year

with increased precipitation that is causing more warming of the stream than would be caused by groundwater? Examining the parameters of interest can also gain significance (and increase the complexity of the study) if considered across multiple sites that are similar, or different, from the site of interest; for example, the impact of land use on e-conductivity, changes in macroinvertebrate indices, or chronicity or severity of stormwater flooding on rural, suburban, and urban sites.

4. Are there other partners or collaborators who might have data that would enrich the understanding of the site of interest? Can other factors be identified that might have influenced the results?

In any presentation, you should know that some streams are less adaptive or resilient than others to land development. Limestone streams may be particularly vulnerable to degradation. Limestone streams are mostly spring-fed due to their underlying geology, which can make the stream colder during the summer and warmer in the winter. Thus, development could disrupt conditions that are particularly beneficial for coldwater fish. The EPA identified in the "Pennsylvania Climate Impact Assessment" (PCIA) limestone spring streams as more "resilient in the face of hot weather extremes than freestone streams that rely on surface and shallow groundwater sources. Trout conservation efforts are likely to be more successful in the limestone streams compared to other coldwater streams." Therefore, increasing development around limestone streams breaks the principle of protecting the best quality resources first, and would decrease your municipality's and county's capacity to adapt to climate heating. The EPA recognizes that if temperatures continue to rise, the survival and breeding of even warmwater fish will be a problem. Thus, the EPA is providing leadership that our individual communities should use as guidance to protect our coldwater fish habitats. Releasing upstream sources of colder water is one strategy that is used. For example, the Delaware River Basin Commission is a quasi-governmental body with representatives from four states (Delaware, New Jersey, New York, Pennsylvania) that can be appealed to both for taking quicker action on decisions to protect colder temperature in the watershed, but also for guidance on informative documents and best practices for protecting temperatures in smaller streams if they are reaching critical limits.

The PCIA also recommends development of an 'adaptation report' that identifies key issues affecting freshwater streams such as increased temperature and the specific fish species in the watershed of interest that would be deleteriously impacted by increased temperature. The PCIA notes "Of special concern is the impact of higher temperatures and altered flow regimes on Eastern Brook Trout" ("Pennsylvania Protects Coldwater Fisheries", 2023).

ii. Concordance with community sentiment

How can municipalities that do not rely economically on recreational fishing be motivated to act on data relating to stream temperatures? One course of action is point out, or otherwise identify, sentiment that exists within the community toward environmental issues in general. Given the emerging consensus for temperature as a primary driver in global climate change, support for action at any level – streams included – might be easily attained.

That positive community sentiment exists, and at times is quite strong, is clear:

- Curricula that cover the environment, and that deal at length with ecological interdependencies, are typically mandated at primary through secondary levels. Recently formulated Pennsylvania Integrated Standards for Science, Environment and Ecology (6th – 12th grade; "Pennsylvania Integrated Standards", n.d.), for instance, specifically state:

  > "Understanding the components of ecological systems and their interrelationships with social systems and technologies is vital to the development of STEM-literate citizens. These components incorporate the disciplines of resource management, agricultural diversity, government and the impact of human actions on natural systems. **This interaction leads to the study of watersheds**, threatened and endangered species and pest management, **and to the development of associated laws and regulations**." [Emphasis added]

- School-based environmental clubs are common and are quite focused on environmental warming. Middle and High School science teachers can integrate field studies of a local stream into their syllabi, and some also encourage their students to write letters to their political representatives about environmental concerns.

- Scouting (for example, Girl Scouts, Boy Scouts) incorporates environmental knowledge and activism as an inherent part of its structure.

- While the economy of a municipality might not rely on fishing, all municipalities – those within the DRB as an example – have an often substantial number of individuals who enjoy fishing as a primary form of recreation. The membership of Trout Unlimited is a prime example of the range and passion for the environment with constant attention to, and discussion of, stream temperatures; members exist in virtually every community.

- Watershed organizations, who assess stream habitats and collect long term and varied information on the streams in a certain regions, are attuned to the relevance of stream temperatures, and many work hand in hand with municipalities on a variety of related endeavors, including stormwater control, erosion control, forestation, and education, both informally and through participation on municipal committees.

- Gardeners have an incredible understanding of the complicated and often delicate balances that exist in ecological settings. Farmers, hunters, backpackers, and all others who love the outdoors, too, share this understanding. Long-term changes in temperatures are a fundamentally important topic to these individuals.

All of this is to say that municipal decision makers, if not already cognizant of community sentiment, can be made so by advocates who articulate the interests and passion of those included above. How strong is the sentiment? It will depend on the community. But there will always be a number of individuals in any municipality who understand and who can be rallied to the cause.

One last point needs to be made. In working with decision makers and interested groups in response to rising stream temperatures, the concept of phenology cannot be overemphasized. Phenology was defined generally in a previous section, but can be defined more specifically here: "[Phenology is] the study of the timing of recurring biological phases, the causes of their timing with regard to biotic and abiotic forces, and interrelation among phases of the same or different species " (attributed Global Phenological Monitoring by Linderholm, 2006). Of note in a phenological context, the impact of rising stream temperatures is not limited to aquatic organisms. The disappearance of macroinvertebrates and fish as a function of temperature leads to the disappearance of insects, birds, reptiles, and mammals that feed on them.

iii. Stream temperature as a proxy for other temperature issues in the community

Stream health can be likened in some ways to the proverbial canary in the coal mine. A stream that is getting warmer implies a warming of the watershed itself and of the regions of the municipality that extend into that watershed. Likely causes, as outlined in other sections of this document, are those of human activity, some that can be controlled by the municipality (growing impervious area and deforestation) and some that cannot (climate change). In either case, the warming of a stream may resonate with residents if they feel other spaces of the community – shopping centers, downtown areas, parks, schools, etc. – are on an upwardly warming trend as well. The threat of becoming an urban heat island, whose repercussions have received much recent attention by the media, is now felt by a number of even small communities with the expansion of megastores and warehouses. The 'canaries' in our example are fish and invertebrates, whose presence in a stream is sensitive to a change in temperature of only a few degrees.

Some of us working with stream monitor stations have had conversations with fishermen who have lived in the area for most if not all their lives. A sad but not infrequent refrain is that "this stream isn't anything like it was." And why should it be, when temperatures (and, yes, certain other factors) have changed through the years? Will these fishermen and others not be receptive to the data – your data – that provide at least some of the explanation?

C. Approaches to engagement

i. Working with like-minded individuals

To reiterate what the document 'Engaging Municipalities' discusses, working with like-minded individuals when you sense a threat to your stream is incredibly useful. If you have a concern, one that you think requires attention by your municipality, air that concern first through one or more watershed associations – you likely belong to one! Some of the larger associations have staff who deal with municipalities. Raise your concern as well through local fishing associations, Riverkeeper and Waterkeeper organizations, and National Fish Hatcheries. The more feedback and interest generated, the better the approach to the municipality.

ii. Bringing ideas to the table

Engaging with a municipality over a threat to your stream should rarely be viewed as a ‘win-at-all-costs’ battle. The engagement should have as its aim an open and constructive conversation about the nature and extent of the threat and how best to deal with it, taking into account all perspectives. Recognize that “how best to deal with it” will require serious thought on your part. This will be expected of you. In most instances, you’ll land in the territory of ‘remediation’. Remediation means to remedy something. Remediation can be proposed for something that’s already happened, something that’s in the process of occurring (climate change), or something that’s anticipated (a developer’s plan).

Deforestation that impacts stream temperature can be met with… reforestation, although reestablishing woodlands or connecting or enhancing forested areas, is not as simple as just planting trees, but this is the beginning. Working with an organization with expertise in reforestation will guide your efforts to maximize effectiveness by learning about critical actions such as analyzing soil quality, understanding the challenges to reestablishing root systems, learning the requirements of different tree species, and creating plans for maintenance. This might occur on the deforested site itself, depending on the nature of the site. But benefits may be gained by downstream reforestation, including increasing the density of tree plantings. Deforestation near or in a riparian buffer is particularly problematic. Many communities and states are recognizing the value of riparian buffers – you might look to those that are emphasizing riparian protections as a point of reference in your arguments.

Fortunately, virtually all governmental agencies by this point recognize the problems inherent to impervious surfaces. While the recognition almost always occurs in the context of stormwater control, the workarounds recommended by these agencies are applicable to averting threats to stream temperature. Non-structural workarounds include minimizing the footprint of proposed impervious surfaces, sometimes through meaningful reduction, clustering, or stacking; substituting with permeable surfaces where possible, for example by use of paving stones, grass pavers, and pervious pavements; and use of green infrastructure, including naturalized infiltration basins, wet pond/retention basins, rain garden/bioretention beds, vegetated swales, subsurface infiltration beds, vegetated roof cover, runoff capture and reuse, and tree trenches.

Other types of threats exist, of course. The approaches described above can provide some semblance of a beginning strategy, one in which individualization would follow to address the specifics of the threat.

5. REFERENCES

"A Quick Guide to Groundwater in Pennsylvania." PennState Extension. https://extension.psu.edu/a-quick-guide-to-groundwater-in-pennsylvania. August 26, 2022.

"Albedo." Wolfram Research. https://scienceworld.wolfram.com/physics/Albedo.html | Accessed September 19, 2023.

Anderson, W.G., Booth, R., Beddow, T.A, et al. Remote monitoring of heart rate as a measure of recovery in angled Atlantic Salmon, Salmo salar (L.). Hydrobiologia (1998) 371:233-240.

"Average Shallow Groundwater Temperatures." U.S. EPA. https://www3.epa.gov/ceampubl/learn2model/part-two/onsite/ex/jne_henrys_map.html | Accessed September 19, 2023.

Barlow, P.M., and Leake, S.A. Streamflow depletion by wells – Understanding and managing the effects of groundwater pumping on streamflow. U.S. Geological Survey Circular 1376, 84 p., 2012. http://pubs.usgs.gov/circ/1376/

Bonacina, L., Fasano, F., Mezzanotte, and Fornaroli, R. Effects of water temperature on freshwater macroinvertebrates: a systematic review. *Biological Reviews* (2023) 98: 191–221. https://doi.org/10.1111/brv.12903

Boyd, J.W., Guy, C.S., Horton, T.B., and S. A. Leathe. Effects of Catch-and-Release Angling on Salmonids at Elevated Water Temperatures. North American Journal of Fisheries Management (2010) 30(4):898-907.

Burton, T.M., and Likens, G.E. The effect of strip-cutting on stream temperatures in the Hubbard Brook Experimental Forest, New Hampshire. *BioScience* (1973) 23: 433-435. https://doi.org/10.2307/1296545

Caraco, D., Claytor, R., Hinkle, P., Kwon, H., Schueler, T., Swann, C., et al. Rapid Watershed Planning Handbook: A Comprehensive Guide for Managing Urbanizing Watershed (1998). Prepared by Center for Watershed Protection, Ellicott City, MD. Prepared for U.S. Environmental Protection Agency, Office of Wetlands, Oceans and Watersheds and Region V.

Caissie, D. The thermal regime of rivers: a review. *Fresh Water Biology* (2006) 51: 1389-1406. https://doi.org/10.1111/j.1365-2427.2006.01597.x

Chadwick, J.G., Nislow, K.H. and McCormick, S.D. Thermal onset of cellular and endocrine stress responses correspond to ecological limits in brook trout, an iconic cold-water fish. *Conservation Physiology* (2015) 3: 1-12. https://doi.org/10.1093/conphys/cov017

Chadwick, J.G. and McCormick, S.D. Upper thermal limits of growth in brook trout and their relationships to stress physiology. *Journal of Experimental Biology* (2017) 220: 3976-3987. https://doi.org/10.1242/jeb.161224

Chown, S.L., Duffy, G.A., and Sørensen, J.G. Upper thermal tolerance in aquatic insects. *Current Opinion in Insect Science* (2015) 11: 78-83. https://doi.org/10.1016/j.cois.2015.09.012

“Climate Change Impacts on Forests.” United States Environmental Protection Agency. May 18, 2023. https://www.epa.gov/climateimpacts/climate-change-impacts-forests

Comte, L. and Grenouillet, G. Do stream fish track climate change? Assessing distribution shifts in recent decades. *Ecography* (2013) 36: 1236-1246. https://doi.org/10.1111/j.1600-0587.2013.00282.x

Condon, L.E., Atchley, A.L., and Maxwell, R.M. Evapotranspiration depletes groundwater under warming over the contiguous United States. Nature Communications (2020): *https://doi.org/10.1038/s41467-020-14688-0*

“Dissolved Oxygen.” United States Environmental Protection Agency. Causal Analysis/Diagnosis Decision Information System (CADDIS), Volume 2, Sources, Stressors and Responses, Dissolved Oxygen. EPA.gov/caddis-vol2/dissolved-oxygen. May 18, 2023.

Eggleston, J., and McCoy, K.J. Assessing the magnitude and timing of anthropogenic warming of a shallow aquifer: example from Virginia Beach, USA. *Hydrogeology Journal* (2015) 23: 105-120. https://doi.org/10.1007/s10040-014-1189-y

Gunawardhana, L.N., and Kazama, S. Using subsurface temperatures to derive the spatial extent of the land use change effect. *Journal of Hydrology* (2012) 460-461: 40-51. https://doi.org/10.1016/j.jhydrol.2012.06.042

Hare, D.K., A.M. Helton, Z.C. Johnson, J.W. Lane, and M.A. Briggs. Continental-scale analysis of shallow and deep groundwater contributions to streams. *Nature Communications* (2021) 12:1450. https://doi.org/10.1038/s41467-021-21651-0.

“High-albedo materials for reducing building cooling use.” Prepared by H. Taha, D. Sailor, and H. Akbari, Energy and Environment Division, Lawrence Berkeley Laboratory, University of California. 1992. https://www.osti.gov/servlets/purl/7000986#:~:text=High%2Dalbedo%20materials%20can%20save,the%20building%20(indirect%20effect).

Hodge, B. An Annotated Bibliography of the Science on Catch and Release Angling of Salmonids. Trout Unlimited Science (2023). https://www.tu.org/wp-content/uploads/2023/04/Annotated-Bibliography-on-CR_TU-Science.pdf

Ilha, P., Schiesar, L., Yanagawa, F.I., Jankowski, K., Navas, C.A. Deforestation and stream warming affect body size of Amazonian fishes. *PLOS|One* (2018) 13: e0196560. https://doi.org/10.1371/journal.pone.0196560

Isaak, D.J., Wollraab, S., Horan, D. and Chandler, G. Climate change effects on stream and river temperatures across the northwest U.S. from 1980-2009 and implications for salmonids fishes. *Climate Change* (2012) 113: 499-524. https://doi.org/10.1007/s10584-011-0326-z

Isaak, D.J., Wenger, S.J. and Young, M.K. Big biology meets microclimatology: Defining thermal niches of ectotherms at landscape scales for conservation planning. *Ecological Applications* (2017) 27: 977-990. https://doi.org/10.1002/eap.1501

Isaak, D.J. and Rieman, B.E. Stream isotherm shifts from climate change and implications for distributions of ectothermic organisms. *Global Change Biology* (2013) 19: 742-751. https://doi.org/10.1111/gcb.12073

Kaarsburg, T., and Akabar, H. Cool roofs cool the planet. www.homeenerg.org, 2006. https://eta-publications.lbl.gov/sites/default/files/HomeEnergy06%20%28Cool%20Roofs%20Cool%20the%20Planet%29.pdf

Kallas, B.F. Asphalt pavement temperatures. The Asphalt Institute. https://onlinepubs.trb.org/Onlinepubs/hrr/1966/150/150-001.pdf

Kaplan, M. and Ayers, M. Impervious surface cover concepts and thresholds. (2000). New Jersey Environmental Digital Library https://doi.org/doi:10.7282/T3TQ60J7

Kim, K.S., Chou, H., Funk, D.H., Jackson, J.K., Sweeney, B.W., and Buchwalter, D.B. Physiological responses to short-term thermal stress in mayfly (Neocloeon triangulifer) larvae in relation to upper thermal limits. *Journal of Experimental Biology* (2017) 220: 2598-2605. https://doi.org/10.1242/jeb.156919

Kinouchi, T. Impact of long-term water and energy consumption in Tokyo on wastewater effluent: implications for thermal degradation of urban streams. Hydrological Processes (2007) 21: 1207-1216. https://doi.org/10.1002/hyp.6680

Lybarger, K. [@nativeplanttok]. (2023, August 1). #nativehabitatproject #ecosystems #climate #biodiversitycrisis #planttrees #grasslands #prairies [video]. TikTok. https://www.tiktok.com/@nativeplanttok/video/7262444412003847470

“Light in the Ocean.” University of Hawai’i at Manoa. https://manoa.hawaii.edu/exploringourfluidearth/physical/ocean-depths/light-ocean#:~:text=Water%20absorbs%20almost%20all%20of,some%20the%20water%20to%20evaporate. | Accessed September 19, 2023.

Linderholm, H.W. Growing season changes in the last century. *Agricultural and Forest Meteorology* (2006) 137: 1-14. https://doi.org/10.1016/j.agrformet.2006.03.006

“Methods to Reduce or Avoid Thermal Impacts to Surface Water.” Prepared by Skillings Connolly Company for Washington Department of Ecology. 2007. https://apps.ecology.wa.gov/publications/documents/0710088.pdf

Meyer, K.A., McCormick, J.L., Kozfkay, J.R. and J. C. Dillon. 2022. Effects of elevated water temperature on cutthroat trout angler catch rates and catch-and-release mortality in Idaho streams. Fisheries Management and Ecology (2022) 30(2):134-141.

Muhlfeld, C.C., Dauwalter, D.W., Kovatch, R.P., Kershner, J.L., Williams, J.E. and Epifanio, J. Trout in hot water: A call for global action. *Science* (2018) 360: 866-867. https://doi.org/10.1126/science.aat8455

Nelson, K.C. and Palmer, M.A. Stream temperature surges under urbanization and climate change: Data, models and responses. *Journal of the American Water Resources Association* (2007) 43: 440-452. https://doi.org/10.1111/j.1752-1688.2007.00034.x

Patra, R.W., Chapman, J.C., Lim, R.P., Gehrke, P.C., and Sunderam, R.M. Interactions between water temperature and contaminant toxicity to freshwater fish. *Environmental Toxicology and Chemistry* (2015) 34: 1809-1817. https://doi.org/10.1002/etc.2990

“Pavement Thermal Performance.” From “Pavement Thermal Performance and Contribution to Urban and Global Climate.” U.S. Department of Transportation Federal Highway Administration. May 27, 2021. https://www.fhwa.dot.gov/pavement/sustainability/articles/pavement_thermal.cfm

Pederson, G.T., Graumlich, J.L., Fagre, D.B., Kipfer, T., and Muhlfeld, C.C. . A century of climate and ecosystem change in western Montana: What do temperature trends portent? *Climate Change* (2010) 98: 133-154. https://doi.org/10.1007/s10584-009-9642-y

“Pennsylvania Integrated Standards.” From “Pennsylvania Integrated Standards for Science, Environment and Ecology (Grades 6-12). https://www.education.pa.gov/Documents/Teachers-Administrators/Curriculum/Science%20Education/PA%20Integrated%20Standards%20for%20Science%20Environment%20Ecology%20Grades%206-12.pdf | Accessed September 19, 2023.

“Pennsylvania Protects Coldwater Fisheries.” From “Pennsylvania Protects Coldwater Fisheries and Water Quality for Climate Change,” United States Environmental Protection Agency, August 21, 2023. https://www.epa.gov/arc-x/pennsylvania-protects-coldwater-fisheries-and-water-quality-climate-change

Petty, J.T., Hansbarger, J.L., Huntsman, B.M., and Mazik, P.M. Brook trout movement in response to temperature, flow, and thermal refugia within a complex Appalachian riverscape. *Transactionsof the American Fisheries Society* (2012) 141: 1060-1073. https://doi.org/10.1080/00028487.2012.681102

Riedel, T. Temperature-associated changes in groundwater quality. *Journal of Hydrology* (2019) 572: 206-212. https://doi.org/10.1016/j.jhydrol.2019.02.059

“Roof Albedo.” Berkeley Lab Heat Island Group. https://albedomap.lbl.gov/#:~:text=Albedo%20is%20the%20fraction%20of,roof%20albedo%20is%20about%200.17. | Accessed September 19, 2023.

Sadler, D.E., Watts, P.C. Uusi-Heikkilä. The riddle of how fisheries influence genetic diversity. Fishes (2023) 8(10):510. https://doi.org/10.3390/fishes8100510

Schmidt-Kloiber, A., and Hering, D. www.freshwaterecology.info – An online tool that unifies, standardises and codifies more than 20,000 European freshwater organisms and their ecological preferences. *Ecological Indicators* (2015) 53: 271-282. https://doi.org/10.1016/j.ecolind.2015.02.007

Schueler, T. The importance of imperviousness. *Watershed Protection Techniques* (1994) 1: 100-111.

Schweighofer, J.A., Wehrl, M., Baumgärtel, S., and Rohn, J. Detecting groundwater temperature shifts of a subsurface urban heat island in SE Germany. *Water* (2021) 13: 1417. https//doi.org/10.3390/w13101417.

“Solar Radiation & Photosynthetically Active Radiation.” Fondriest Environmental Learning Center. https://www.fondriest.com/environmental-measurements/parameters/weather/photosynthetically-active-radiation/#:~:text=Infrared%20Light,-Infrared%20radiation%20is&text=This%20radiation%20has%20a%20wavelength,the%20substances%20that%20absorb%20them. | Accessed September 19, 2023.

Sponseller, R.A., Benfield, E.F., and Valett, H.M. Relationships between land use, spatial scale and stream macroinvertebrate communities. *Freshwater Biology* (2001) 46: 1409-1424. https://doi.org/10.1046/j.1365-2427.2001.00758.x

Stauffer, J.R., Criswell, R.W., and Fischer, D.P. The Fishes of Pennsylvania. 2016. Cichlid Press, El Paso, TX.

Steel, E.A., Beechie, T.J., Torgersen, C.E., and Fullerton, A.H. Envisioning, quantifying, and managing thermal regimes on river networks. *Bioscience* (2017) 67(6), 506-522. https://doi.org/10.1093/biosci/bix047

Studinski, J.M., Hartman, K.J., Niles, J.M., and Keyser, P. The effects of riparian forest disturbance on stream temperature, sedimentation, and morphology. *Hydrobiologia* (2012) 686: 107-117. https://doi.org/10.1007/s10750-012-1002-7

Sullivan, C.J., Vokoun, J.C., Helton, A.M., et al. An ecohydrological typology for thermal refuges in streams and rivers. *Ecohydrology* (2021);14;e2295. https://doi.org/10.1002/eco.2295.

Sweeney, B.W., and Newbold, J.D. Streamside forest buffer width needed to protect stream water quality, habitat, and organisms: a literature review. *Journal of American Water Resources Association* (2014) 50: 560-584. https://doi.org/10.1111/jawr.12203

Taniguchi, Y.F., Rahel, F.J., November, D.C. and Gerow, K.G. Temperature mediation of competitive interactions among three fish species that replace each other along longitudinal stream gradients. *Canadian Journal of Fisheries and Aquatic Sciences* (1998) 55(8):1894-1901. https://doi.org/10.1139/f98-072

“Temperature and Water.” USGS | Water Science School. https://www.usgs.gov/special-topics/water-science-school/science/temperature-and-water. June 6, 2018.

“Thermal Toxicity Literature Evaluation.” EPRI|Electrical Research Power Institute, Palo Alto CA. 2011. https://www3.epa.gov/region1/npdes/merrimackstation/pdfs/ar/AR-1558.pdf

Thompson, A.M., Kim, K., and Vandermuss, A.J. Thermal characteristics of stormwater runoff from asphalt and sod surfaces. *Journal of the American Water Resources Association* (2008) 44: 1325-1336. https://doi.org/10.1111/j.1752-1688.2008.00226.x

Tomczyk, N.J., Rosemond, A.D., Rogers, P.A., and Cummins, C.S. Thermal traits of freshwater macroinvertebrates vary with feeding group and phylogeny. *Freshwater Biology* (2022) 67: 1994-2003. https://doi.org/10.1111/fwb.13992

Van Leeuwen, T.E., Dempson, B. Cote, D., Kelly, N.I., and Bates, A.E. Catchability of Atlantic salmon at high water temperatures: Implications for river closure temperature threshold to catch and release angling. Fisheries Management and Ecology (2020) 28(2):147-157

Vanney, R.L., and Sweeney, B.W. Geographic analysis of thermal equilibria: A conceptual model for evaluating the effect of natural and modified thermal regimes on aquatic insect communities. The American Naturalist (1980) 115(5):667-695. https://doi.org/10.1086/283591

Wang, L., Lyons, J., and Kanehl, P. Impacts of urban land cover on trout streams in Wisconsin and Minnesota. *Transitions of the American Fisheries Society* (2003) 132: 825-839. https://doi.org/10.1577/t02-099

"Watershed Percent Impervious Cover." United States Environmental Protection Agency, Office of Water Recovery. 2011. https://www.epa.gov/sites/default/files/2015-11/documents/rp2wshedimperv1109.pdf

"Watersheds 2045," Chester County Water Resources Authority for the County of Chester, PA. September 2023. https://www.chesco.org/DocumentCenter/View/73401/DRAFT-Watersheds-2045-Plan-91523?bidId=

"What is Reflectance Spectroscopy?" Space Exploration Resources, Arizona State University. https://ser.sese.asu.edu/SPECTRA/intro.html#:~:text=Albedo%20is%20simply%20a%20measure,it%20has%20a%20low%20albedo. | Accessed September 19, 2023.

White, S.L., Kline, B.C., Hitt, N.P. and Wagner, T. Individual behaviour and resource use of thermally stressed brook trout Salvelinus fontinalis portend the conservation potential of thermal refugia. *Journal of Fish Biology* (2019) 95: 1061-1071. https://doi.org/10.1111/jfb.14099

Wilkie, M.P., Brobbel, M A., Davidson, K., et al. Influences of temperature upon the postexercise physiology of Atlantic salmon (Salmo salar). Canadian Journal of Fisheries and Aquatic Sciences (1997) 54(3):503-511

Woods, T., Kaz, A., and Giam, X. Phenology in freshwaters: a review and recommendations for future research. *Ecography* (2022), e05564. https://doi.org/10.1111/ecog.05564

Zaidel, P.A., Roy, A.H., Houle, K.M., Lamber, B., Letcher, B.H., Nislow, K.H., and Smith, C. Impacts of small dams on stream temperature. Ecological Indicators (2021), 106878. https://doi.org/10.1016/j.ecolind.2020.106878

Zhi, W., Klingler, C., Liu, J., and Li, L. Widespread deoxygenation in warming rivers. Nature Climate Change (2023), 13(October 2023), 1105-1113. https://doi.org/10.1038/s41558-023-01793-3

6. APPENDIX

A.1. State Classifications of Freshwater Bodies and Corresponding Temperature Criteria in the Delaware River Basin

DELAWARE

Delaware classifies freshwater bodies according to conforming to one and usually more of designated uses.

Designated uses are:

- Public Water Supply Source
- Industrial Water Supply
- Primary Contact Recreation
- Secondary Contact Recreation
- Fish, Aquatic Life & Wildlife, Cold Water Fish (Put-and-Take)
- Agricultural Water Supply
- ERES Waters (*i.e.*, 'Exception Recreational or Ecological Significance')
- Harvestable Shellfish Waters (for certain bays)_

These uses "must be maintained and protected through application of appropriate criteria." See Delaware's Administrative Code Section 7410 'Surface Water Quality Standards'.

ERES waters are discussed in Section 7410.5, wherein various statements conform to "Existing instream water uses and the level of water quality necessary to protect the existing uses shall be maintained." **Temperature is not explicitly mentioned**, but problematic temperature increases or decreases can reasonably be argued to be among the pollutants otherwise discussed in this section (*i.e.*, thermal pollution).

For waters of the Delaware River (and Bay), the water quality regulations of the Delaware River Basin Commission are in effect.

Temperature for freshwater bodies is discussed specifically only in Section 7410.4.5, in which it is stated that "the following criteria shall be applied outside approved regulatory mixing zones unless otherwise specified" and which seems to form a set of restrictions on human activity:

- Maximum increase above natural conditions shall be 5^{o}F.
- No human-induced increase of the true daily mean temperature above 82^{o}F shall be allowed.
- No human-induced increase of the daily maximum temperature above 86^{o}F shall be allowed.

MARYLAND

Maryland classifies fresh surface waters bodies according to usages.

The classifications are:

- Use Class I: Water Contact Recreation, and Protection of Nontidal Warmwater Aquatic Life
- Use Class I-P: Water Contact Recreation, Protection of Aquatic Life, and Public Water Supply
- Use Class III: Nontidal Cold Water
- Use Class III-P: Nontidal Cold Water and Public Water Supply
- Use Class IV: Recreational Trout Waters
- Use Class iV-P: Recreational Trout Waters and Public Water Supply

‘Growth and propagation of trout’ is included in III and III-P. ‘Capable of supporting adult trout for a put and take fishery’ is included in IV and IV-P.

The following are temperature criteria for the different use classes as per Code of Maryland Regulations, Title 26 (Department of Environment), Part 2. Subtitle 08 (Water Pollution), Chapter 26.08.02 (Water Quality). These relate to possible perturbations by point source discharges. ‘Ambient temperature’ in the following is defined as water temperature that is not impacted by a point source discharge.

- Use Class I: The maximum temperature outside the mixing zone… may not exceed 90°F (32°C) or the ambient temperature of the surface waters, whichever is greater.
- Use Class III and III-P: The maximum temperature outside the mixing zone… may not exceed 68 °F (20°C) or the ambient temperature of the surface waters, whichever is greater.
- Use Class IV and IV-P: The maximum temperature outside the mixing zone… may not exceed 75°F (23.9°C) or the ambient temperature of the surface waters, whichever is greater.

NEW YORK

New York classifies fresh surface waters bodies according to best usages, as discussed in New York Codes, Rules and Regulations (CRR-NY), Title 6, Section 701 'Classifications –Surface Waters and Groundwaters: Fresh Surface Waters'.

The classifications are:

N: enjoyment of water in its natural condition

AA-S: a source of water supply for drinking, culinary or food processing purposes; primary and secondary contact recreation; and fishing. The waters shall be suitable for fish, shellfish and wildlife propagation and survival.

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B: a primary and secondary contact recreation and fishing. These waters shall be suitable for fish, shellfish and wildlife propagation and survival.

C: fishing. These waters shall be suitable for fish, shellfish and wildlife propagation and survival. The water quality shall be suitable for primary and secondary contact recreation, although other factors may limit the use for these purposes.

D: fishing. Due to such natural conditions as intermittency of flow, water conditions not conducive to propagation of game fishery, or stream bed conditions, the waters will not support fish propagation. These waters shall be suitable for fish, shellfish and wildlife survival. The water quality shall be suitable for primary and secondary contact recreation, although other factors may limit the use for these purposes.

Virtually all the classifications contain the statement "The waters shall be suitable for fish, shellfish and wildlife propagation and survival."

Of importance, the freshwater bodies with classifications 'AA', 'A', 'B', and 'C' can additionally be designated 'T' for Trout Waters and/or 'TS' for Trout Spawning Waters, meaning that they must comply with any water quality standard, guidance value, or thermal criterion that specifical refers to trout or trout spawning.

Thermal criteria are limited, at least in CRR-NY, to those governing thermal *discharges* (see Section CRR-NY 704.2). They are the following (quoted):

> **(a) General criteria.**
>
> The following criteria shall apply to all waters of the State receiving thermal discharges, except as provided in section 704.6 of this Part:
>
> (1) The natural seasonal cycle shall be retained.
> (2) Annual spring and fall temperature changes shall be gradual.
> (3) Large day-to-day temperature fluctuations due to heat of artificial origin shall be avoided.
> (4) Development or growth of nuisance organisms shall not occur in contravention of water quality standards.
> (5) Discharges which would lower receiving water temperature shall not cause a violation of water quality standards and section 704.3 of this Part.
> (6) For the protection of the aquatic biota from severe temperature changes, routine shut down of an entire thermal discharge at any site shall not be scheduled during the period from December through March.
>
> **(b) Special criteria.**
>
> The following criteria shall apply to all waters of the State receiving thermal discharges, except as provided in section 704.6 of this Part:
>
> (1) Nontrout waters - Protecting Warm water fish? macroinvertebrates? aquatic plants?.
>
> (i) The water temperature at the surface of a stream shall not be raised to more than 90 degrees Fahrenheit at any point.
> (ii) At least 50 percent of the cross sectional area and/or volume of flow of the stream including a minimum of one-third of the surface as measured from shore to shore shall not be raised to more than five Fahrenheit degrees over the temperature that existed before the addition of heat of artificial origin or to a maximum of 86 degrees Fahrenheit whichever is less.
> (iii) At least 50 percent of the cross sectional area and/or volume of flow of the stream including a minimum of one-third of the surface as measured from shore to shore shall not be lowered more than five Fahrenheit degrees from the temperature that existed immediately prior to such lowering.
>
> (2) Trout waters (T or TS).
>
> (i) No discharge at a temperature over 70 degrees Fahrenheit shall be permitted at any time to streams classified for trout.
> (ii) From June through September no discharge shall be permitted that will raise the temperature of the stream more than two Fahrenheit degrees over that which existed before the addition of heat of artificial origin.

(iii) From October through May no discharge shall be permitted that will raise the temperature of the stream more than five Fahrenheit degrees over that which existed before the addition of heat of artificial origin or to a maximum of 50 degrees Fahrenheit whichever is less.
(iv) From June through September no discharge shall be permitted that will lower the temperature of the stream more than two Fahrenheit degrees from that which existed immediately prior to such lowering.

NEW JERSEY

New Jersey designates its freshwaters as:

- FW1 waters (not subject to any man-made wastewater discharges) and

- FW-2 waters (all other freshwaters except Pinelands waters). FW-2 is subdivided into:

1. FW2-TP (Trout Production),
2. FW2-TM (Trout Maintenance), and
3. FW2-NT (Non-trout Waters).

Shown are temperature criteria for FW2 waters:

FW2-TP (Trout Production): ≤22 °C or rolling 7-day average daily maximum of 19 °C, unless due to natural conditions.

FW2-TM (Trout Maintenance): ≤25 °C or rolling 7-day average daily maximum of 23 °C, unless due to natural conditions.

FW2-NT (Non-trout Waters): ≤31 °C or rolling 7-day average daily maximum of 28 ° C, unless due to natural conditions.

PENNSYLVANIA

Pennsylvania Code, Chapter 93, provides for a considerable number of designated uses, among which are those for ‘Aquatic Life’. Special protections are afforded High Quality Waters and Exceptional Value Waters.

The protected uses of freshwaters as they relate to aquatic life are:

TSF: Trout Stocking

CWF: Cold Water Fishes

WWF: Warm Water Fishes

MF: Migratory Fishes

Additional protections, often overlapping with those for aquatic life are:

HQ: High Quality Waters

EV: Exceptional Value Waters

Pennsylvania Code, Chapter 93.7 provides specific water quality data, inclusive of those relating to maximum temperatures in the receiving water body, as given below, from heated waste sources:

	CWF **TSF**	**WWF**	
Dates	*°F (°C)*	*°F (°C)*	*°F (°C)*
January 1-31	38 (3.3)	40 (4.4)	40 (4.4)
February 1–29	38 (3.3)	40 (4.4)	40 (4.4)
March 1–31	42 (5.6)	46 7.8)	46 (7.8)
April 1–15	48 (8.9)	52 (11.1)	52 (11.1)
April 16–30	52 (11.1)	58 (14.4)	58 (14.4)
May 1–15	54 (12.2)	64 (17.8)	64 (17.8)
May 16–31	58 (14.4)	72 (22.2)	68 (20.0)
June 1–15	60 (15.6)	80 (26.7)	70 (21.1)
June 16–30	64 (17.8)	84 (28.9)	72 (22.2)
July 1–31	66 (18.9)	87 (30.6)	74 (23.3)
August 1–15	66 (18.9)	87 (30.6)	80 (26.7)
August 16–30	66 (18.9)	87 (30.6)	87 (30.6)
September 1–15	64 (17.8)	84 (28.9)	84 (28.9)

September 16–30	60	(15.6)	78	25.6)	78	(25.6)
October 1–15	54	(12.2)	72	(22.2)	72	(22.2)
October 16–31	50	(10.0)	66	(18.9)	66	(18.9)
November 1–15	42	(5.6)	50	(10.0)	50	(10.0)
December 1–31	40	(4.4)	43	(6.1)	42	(5.6)