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Water Temperature – Part 1 – Thermal Characteristics of Streams

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EnviroDIY
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Points to Remember

- Temperature is important to life in water
- Temperature varies naturally – diel, seasonal, annual – within a watershed, among watersheds
- Humans have already modified stream temperature, and climate change will make streams warmer

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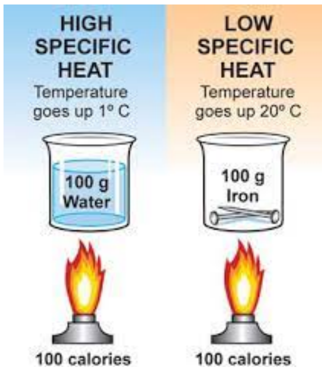
Why is Water Temperature Important?

- Temperature varies temporally and spatially
  - Day versus night
  - Winter versus summer
  - Mountain versus valley
- Thermal pollution – controlled releases
  - Power plants and factories
  - Big dams – top release – hot – bottom release – cold
- Habitat modifications – deforestation, small dams, urbanization – hard surfaces, stormwater ponds, pipes
- Climate Change

4

Water Is Thermally Stable

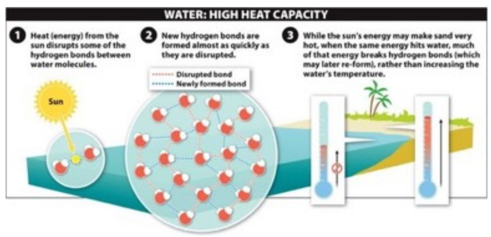


Specific Heats of Common Materials

MATERIAL	SPECIFIC HEAT (Joules/gram • °C)
Liquid water	4.18
Solid water (ice)	2.11
Water vapor	2.00
Dry air	1.01
Basalt	0.84
Granite	0.79
Iron	0.45
Copper	0.38
Lead	0.13

Concrete

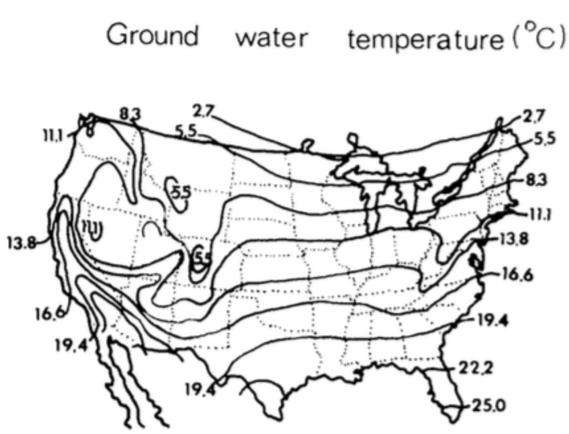
Sand

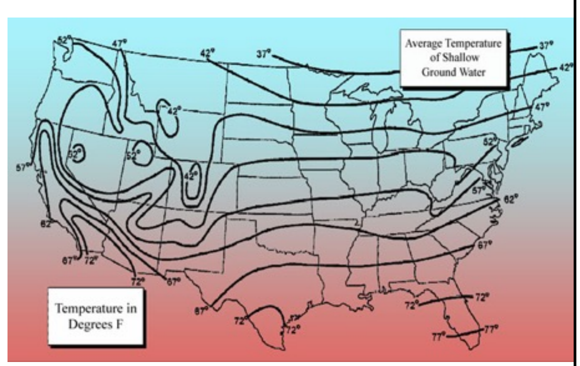


5

Stream Temperature Starts with Ground Water Temperature

Colder in the North



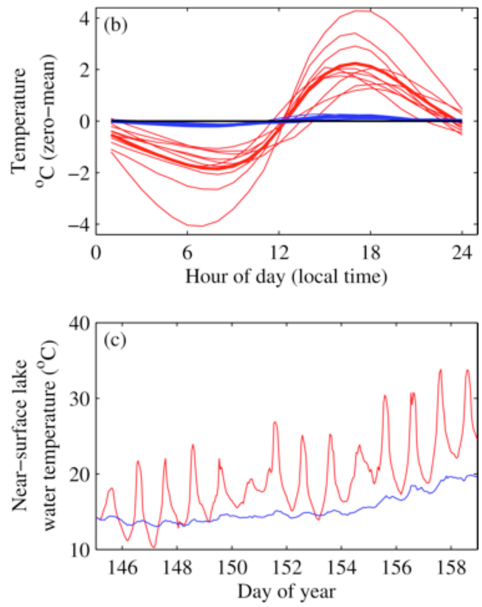


Vannote and Sweeney 1980

http://waterheatertimer.org/Average-temperature-of-shallow-ground-water.html

6

Water Temperature Varies Within a Day



Small lake (red)
versus
Large lake (blue)

Woolway RI, Jones ID, Maberly SC, French JR, Livingstone DM, Monteith DT, et al. (2016) Diel Surface Temperature Range Scales with Lake Size. PLoS ONE 11(3): e0152466. https://doi.org/10.1371/journal.pone.0152466

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Diel Regime Varies – Stream Size

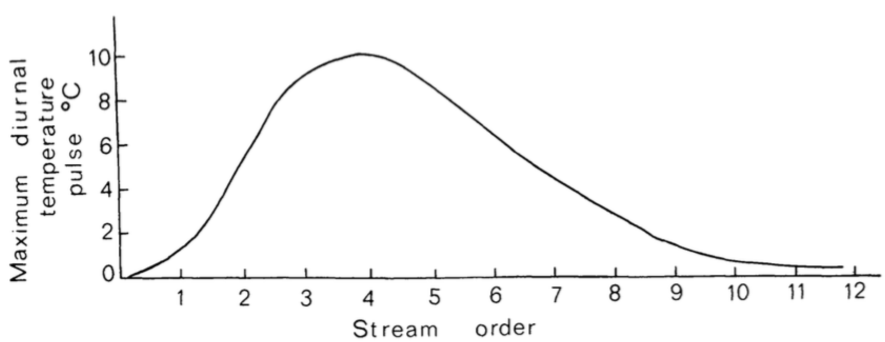

FIG. 3.—Maximum diurnal change in temperature as a function of stream order in temperate North America. Data are from unpublished White Clay Creek studies and water resource reports of the United States Geological Survey (U.S.G.S.).

Vannote and Sweeney 1980

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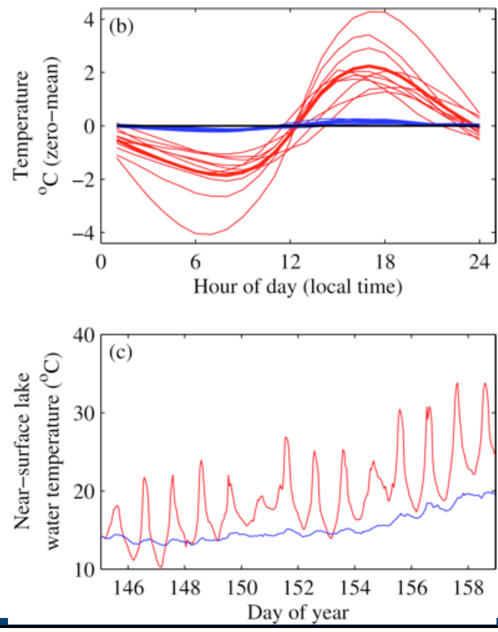
Water Temperature Varies – Lake Size



Small lake (red)
versus
Large lake (blue)

Woolway RI, Jones ID, Maberly SC, French JR, Livingstone DM, Monteith DT, et al. (2016) Diel Surface Temperature Range Scales with Lake Size. PLoS ONE 11(3): e0152466. https://doi.org/10.1371/journal.pone.0152466

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Temperature Varies Seasonally

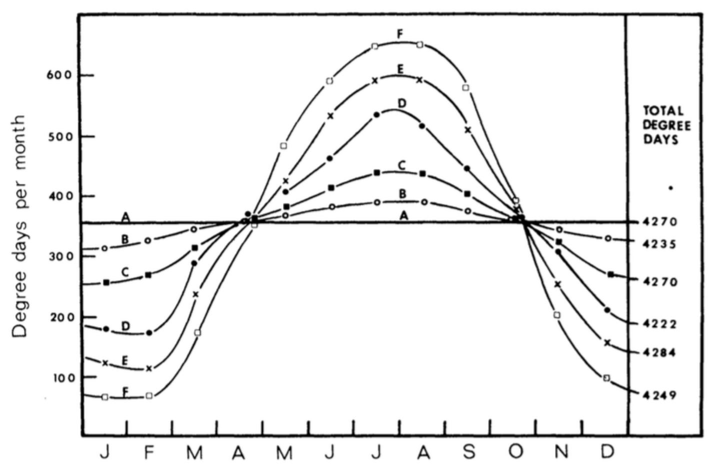

FIG. 2.—Distribution of monthly degree-day accumulations at various recording stations along White Clay Creek. Total degree-days are the annual sum of monthly records for each station. *A*, outflow of groundwater; *B*, woodland spring seeps; *C*, first order spring brooks; *D*, second order streams; *E*, third order stream (upstream segment); *F*, third order stream (downstream segment).

Winter is Colder Than Summer

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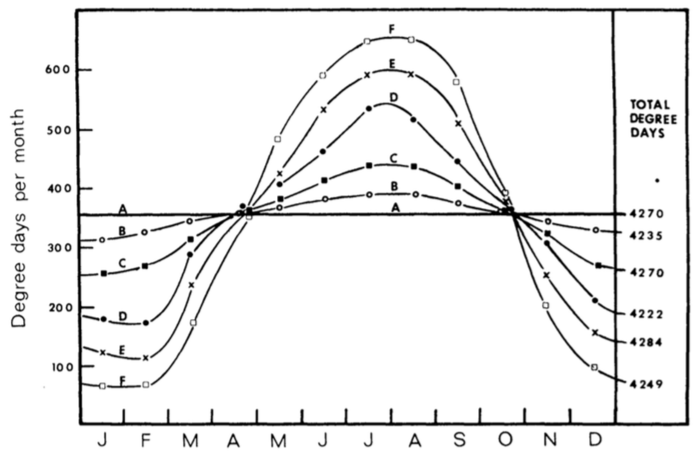
Seasonal Regime Varies – Stream Type



Large streams vary more than small streams (more sun versus more groundwater influence)

FIG. 2.—Distribution of monthly degree-day accumulations at various recording stations along White Clay Creek. Total degree-days are the annual sum of monthly records for each station. *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).

Vannote and Sweeney 1980

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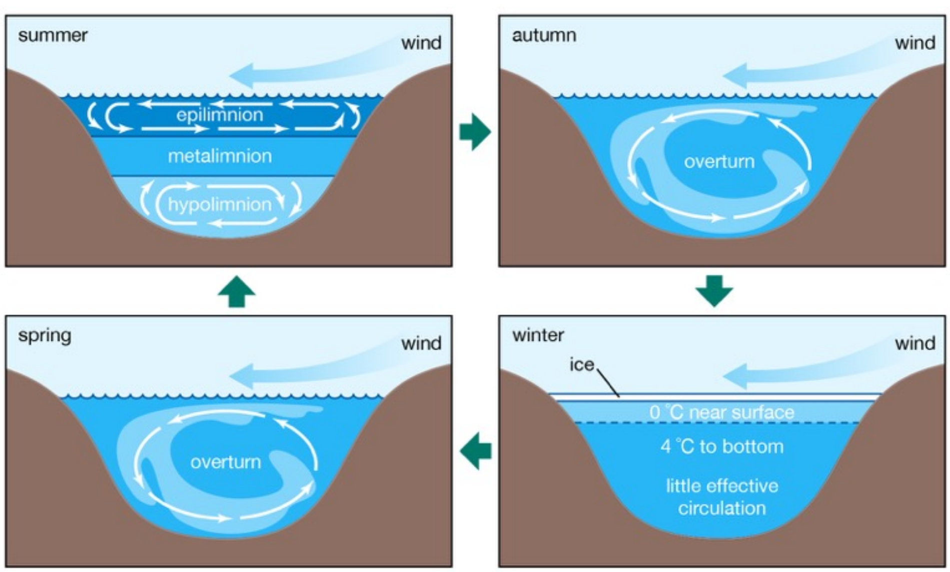
Seasonal Temperature & Stratification



https://www.britannica.com/science/dimictic-lake

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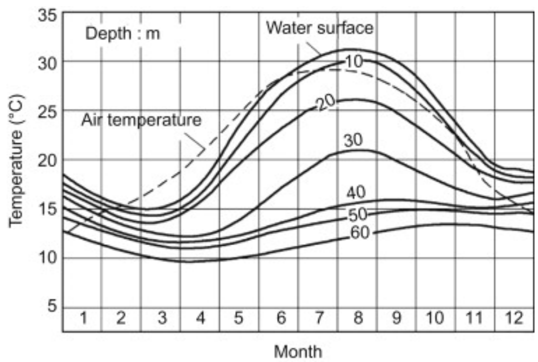
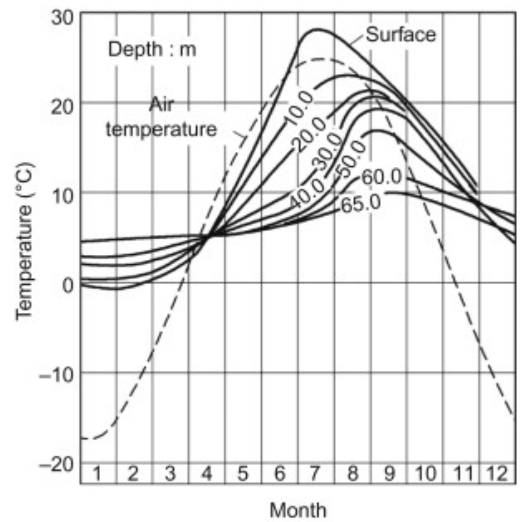
Seasonal Temperature & Stratification

Warm lake



Cold lake



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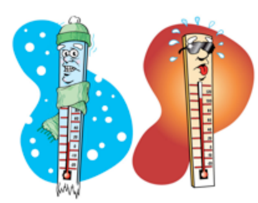
People Change Thermal Regimes

- Forests thinned, fragmented, or removed
- Running water turned to standing water – ponds and reservoirs
- Urban area become heat sinks
- Municipal and industrial effluents discharged to streams



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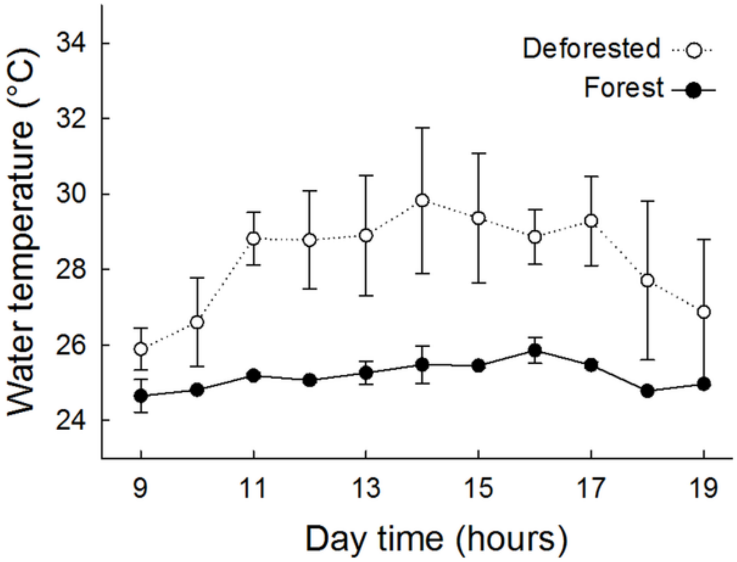
Deforestation Warms Thermal Regime



Difference =
+ 3.5 ° C
+ 6.3 ° F

Ilha, P., Schiesari, L., Yanagawa, F.I., Jankowski, K. and Navas, C.A., 2018. Deforestation and stream warming affect body size of Amazonian fishes. *PloS one*, *13*(5), p.e0196560.

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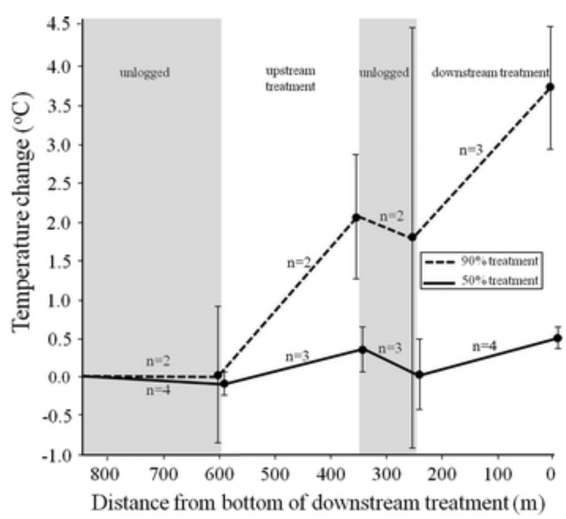
Deforestation Warms Thermal Regime



Appalachian headwater streams in summer 2008

Difference =
+ 2 or 4 ° C
+ 3.6 or 7.2 ° F

Fig. 3 Cumulative temperature change as water flowed through unlogged and logged sections of headwater streams. Differences were calculated from daily high temperatures over a one-month period during summer.

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

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Deforestation affects a thermal regime

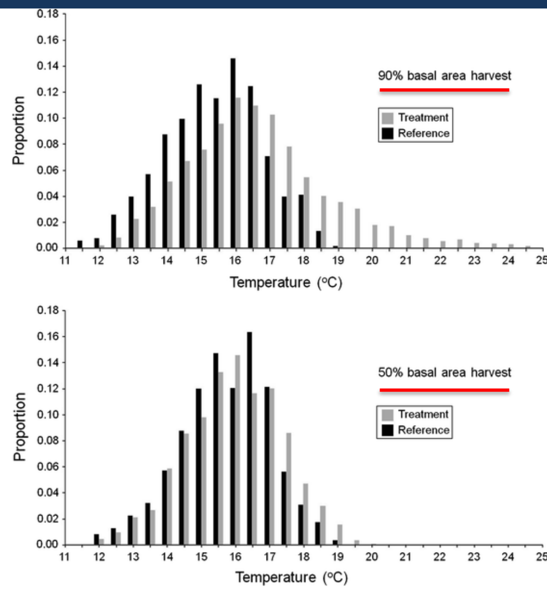

Fig. 4 Frequencies of hourly temperature observations of reference and treatment sections (50 and 90% basal area harvest) in Appalachian headwater streams. Data were gathered during two sampling events in summer 2008

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

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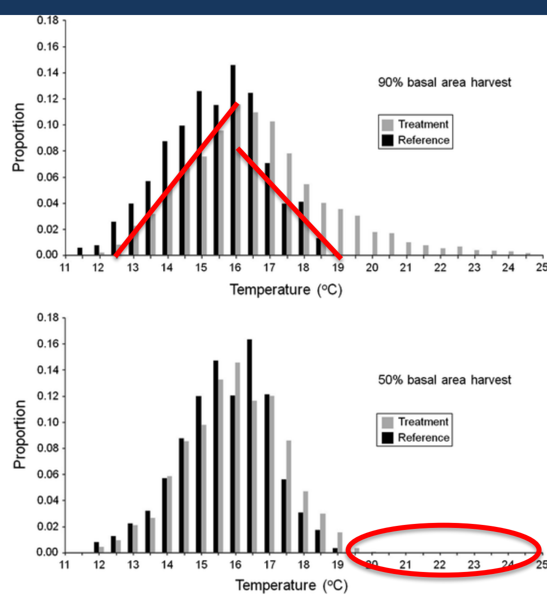
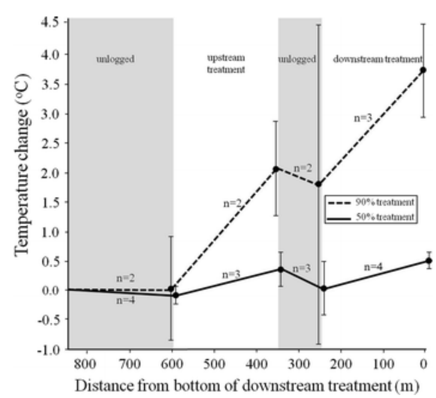
Deforestation Warms Thermal Regime





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

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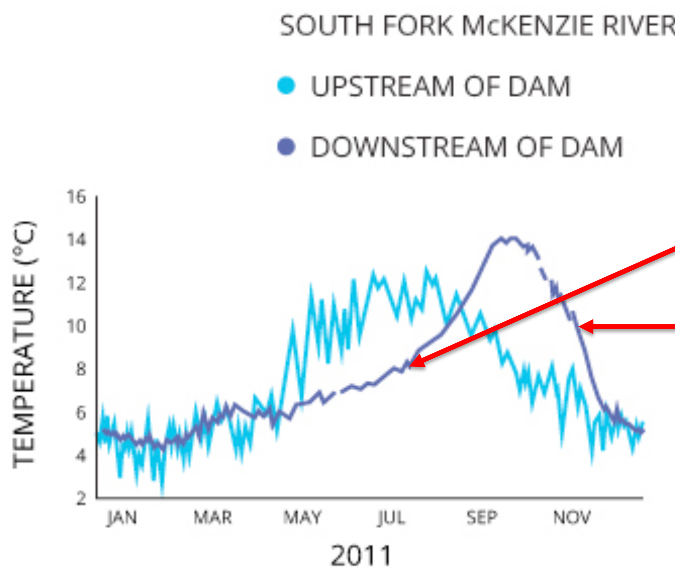
Dams Warm or Cool Thermal Regime



Cooler than normal at some times

Warmer than normal at some times

Depends on reservoir size and operation

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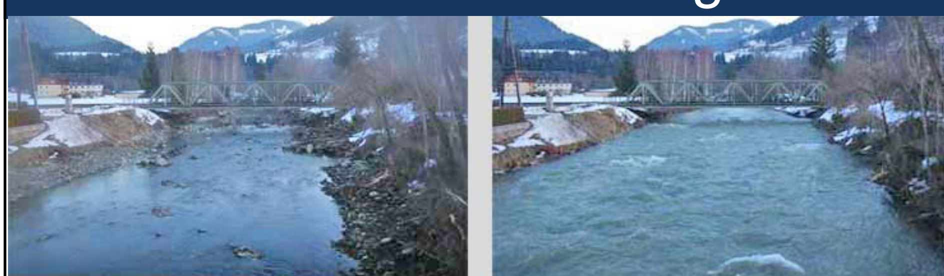
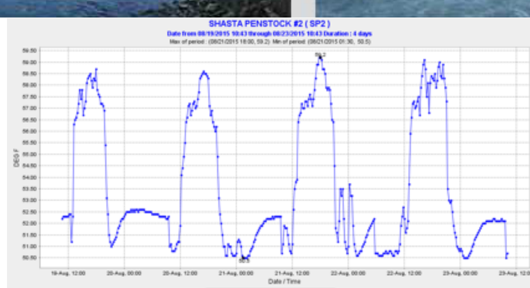
Hydroelectric Dam Operation Affects the Thermal Regime



"Hydropeaking"



Difference =
+ 5.0 ° C
+ 9.0 ° F

http://wiki.reformrivers.eu/index.php/File:Instream_flow_fluctuations.jpg
https://calsport.org/fisheriesblog/wp-content/uploads/2015/08/Temperature-of-water-in-penstocks-to-powerhouse-from-Shasta-Reservoir.png

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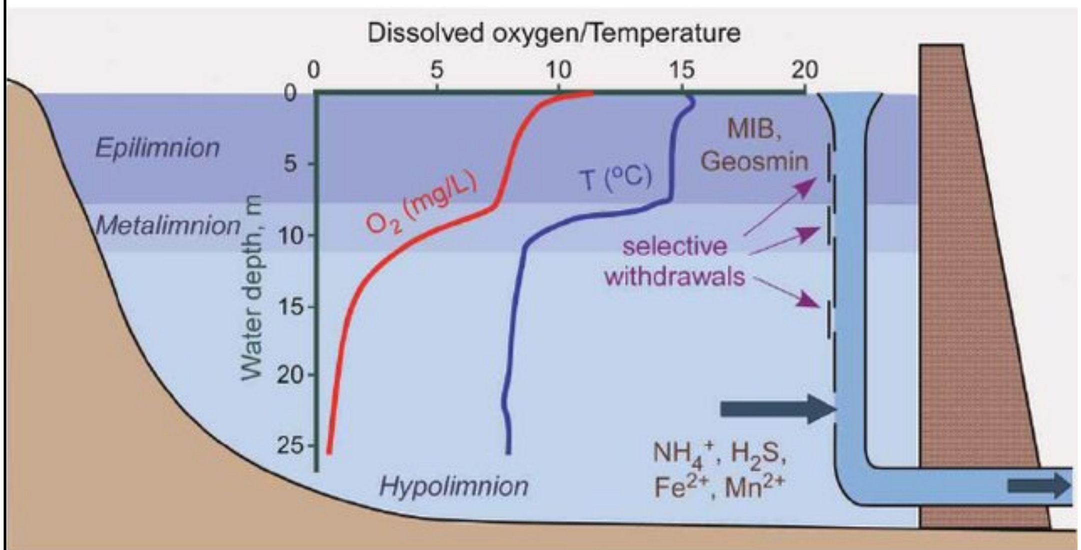
Withdrawal Depth Affects Thermal Regime



Mitrakas, M., Samaras, P., Stylianou, S., Kakalis, C. and Zouboulis, A., 2013. Artificial destratification of Dipotamos reservoir in Northern Greece by low energy air injection. *Water Science and Technology: Water Supply*, *13*(4), pp.1046-1055.

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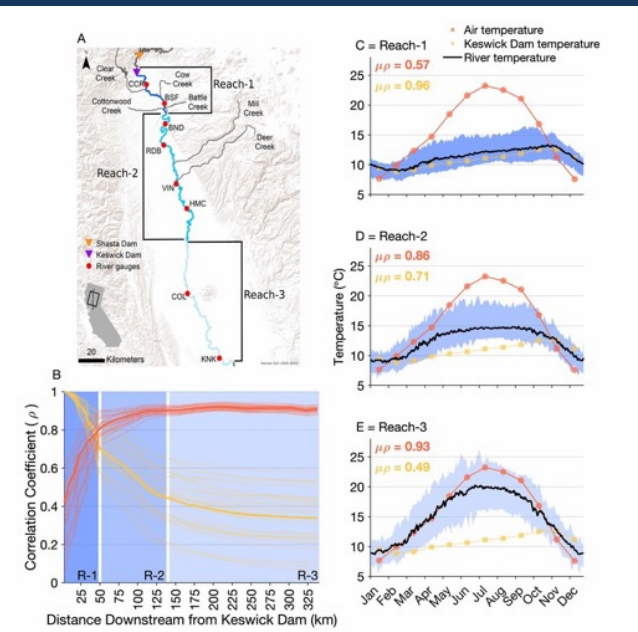
Cooling Effect Reduced Downstream



Keswick Dam
Sacramento River

72-164 km
downstream

250-338 km
downstream

Daniels, M.E. and Danner, E.M., 2020. The drivers of river temperatures below a large dam. *Water Resources Research*, *56*(5), p.e2019WR026751.

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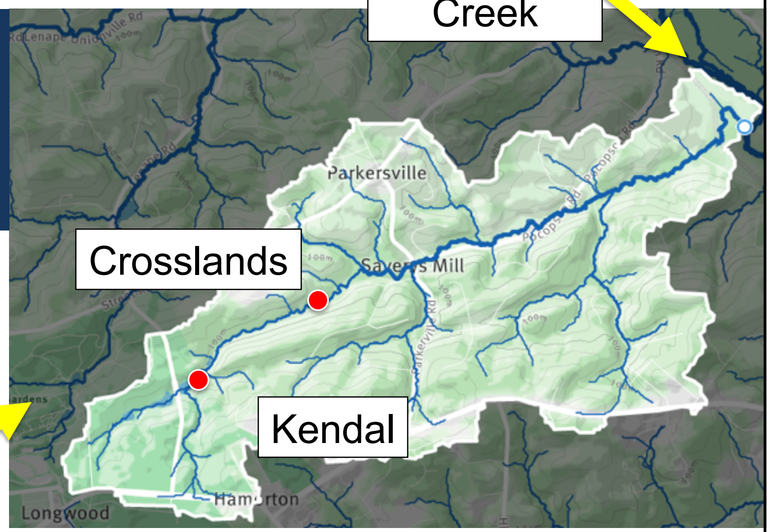
Small Dams/Ponds Increase Stream Temperature

Bennett's Run at Brandywine Creek
7.5 km ^{2}
6 km of stream



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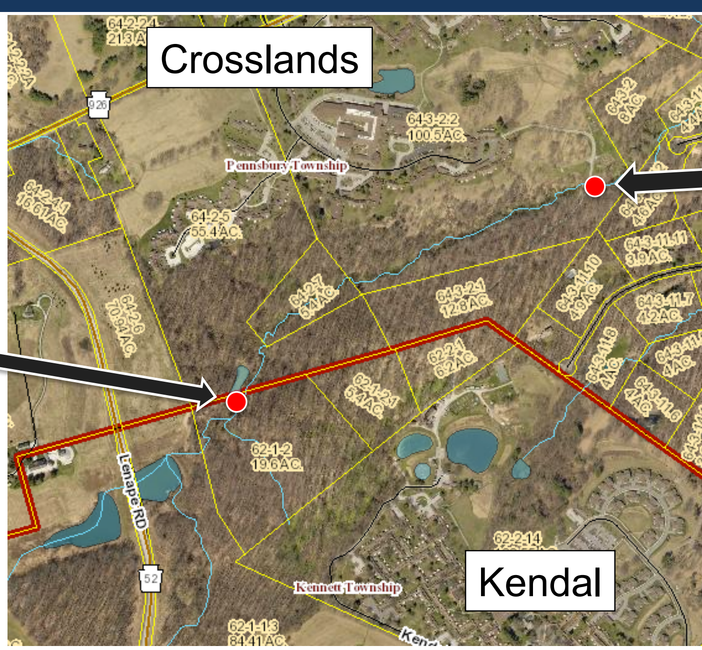
Upstream Ponds at Bennett's Run



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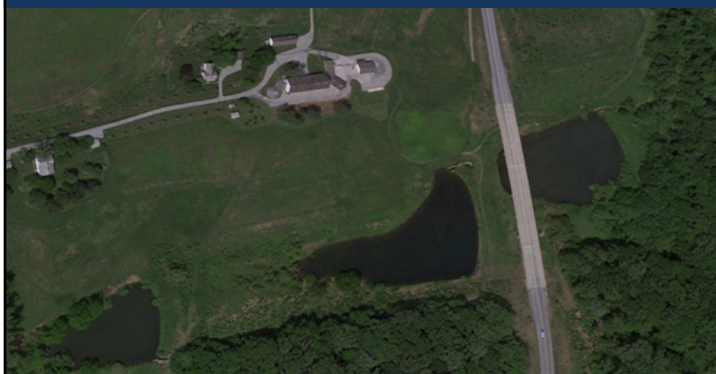
Upstream Ponds @ Bennett's Run



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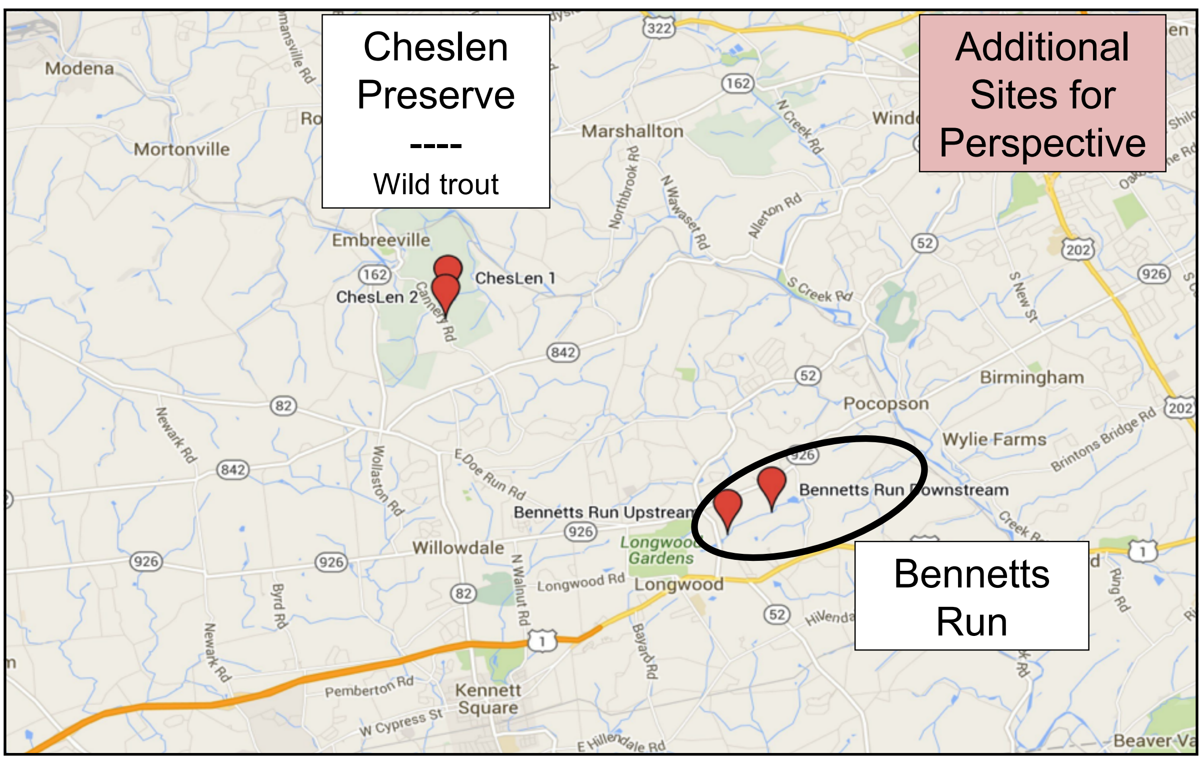

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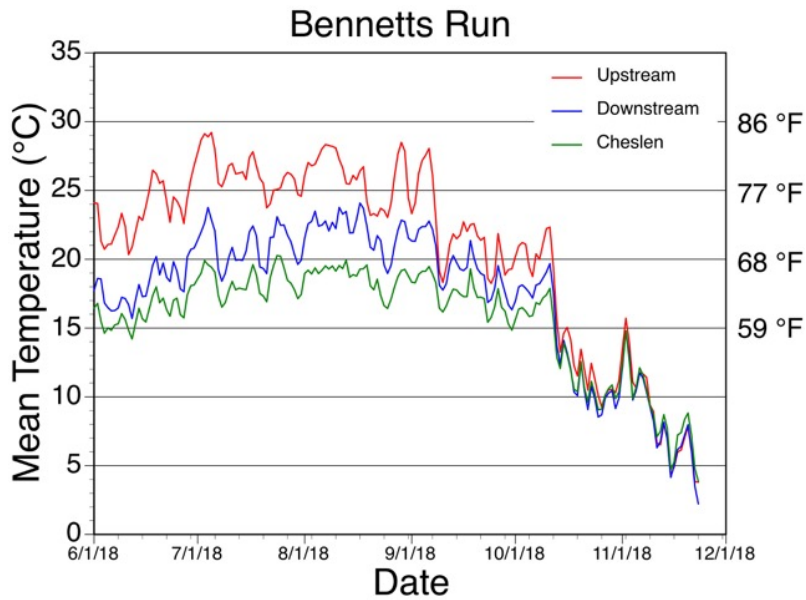
Small Dams/Ponds Increase Stream Temperature



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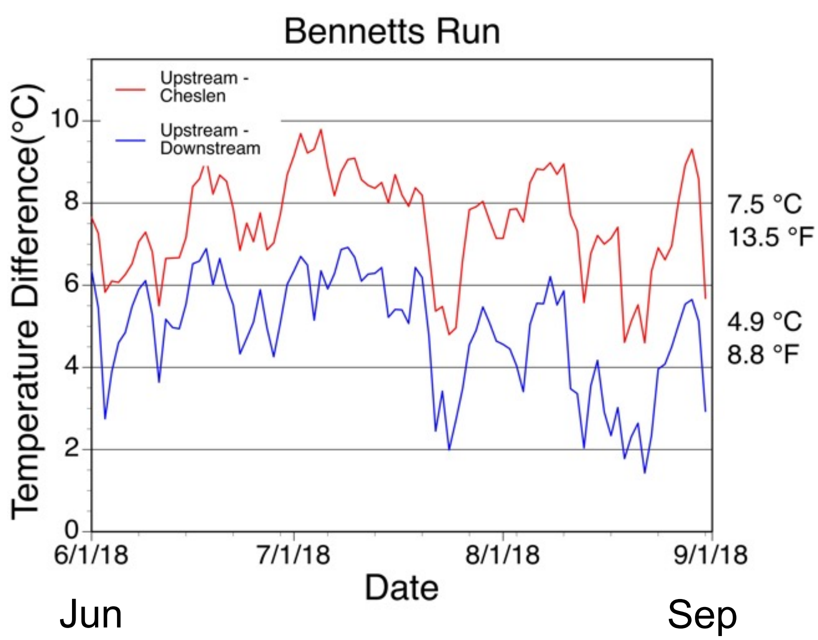
Small Dams/Ponds Increase Stream Temperature



Pond Effect =
+ 7.5 ° C
+ 13.5 ° F

900 m Forest Difference =
- 4.9 ° C
- 8.8 ° F

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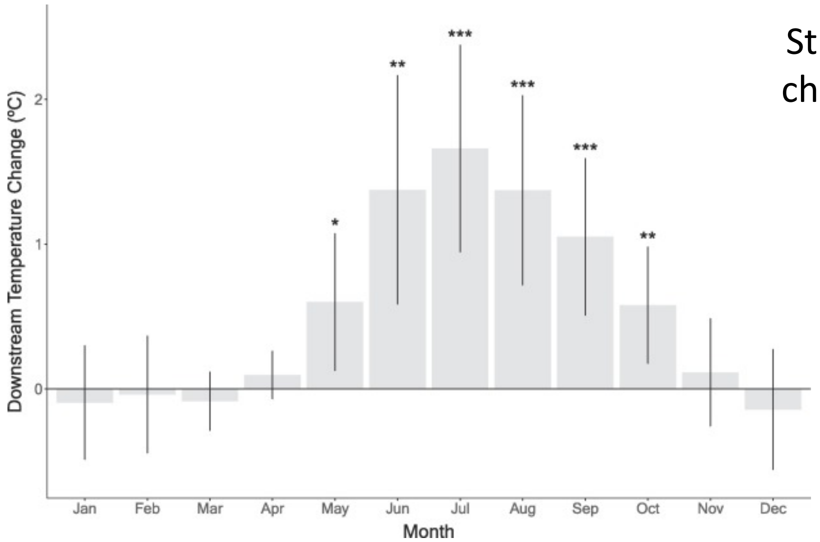
Small Dams/Ponds Increase Stream Temperature



Stream temperature changes due to small (<15 m) dams in Massachusetts

Fig. 4. Change in mean monthly temperature from upstream to downstream at each dam.

Zaidel, P.A., Roy, A.H., Houle, K.M., Lambert, B., Letcher, B.H., Nislow, K.H. and Smith, C., 2021. Impacts of small dams on stream temperature. *Ecological Indicators*, *120*, p.106878.

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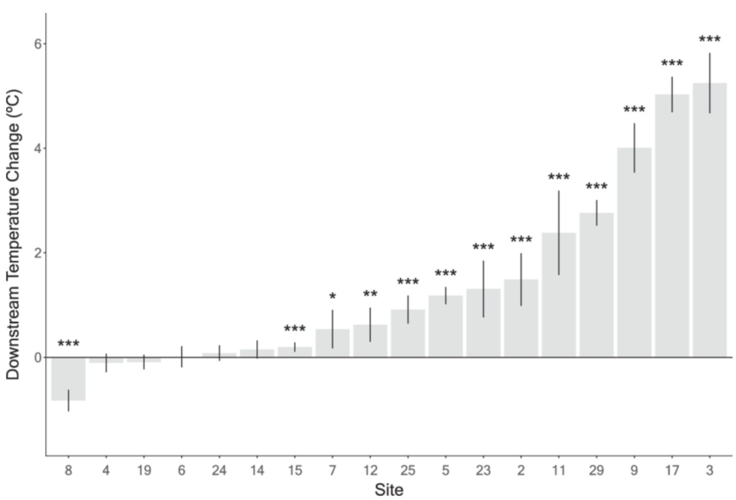
Small Dams/Ponds Increase Stream Temperature



Factors affecting temperature change: dam height, impoundment volume, impoundment widening, impoundment residence time, impoundment area:watershed area, and watershed forest cover

Fig. 4. Change in mean July temperature from upstream to downstream at each dam.

Zaidel, P.A., Roy, A.H., Houle, K.M., Lambert, B., Letcher, B.H., Nislow, K.H. and Smith, C., 2021. Impacts of small dams on stream temperature. *Ecological Indicators*, *120*, p.106878.

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Small Dam Impact Greater on Colder Streams

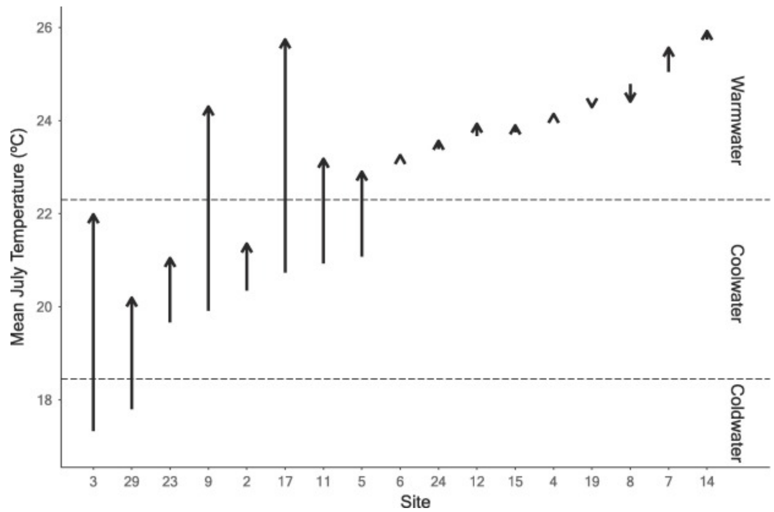

Fig. 4. Change in mean July temperature from upstream to downstream at each dam, with the direction and length of each arrow representing the direction and magnitude of change, respectively.

Zaidel, P.A., Roy, A.H., Houle, K.M., Lambert, B., Letcher, B.H., Nislow, K.H. and Smith, C., 2021. Impacts of small dams on stream temperature. *Ecological Indicators*, *120*, p.106878.

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Dam Impact Decreased Downstream

Table 2

Predicted thermal footprint (distance to recovery of upstream temperatures given observed downstream decay rates) for seven sites with both significant warming and subsequent cooling patterns with distance downstream of the dam.

Site	Warming (°C)	Decay rate (°C/km)	Footprint (km)
7	0.54	−1.93	0.28
5	1.18	−3.72	0.33
23	1.31	−3.75	0.34
2	1.49	−4.32	0.35
3	5.25	−4.10	1.35
9	4.72	−2.65	2.04
29	2.76	−0.64	4.47
Mean	2.46	−3.02	1.31

Footprint due to heat loss depends (in part) on water volume, velocity, shade

Zaidel, P.A., Roy, A.H., Houle, K.M., Lambert, B., Letcher, B.H., Nislow, K.H. and Smith, C., 2021. Impacts of small dams on stream temperature. *Ecological Indicators*, *120*, p.106878.

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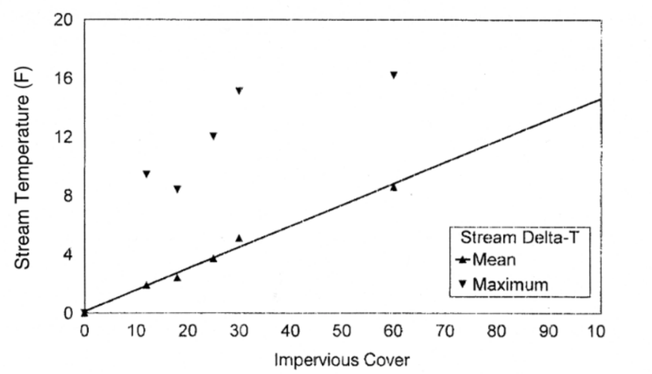
Urbanization Increases Stream Temperature



Delta-t is the difference in mean or max stream temperature from a developed stream, compared to an undisturbed stream.

Figure 4: The Effect of Impervious Cover on Stream Temperature (Galli, 1991)

Urban areas tend to be warmer (heat island)

Urban streams tend to be warmer than normal

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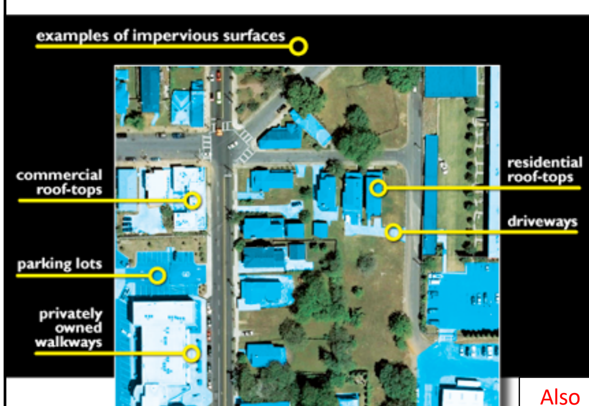
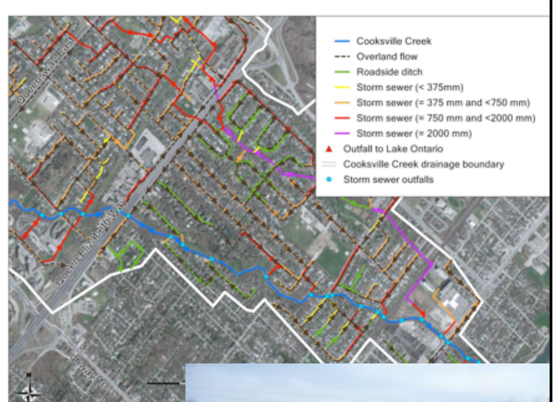
Urbanization = Roads, Pipes and Ponds



Also Roads



Hard surfaces = warmer (deforested)
Standing water ponds = warmer (dams)
Pipes = cooler (groundwater)

https://www.slideshare.net/MarylouMoore/maryloumooremastersthesis-42738042
https://www.dcwater.com/impervious-area-charge

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Old Urbanization = Streams in Pipes

https://www.hiddenhydrology.org/philly-h20/

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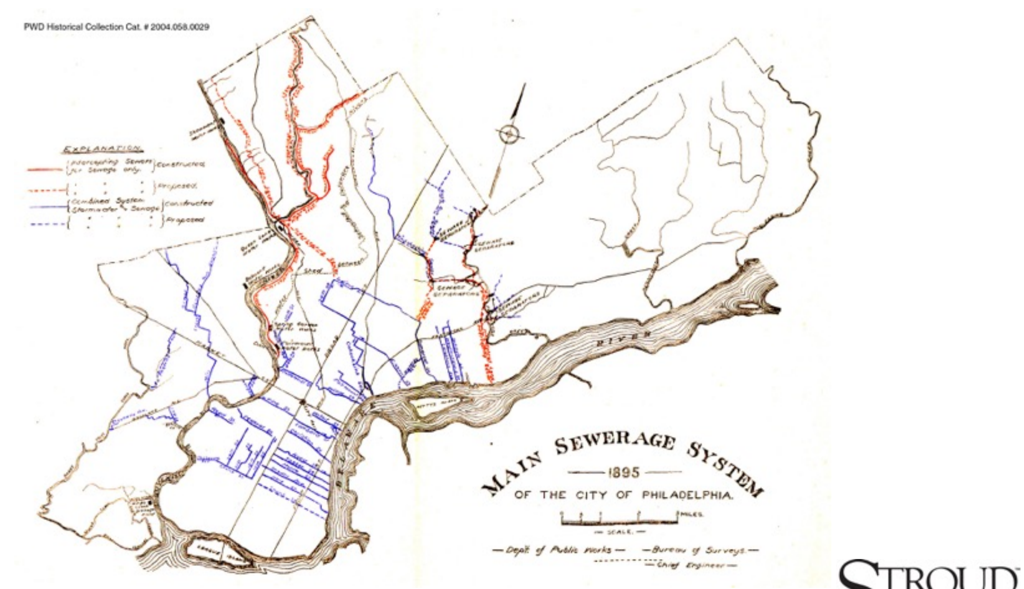
Old Urbanization = Streams in Pipes



https://www.hiddenhydrology.org/philly-h20/

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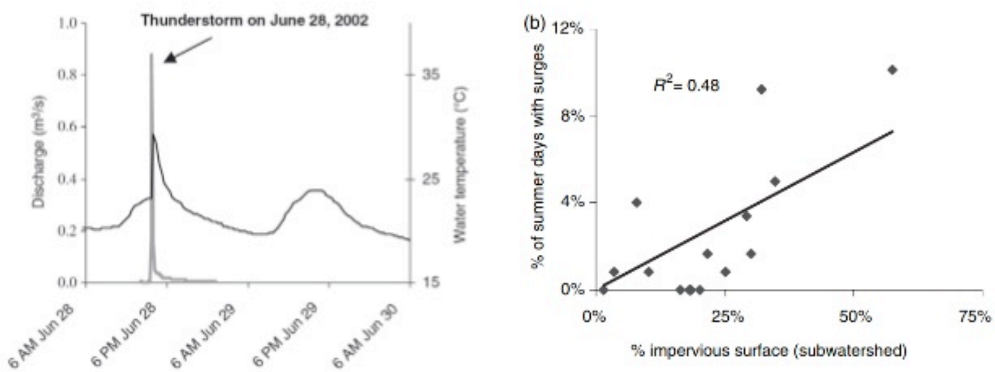
Summer storms bring in warm water as temperature surges



From Nelson & Palmer, 2007[10]

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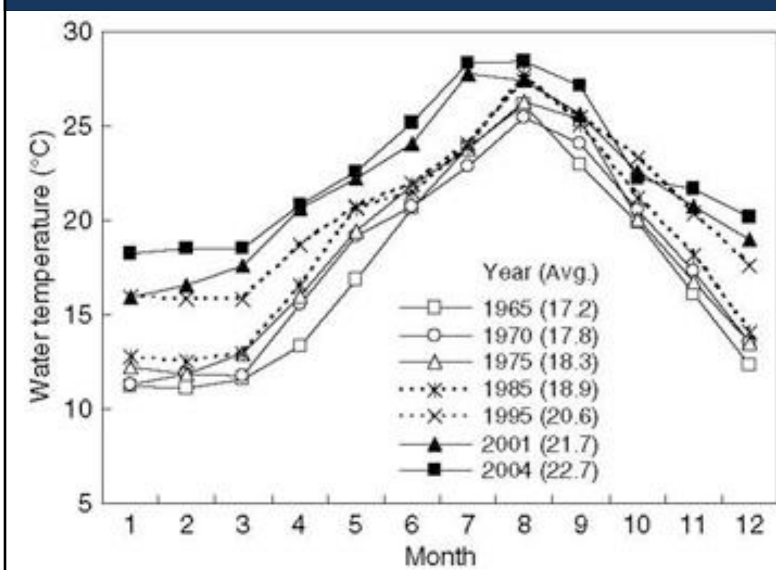
Urban Wastewater Increases Stream Temperature



Wastewater can warm the stream throughout the year (due to heated household water)

Kinouchi T. 2007. Impact of long-term water and energy consumption in Tokyo on wastewater effluent: implications for the thermal degradation of urban streams. Hydrological Processes 21:1207-1216

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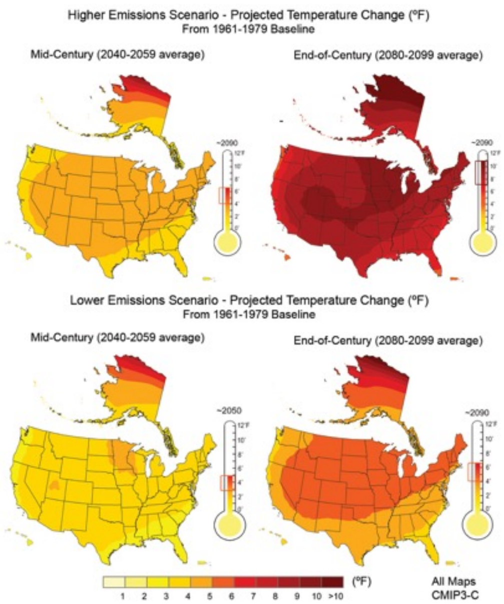
Climate Change Will Increase Temperature



High Emissions Difference =
+ 5.0 ° C
+ 9.0 ° F

Low Emissions Difference =
+ 3.1 ° C
+ 5.5 ° F

https://climatechange.chicago.gov/climate-change-science/future-climate-change

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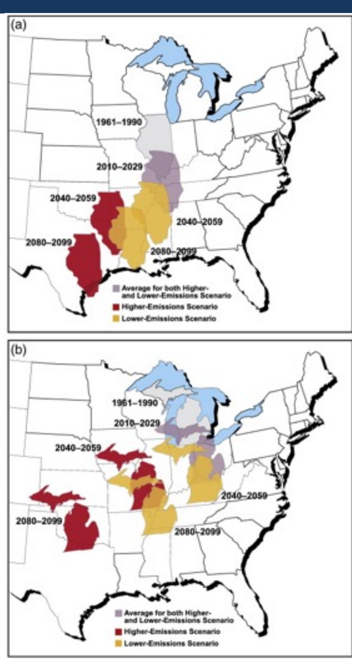
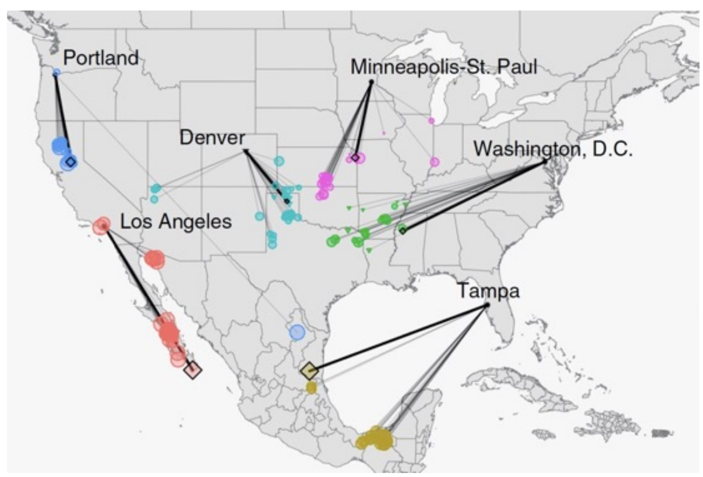
Climate Change Will Increase Temperature





Fitzpatrick, M.C. and Dunn, R.R., 2019. Contemporary climatic analogs for 540 North American urban areas in the late 21st century. *Nature communications*, *10*(1), pp.1-7.

Hayhoe, K., VanDorn, J., Croley II, T., Schlegal, N. and Wuebbles, D., 2010. Regional climate change projections for Chicago and the US Great Lakes. *Journal of Great Lakes Research*, *36*, pp.7-21.

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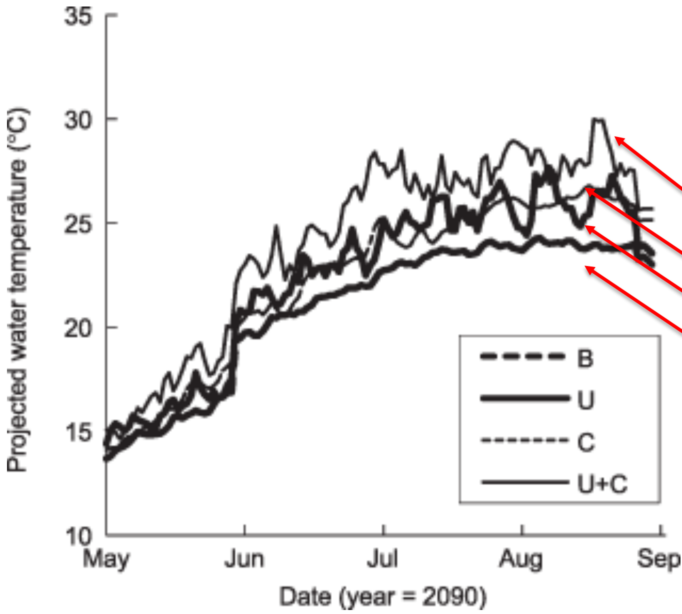
Climate Change Will Increase Temperature



Projected maximum daily water temperatures for the year 2090 under four scenarios:
urbanization plus climate change (U+C)
climate change only (C),
urbanization only (U),
baseline (B).

Nelson KC et al. 2009. Forecasting the combined effects of urbanization and climate change on stream ecosystems: from impacts to management options. Journal of Applied Ecology 46:154-163

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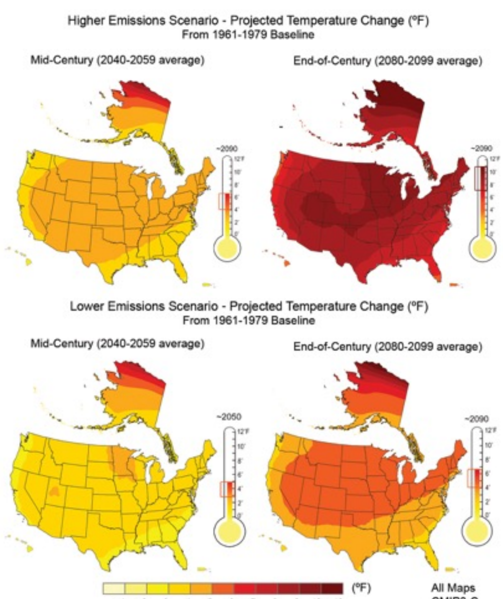
Climate Change Will Increase Temperature



High Emissions Difference =
+ 5.0 ° C
+ 9.0 ° F

Low Emissions Difference =
+ 3.1 ° C
+ 5.5° F

In addition to existing thermal pollution: deforestation, dams/ponds, urbanization, wastewater

https://climatechange.chicago.gov/climate-change-science/future-climate-change

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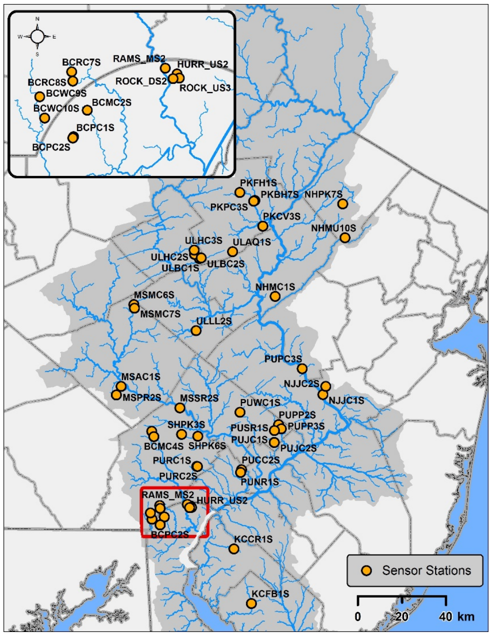
Delaware River Basin Sensor Network



DRB Sensor Network

Temperature, Conductivity (salt), Depth

Sensor sites with complete data
summer (June-August) and
winter (December-February)

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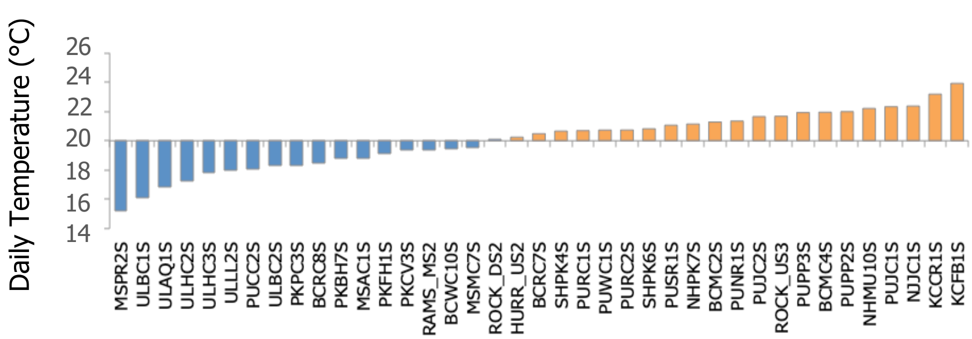
Summer Stream Temperature

39 DRB watersheds of different size with varying land uses



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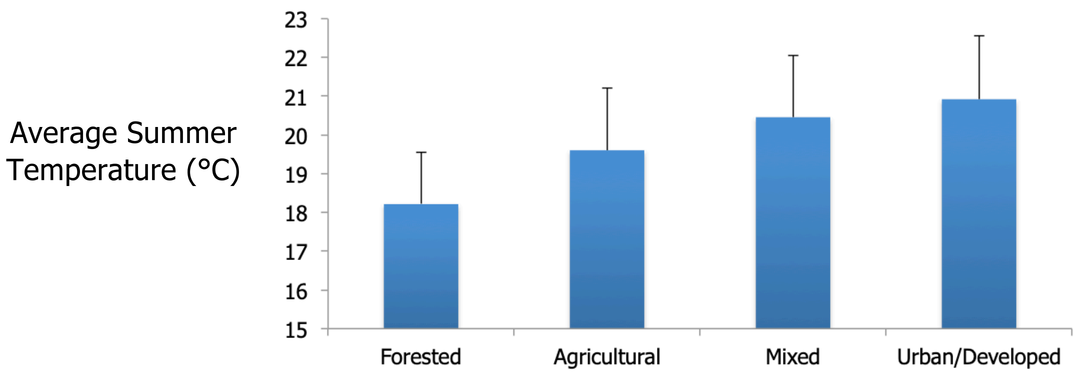
Land use and stream temperature

39 DRB watersheds of different size with varying land uses



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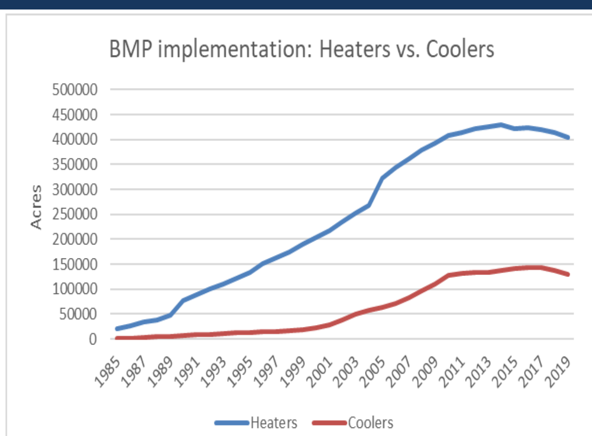
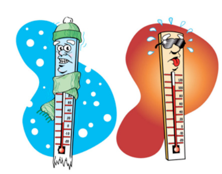
Pollution-reduction/stormwater BMPs act as "Heaters" or "Coolers"





3x more Heaters In Chesapeake watershed

"Heaters" include stormwater retention ponds, floating treatment wetlands and vegetated open channels.
"Coolers" include riparian forest buffers, upstream tree planting, urban stormwater infiltration, and wetlands restoration, enhancement and rehabilitation.

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Consider Temperature in Restoration and Design Planning

Avoid/restore "**Heater**" BMPs and landscape amenities

- Deforested, open stream channels
- Stormwater retention ponds
- Standing-water treatment wetlands
- On-stream ponds and slow moving water (dams and diversions)

Install "**Cooler**" BMPs and landscape amenities

- Riparian forest buffers
- Upland tree planting (including over impervious cover)
- Urban and agricultural stormwater infiltration
- Disconnect activities from the stream (off-channel watering)

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Thermal Pollution

Sources of thermal pollution for small streams

Deforestation	– streamside, but also upland
Standing water	– stormwater and ornamental ponds, dams that create ponds
Runoff	– precipitation warmed by hot surfaces
Effluents	– storage ponds and treatments

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https://www.wayfair.com/furniture/pdp/advanced-graphics-construction-worker-stop-sign-standin-cardboard-standup-bbbm1372.html

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Why is Water Temperature Important?

- Temperature affects chemical reactions
  - On land and in water
  - Inside microbes to vertebrates
- Aquatic macroinvertebrates and fish are poikilotherms
  - Body temperature varies with environmental temperature
  - Temperature controls physiological processes
- Temperature affects distribution and abundance of species
  - Body temperature impacts survival, growth rates, development time, and body size/fecundity

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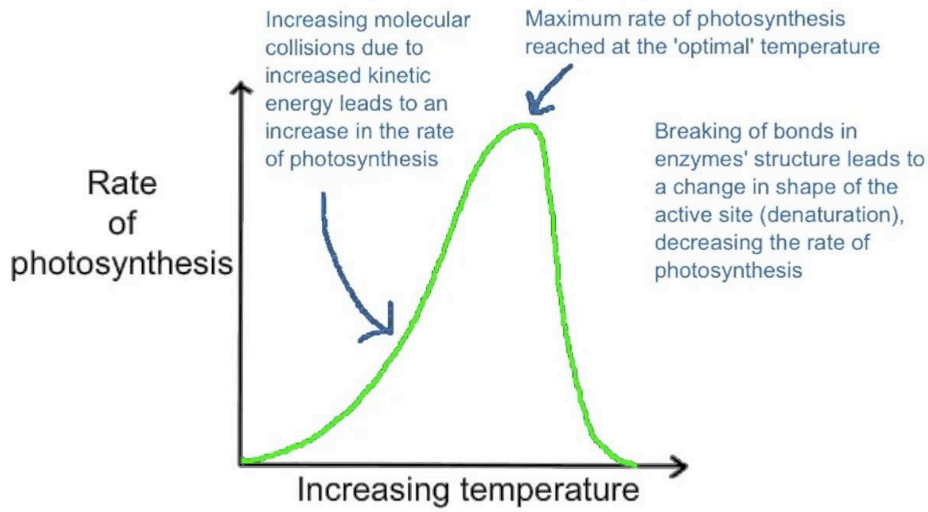
Chemical Reaction Rates Increase with Temperature



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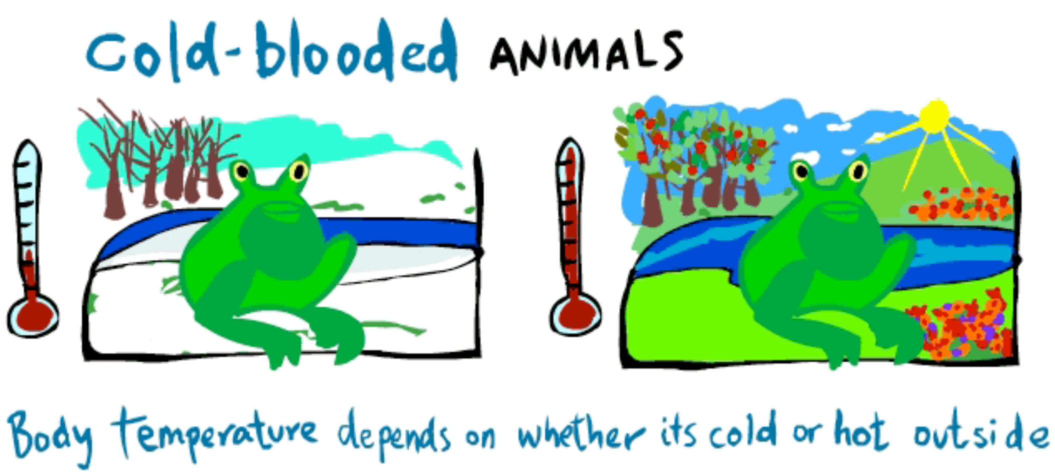
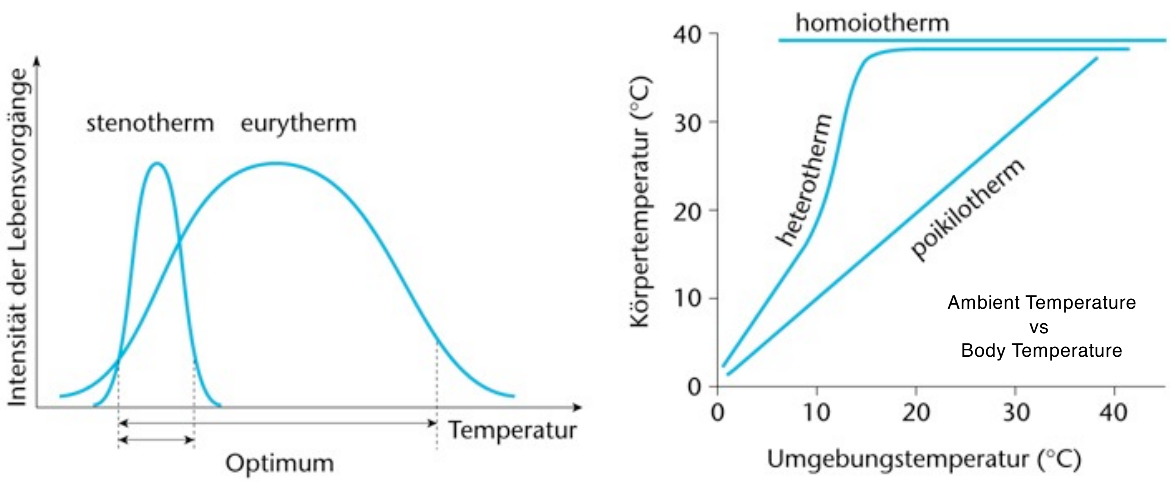
Aquatic Macroinvertebrates and Fish are Poikilotherms



52

Aquatic Macroinvertebrates and Fish are Poikilotherms



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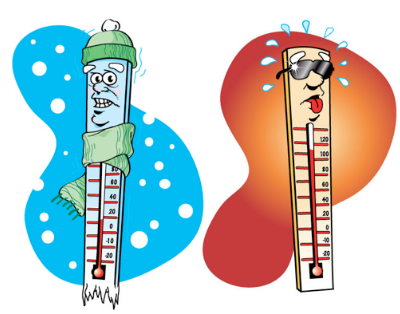
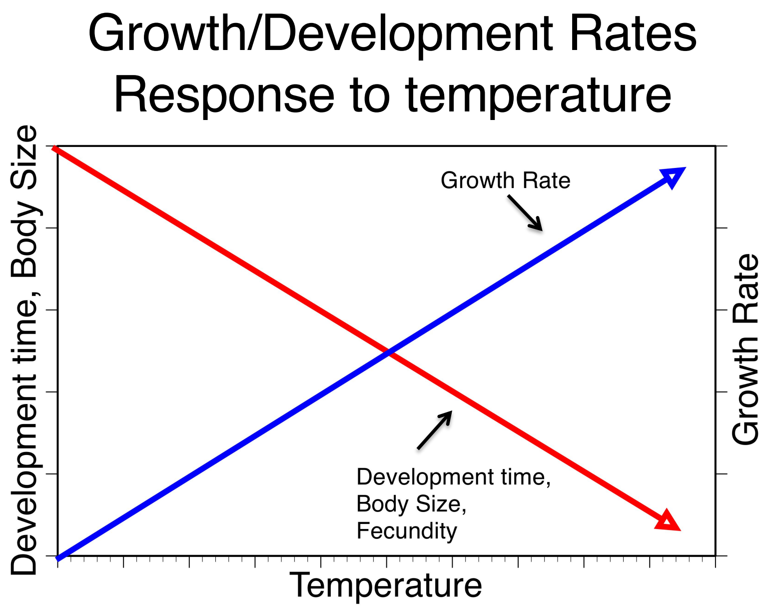
Temperature Affects Life Cycles

- Temperature known to be important for many stream organisms
- It has an effect on all macroinvertebrate **individuals** (and therefore **populations** and **communities)**
- Temperature affects individual
  - **Survival**
  - **Growth rate**
  - **Development time**
  - **Body size/fecundity**



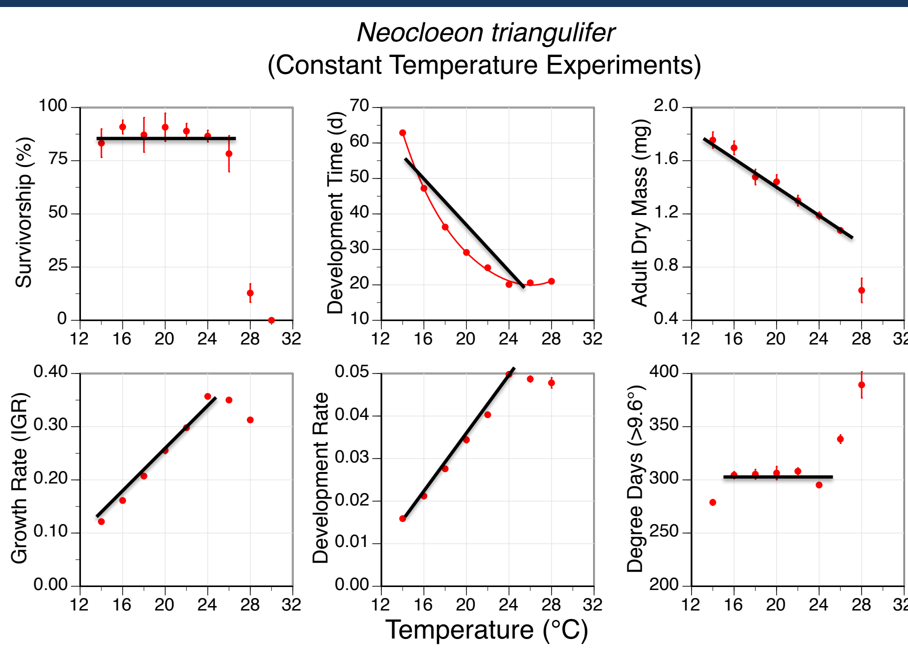
54

Why is temperature important?



55

Why is temperature important?



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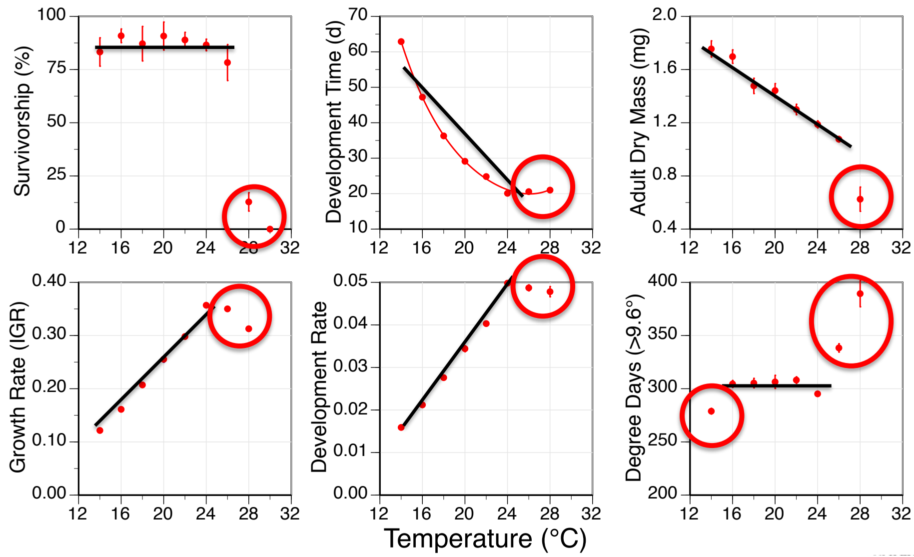
Why is temperature important?

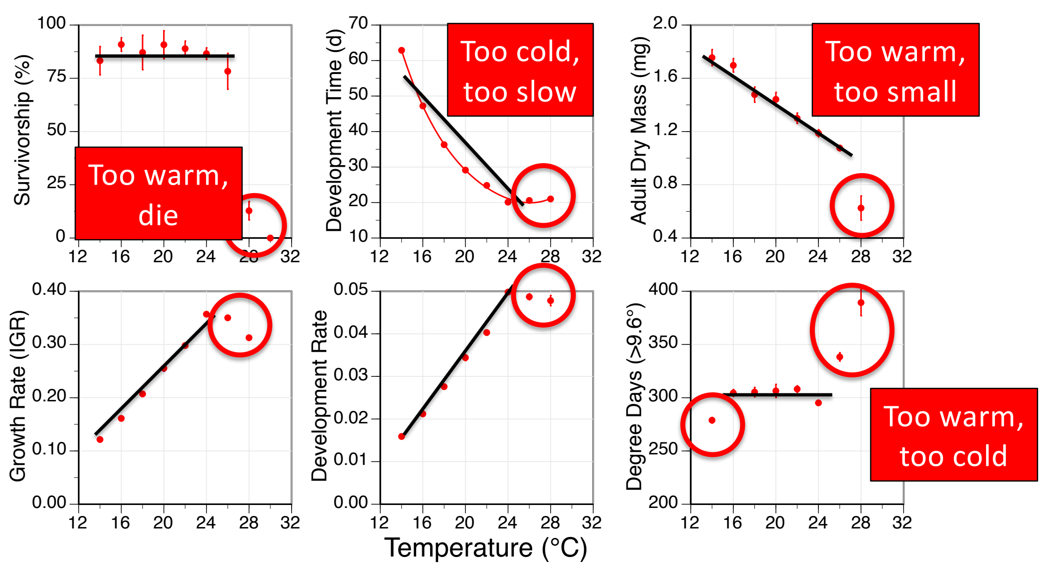
Neocloeon triangulifer
(Constant Temperature Experiments)



57

Why is temperature important?

Neocloeon triangulifer
(Constant Temperature Experiments)



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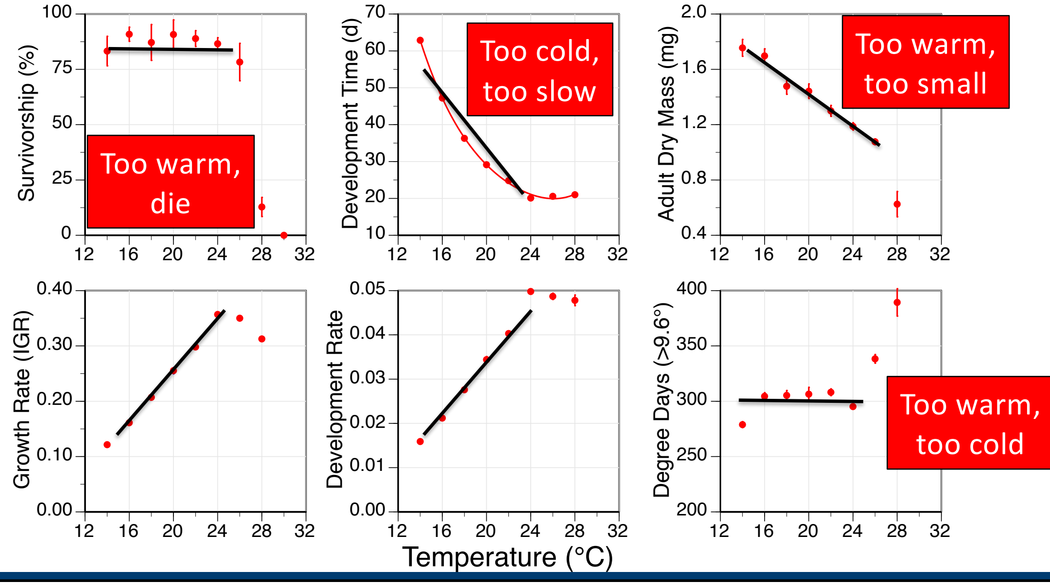
Why is temperature important?

Neocloeon triangulifer
(Constant Temperature Experiments)



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Why is temperature important?

Temperature Impacts

Distribution and Abundance by changing

Survival, Growth, Development

Temperature (°C)

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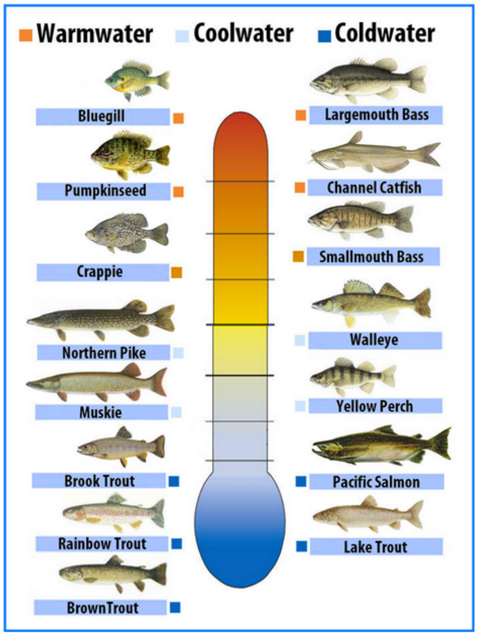
Temperature Defines Communities



Coldwater Fisheries
versus
Warmwater Fisheries

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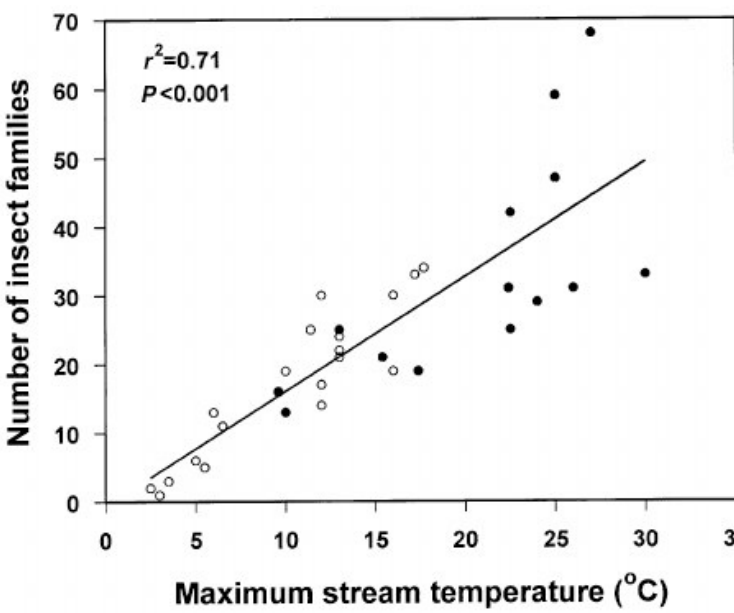
Temperature Defines Communities



Stream insect family richness increases with stream temperature for three regions in Ecuador and one in Denmark.
Jacobsen et al 1997

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Temperature Defines Communities

Ho and Michalak — *Climatic impacts on harmful algal blooms*

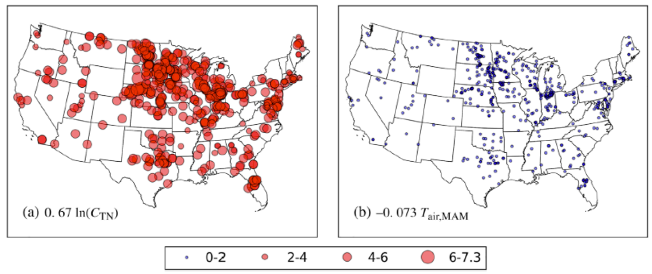

Fig. 5. Geographic distribution of the contributions of each predictor variable to predicted log of microcystin concentration (at locations where the measured concentration was above the detection limit), ln(C_{mc}), based on the model in Table 2. Each circle represents one location from either the NLA 2007 or NLA 2012 data sets, 496 in total (*see* Table 1). The size of each circle represents the magnitude of the contribution of each term in the model, including the contribution of (**a**) natural log-transformed TN concentration, ln(C_{TN}) and (**b**) air temperature averaged over March, April, and May, $T_{air,MAM}$. ln(C_{TN}) was minimum-deviated while $T_{air,MAM}$ was maximum-deviated (due to its negative drift coefficient; Eq. 1, Table 2) to better represent the geographic and across-term variability in contributions. Red circles indicate an increase in predicted ln(C_{mc}) while blue circles indicate a decrease in predicted ln(C_{mc}).

Harmful algal blooms (cyanobacteria biovolume, microcystin concentration) best predicted by nutrients, then temperature, precipitation, and geomorphology. Summer temperature drives total abundance, the length of the summer drives cyanobacterial abundance, and increased temperature may reduce the observed toxicity of blooms in some cases.

Ho and Michalak 2020

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Solutions to Thermal Pollution

- Protect cold water – protect existing shade.
- Reduce warm-water production – drain or disconnect ponds, remove existing dams where possible, increase shade by planting trees/restoring forests
- Prevent future warm-water production – don't promote new ponds with standing water – infiltrate stormwater to recharge ground water

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Consider Temperature in Restoration and Design Planning

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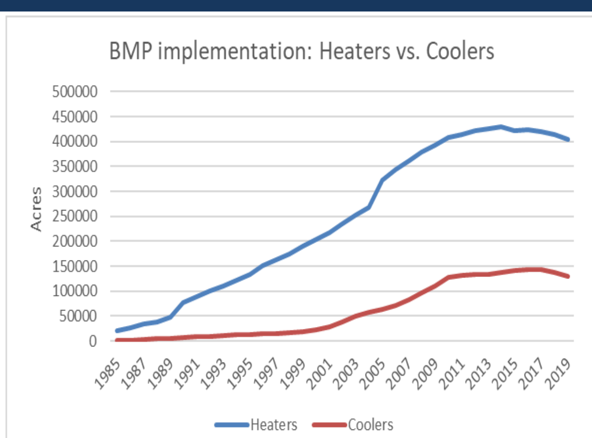
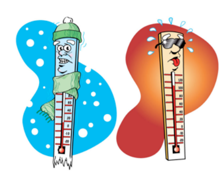
Pollution-reduction/stormwater BMPs act as "Heaters" or "Coolers"





3x more Heaters
In Chesapeake
watershed

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Points to Remember

- Temperature is important to life in water
- Temperature varies naturally – diel, seasonal, annual – within a watershed, among watersheds
- Humans have already modified stream temperature, and climate change will make streams warmer

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