Impacts of BMPs and Habitat Restoration on Water Temperatures: opportunities to mitigate rising water temperatures

A. Contributors

Katie Brownson, USFS; Tom Schueler, CSN; Matt Ehrhart, Stroud; Jeremy Hanson, VT; Lucinda Power, EPA CBPO; Anne Hairston-Strang, MD DNR Forestry; Iris Allen, MD DNR Forestry; Judy Okay, J&J Consulting; Mark Dubin, UMD, Sally Claggett, USFS; Stephen Faulkner, USGS; Frank Borsuk, EPA; Katie Ombalski, Woods & Waters Consulting

B. Resources

The synthesis was primarily developed from a limited review of the scientific literature, as well as several group discussions to formulate the overall approach and provide supporting science.

C. Approach

The group decided to focus efforts on non-tidal and near-shore tidal water temperature, given the limited influence BMPs have on main-stem tidal water temperature. Research by Hinson et al (2021) indicate that atmospheric changes and ocean warming are the driving forces for warming in the Chesapeake Bay, while river inputs have little impact, except at the head of tidal tributaries.

For stream temperature, the group discussed a simple model for assessing the impact of historic and future BMPs on rising stream temperatures using a basic watershed BMP delta-T equation, as follows:

[Stream Temp Δ] =

∑ [Δ Land Use] + [Upland BMP Δ] + [Stream Corridor Δ] + [Corridor BMP Δ] + [Riverine Δ]

- *Land Use* Temp Effect: ambient stream temps as influenced by heat island effect: Forest << Pasture/Crops << Suburban <<< Urban. The cumulative land use effect is generally + relative to the baseline.
- *Upland BMP* Effect: reflects how ponding, infiltration or filtration of runoff modifies baseflow and runoff temps (+ or - or no change, relative to the land use baseline)
- *Stream Corridor* Effect: reflects the *current* presence or absence of riparian/floodplain cover along the corridor (+ or -)
- *Corridor BMP* Effect: Whether the installation of a new BMP in the corridor from influences stream temps, relative to the historical corridor baseline. (+ or -)

- *Riverine/Reservoir* Effect: the increase in stream temp as it moves from headwaters thru rivers and is warmed by reservoirs and impoundments along the way, until it ultimately reaches head of tide (+).

To better account for the multiple factors that influence stream temperature, and the multiple pathways through which BMPs might impact stream temperature, the group also developed an accompanying conceptual model:
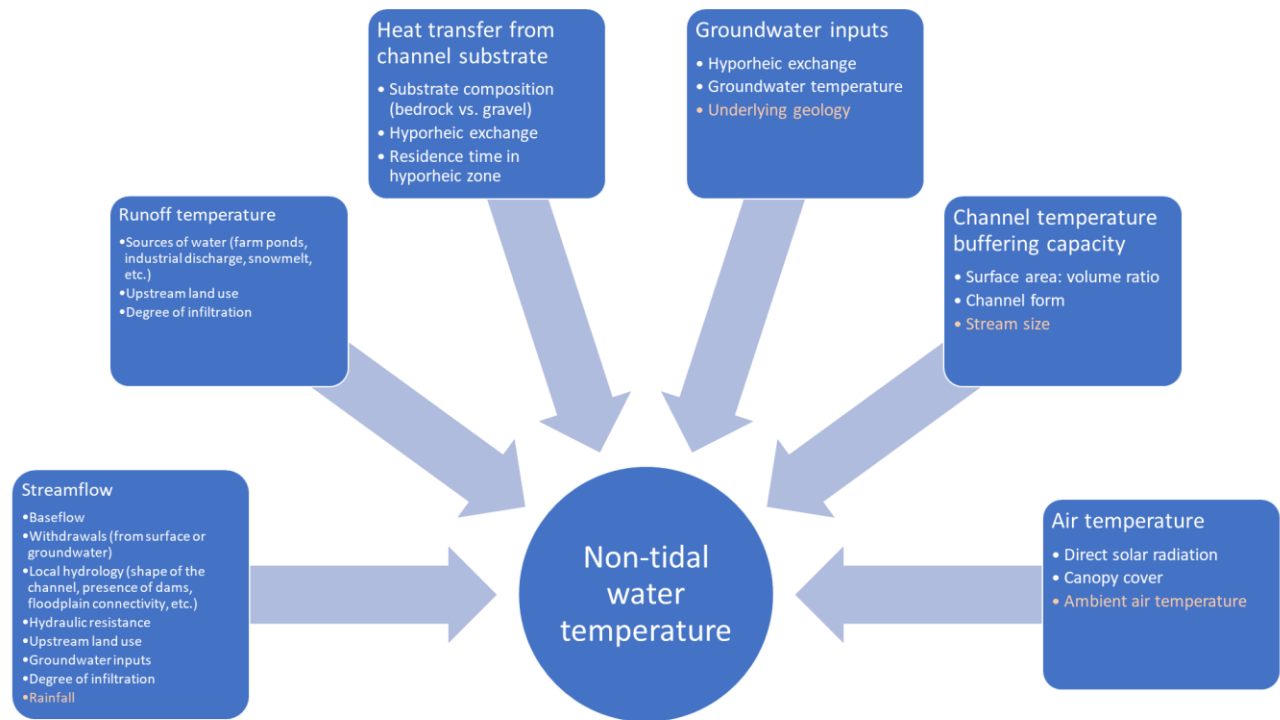
Next, the group developed an eight-bin classification system for evaluating the impacts of BMPs on water temperature, based on available monitoring and engineering and hydrologic considerations.

1. Known Heaters: Upland BMPs that have been shown to increase downstream temperatures due to surface ponding via detention or retention of runoff, to a depth of 10 feet. Examples include wet ponds, created wetlands, dry extended detention ponds, farm ponds, reservoirs, and CAFO lagoons.

2. Suspected Heaters: These BMPs have some, but not all, of the characteristics of known heaters, but have not been well studied from a temperature standpoint. Examples include sand filters, underground vaults and manufactured treatment devices (MTDs) that have closed bottoms and short runoff detention times.

3. Shaders: Upland or corridor forestry practices that maintain or increase forest canopy/forest cover after 10-15 years. Upland practices include tree planting, tree pits,

foundation planters, which exert the greatest cooling effect when they occur over impervious cover. Corridor BMPs include riparian forest buffers and some forms of floodplain restoration.

4. Shade Removers: Land development activities, farming and drainage practices that remove riparian forests from the stream corridor, relative to the historic baseline year. Examples may include: farm buffers that have expired, some forms of stream channel restoration involving extensive tree clearing, and construction of new land development. Other potential examples include "improved" urban and agricultural drainage, such as grass channels, ditches and swales.

5. Known Coolers: These BMPs are designed to shift a large fraction of surface runoff back into shallow groundwater, where it may reside for several days before reaching the headwater stream network. Good examples include infiltration and bioretention practices that lack underdrains, and level spreaders/vegetated filter strips.

6. Suspected Coolers: These urban BMPs also rely on LID practices such as infiltration, permeable pavement, dry swales and bioretention, but are located in tight soils, and therefore require underdrains. Other suspected coolers might include green roofs and floating treatment wetlands?

7. Thermally Neutral: A range of urban of and ag practices that do not appear to have much potential to change downstream temps. On the urban side, these include street and storm drain cleaning, urban nutrient management plans and IDDE. On the ag side, this might include agricultural nutrient management and various tillage and cropping practices.

8. Uncertain or Unknown: Practices that may increase or decrease temperature via multiple mechanisms and the net impact is uncertain. This is the category for all the BMPs that lack research or monitoring data to gauge their temperature impact. Given how many different BMPs exist in the Bay restoration effort, quite a few may fall into the unknown or uncertain category. The research focus should be on BMPs that treat a large watershed acreage.

Lastly, the group discussed some analytical issues in regard to the cumulative temperature impacts of BMPs in the watershed. They include the need to select which land use/BMP "year" will define the watershed temperature baseline, against which future warming due to climate change will be measured (2020?).

The cumulative impact of BMP on stream temperature can be expressed as the relative fraction of ("cool" BMPs * treated BMP acres) vs. ("heater" BMPs * treated BMP acres). The treated acres for each BMP category can be determined from CBWM inputs.

Two scenarios are of particular interest.

- The first is whether historic BMP implementation from 1970 to 2020 has cumulatively increased, decreased or has had no impact on stream temperatures discharged to the Bay.

- The second is whether a different mix of BMPs implemented in future years could potentially mitigate stream warming caused by climate change post-2020 and/or compensate for any heating by historic BMPs prior to 2020.

D. Synthesis

Most of the attention devoted to the impact of climate change on stormwater BMP performance has focused on more intense extreme rainfall events, and not as much has been paid on the potential to mitigate rising stream temperatures. Some recent resources on adapting stormwater BMPs to be more resilient to extreme rainfall in terms of their performance and design life include Wood (2020a, 2020b and 2021) and Miro et al (2021).

The increased attention on stream warming issues is most welcome given the difficulties of managing stormwater in cold-water watersheds and making habitat restoration projects more sustainable in the face of rising water temperatures in the Bay watershed.

Ding and Elmore (2015) noted that the rise in stream temperatures in the Bay watershed over the last 30 years cannot be fully explained by the corresponding increase in air temperatures over the same time period. This suggests that other landscape factors, such as some BMPs and the drainage/stream channels, may also contribute to stream warming in the Bay watershed.

Table 1 shows which types of BMPs fall into the temperature classification system, and provides a comparative summary of the strength of the available research and the strength and direction of their effect on stream temperature, resulting from BMP impacts on air, baseflow, runoff and groundwater temperature. Although there are other pathways through which these BMPs may impact water temperature, we found the most evidence around these four mechanisms. In addition, Table 2 compares the historic and future prevalence of each BMP category in the Bay watershed, any lag time needed for the temperature impact to occur, and whether that impact can be enhanced (cooling) or mitigated (warming).

Known and Suspected Heaters. Many of our historic urban BMPs have been shown induce stream warming, particularly those built from 1970 to 2010. These include wet and dry stormwater ponds, which have been shown to increase baseflow and runoff temps in multiple studies (Galli, 1990, Schueler, 2000, Jones and Hunt, 2010 and UNHSC, 2010). Monitoring also indicates that created stormwater wetlands increase downstream baseflow and runoff temps. In general, the magnitude of the temperature increase for stormwater ponds ranges from 2 to 10 degrees F above the local land use baseline.

Although not much monitoring data is available, it is likely that other shallow ponds exposed to sunlight have the same heating effect, such as CAFO lagoons and farm ponds. It should be noted that while stormwater ponds were extremely common before 2010, they are not widely used today, and are often restricted or prohibited in cold-water watersheds.

Category	BMP Types	Available Research	Strength of BMP Temperature Effect		
			Baseflow	Runoff	G/W
Known Heaters	Wet ponds, created wetlands, dry ED ponds, farm ponds, CAFO lagoon	Strong	+++	++	?
Suspected Heaters	Sand filters, MTDs,	Weak	++	+	-
Shaders/ Interceptors	Upland and stream corridor forestry practices. Ag buffers & fencing??	Strong	- -	?	?
Shade Removers	Land clearing, some channel restoration practices, expired farm buffers, open channels ag ditches	Weak	++	+	?
Known Coolers	Bioretention, porous pavement, infiltration, w/o underdrains	Strong	- -	- -	-
Suspected Coolers	LID practices w/ under-drains, floodplain habitat restoration	Weak	-	-	-
Uncertain/ Unknown	Ag tillage and soil health practices??	Weak	??	??	??
Thermally Neutral	Street cleaning, ag & urban NMPs, IDDE	Weak	?	?	?

Table 1
Initial Classification of BMPs
Based on Ability to Influence Stream and Subwatershed Temperatures

Known and Suspected Coolers. Many LID practices such as infiltration, bioretention and porous pavement appear to have some capability to cool runoff temperatures, depending on how much surface runoff is diverted into the soil/groundwater and how long it resides there. The key engineering variable appears to be the underground runoff residence time. Runoff that enters LID practices w/o underdrains make take many days or even weeks before they reach the headwater stream network.

In these cases, limited research suggests that the cooling effect can range from 2 to 5 degrees F, depending on underlying soils and hydro-geological conditions. Both monitoring and modeling research indicate that bioretention areas and vegetated filter strips have the capability to cool runoff that has been heated by the contributing pavement treated by the BMP (Jones 2008, UNH, 2010, Winston et al, 2009 and Long and Dymond 2013).

The cooling effect, however, was not great enough to meet cold-water temperature standards at either the site or sub-watershed scale (Jones, 2008 and Chen et al 2020). This suggests that even the best LID practices cannot act like refrigerators – they can prevent further BMP warming, but generally cannot compensate for the land use effect on stream temperatures.

However, the majority (~90%) of LID practices are designed with underdrains to overcome soil constraints on infiltration. The underdrains reduce runoff residence times to a few hours to a day or so for most storm events, which sharply reduces their cooling potential (Selbig and Beun 2018).

More research is needed to see whether "surface" LID practices such as permeable pavement and green roofs have the potential to mitigate the temp increases caused by the impervious surfaces they replace.

Shaders and Shade Removers:

StStream corridor (riparian) forestry practices. Extensive research supports the role of riparian forests in cooling streams. Forested reaches have cooler maximum water temperatures and less temperature variation than non-forested reaches (Malcolm et al. 2008, Bowler et al. 2012, Turunen et al. 2021), and shade removal increases stream temperature (Nelson and Palmer, 2007). Riparian forests cool streams by both providing shade that directly reduces solar radiation reaching streams. Abdi et al. (2020) found that by diminishing shortwave radiation to streams, riparian forests could reduce average river temperatures by 3.6° C. Simulations of mature forest also generated an 80% reduction in heat gains from shortwave radiation and a 48% reduction from young open forest (Wondzell et al. 2019).

Modeling has also suggested that both riparian and floodplain forests can cool ambient air temperatures and stream temperatures (Abdi et al. 2020), with another study demonstrating that shade and evapotranspiration can reduce temperatures in ponds and streams (Sun et al. 2015). Tree evapotranspiration can lower ambient temperatures by as much as 6 degrees C, although this effect can vary with tree species, the size of leaves, and their stomatal aperture (Gkatsopoulos, 2017). However, it is also important to consider the relationship between evapotranspiration and streamflow levels, as reducing streamflow can further exacerbate increasing stream temperatures, especially when there is already low flow.

The correlation between stream flow and tree evapotranspiration has been studied for decades. Federer in 1973 reported that streamflow recessions proceeded more quickly with the onset of tree transpiration in the spring and slowed with leaf drop in the fall. However, Dawson and Elheringer (1991) found that mature deep-rooted riparian zone trees do not use groundwater flow into streams as their primary water source. They observed that it is primarily younger more shallow rooted trees and herbaceous riparian vegetation whose transpiration affect streamflow. Taken together, this suggests that while newly-planted buffers may reduce streamflow and potentially increase water temperature in low-flow situations, over the long-term, a mature buffer will provide a substantial net cooling benefit.

Riparian forests have the greatest cooling effect in smaller headwater streams. In mid-order streams where there are wider channels and greater thermal inertia, riparian forests do not

have as strong of an effect (Turunen et al. 2021). The type and structure of riparian forest cover can also influence stream cooling, with one study finding greater cooling benefits from dense conifer plantations than deciduous woodlands (Dugdale et al. 2018). For practices that remove shade, the obvious mitigation technique is to avoid removing trees where possible, especially mature trees that are directly shading streams.

In terms of the space and time needed to generate impacts on stream temperature, one study found that only 300 m of seminatural riparian vegetation in a headwater stream was needed to generate 1°C of cooling in the summer (Ryan et al. 2013), while another found that 1 km of riparian forests could reduce temperature by 1.5°C (Stanford et al 2019). However, newly planted trees will not provide any of these benefits immediately. Recent analysis by Iris Allen (MD DNR Forest Service) suggests that newly planted trees in the Chesapeake Bay Watershed require up to 15 years to generate enough canopy to be detected by aerial imagery, at which point, the trees would also provide significant shading benefits. This illustrates the value of conserving existing forests that are already providing valuable shading and stream health benefits.

Upland forestry practices. There is not as much research available about the stream temperature benefits of upland forestry practices. However, some research suggests that increased upstream shading reduces mean water temperature by cooling soils and impervious surfaces, with greater simulated benefits of cooling impervious surfaces, due to the fact that they store more heat and generate more runoff than pervious surfaces (Ketabchy et al. 2019).

When considering the implications of upland shade removal, in cases where riparian forests are maintained, one study found that upland forest harvesting had limited adverse effects on stream temperature, even with buffers that are only 10m wide (Clinton 2011). However, another study found that when harvest had smaller buffers and less overall canopy retention, there was greater daily stream temperature fluctuations (Witt et al. 2016). This suggests maintaining larger buffers and more upland canopy can help minimize the stream temperature implications of upland forest harvesting. At the same time, when upland forest is removed and converted to development, there can be significant implications for water temperature. Built surfaces can increase the temperature of runoff due to their tendency to absorb more thermal energy than many natural surfaces (Janke et al. 2013).

Urban tree planting and urban forestry practices are increasing throughout the watershed. We expect these efforts will continue to grow with various state, regional, and national initiatives to plant more trees, with a particular emphasis on growing tree canopy in underserved communities.

Uncertain/Unknown practices: This is the category for all the BMPs that lack research or monitoring data to gauge their temperature impact

Stream and Floodplain Restoration. There has been quite a bit of debate about the impact of stream restoration projects on downstream temperatures. A recent review of the rather scanty literature on the topic can be found in Wood and Schueler (2020c – Section 7 and Appendix F). Some practices, such as certain kinds of floodplain and wetland restoration appear to be able to cool baseflow temperatures, at least to some degree.

On the other hand, abundant evidence exists that stream channel restoration projects that require extensive riparian tree clearing can induce stream warming, at least until such time as the post-project reforestation matures. A series of best practices for design and construction of stream/floodplain restoration practices has been developed to minimize the unintended consequences of this class of projects (Wood and Schueler, 2020c).

Agricultural BMPs: Still looking for data here

Habitat Restoration Projects: Still looking for data here

Table 2 Other Key Factors Associated with the BMP Categories				
Category	**BMP Types**	**BMP Prevalence In Watershed?**	**Lag Time to Change Temp?**	**Can Impact be Enhanced or Mitigated?**
Known Heaters	Wet ponds, created wetlands, dry ED ponds, farm ponds, CAFO lagoon	*Historic*: very common *Future:* highly restricted	None	Limited ability to mitigate, unless deeper than 10 ft
Suspected Heaters	Sand filters, MTDs,	*Historic:* Uncommon *Future:* Uncommon	None	Limited ability to mitigate
Shaders	Upland and stream corridor forestry practices. Ag buffers & fencing??	*Historic:* Common *Future:* Common	10 to 15 yrs	Can be enhanced by practices that accelerate tree canopy
Shade Removers	Land clearing, some channel restoration practices, expired farm buffers, forest harvesting, open channels	*Historic:* Common *Future:* Less Common?	None, unless the site is reforested	Can be mitigated in headwater streams (e.g., forest buffer)
Known Coolers	Bioretention, infiltration, porous pavement w/o underdrains	*Historic:* Uncommon *Future:* Uncommon	Weeks	Limited ability to enhance w/ urban soils
Suspected Coolers	LID practices that use under-drains, floodplain habitat restoration	*Historic:* Common *Future:* More Common	Hours	Need more data about GW & hyporheic exchange
Uncertain or Unknown	Ag tillage, soil health practices, ??	N/A	??	N/A
Thermally Neutral	Street cleaning, ag & urban NMPs, IDDE	N/A	??	No evident mechanism to change temps

E. Evaluation

How good is the data? While significant gaps remain, there is enough data for urban and forestry practices to get a general sense of their impact of historic and future BMPs on stream temperatures in the watershed. At this time, we lack enough data to make a similar assessment for agricultural and habitat restoration practices.

In all cases, we lack enough data to model past and future changes in stream temperatures at the scale of the Bay watershed, especially in response to future management and BMP implementation scenarios.

What do we know about the watershed impact of BMPs on stream temperatures? On the urban side, stormwater BMPs have a mixed effect, but it appears historically, that we have installed more "heaters" than "coolers", at least in terms of treated acreage. When combined with increased upland and corridor tree clearing and the construction of urban ditches and swales to convey stormwater runoff, it is likely that that the urban sector has had the net effect of further exacerbating stream warming, beyond the heat island/land use effect associated with urban impervious cover.

The trend toward more widespread use of LID practices suggests that the BMP effect on downstream temperatures could be significantly reduced in the future. As noted earlier, however, stormwater BMPs are not refrigerators, and no evidence exists that they can compensate for the predominant impact of urban land use on stream warming.

What we can take action on now based on what we know: Some potential actions include:

- Reinforce the need for state and local stormwater permitting agencies to prevent BMP warming in cold-water watersheds by restricting or prohibiting the use of known heaters (and possibly also suspected heaters, as well).

- Do more training and outreach to support best practices to avoid unintended consequences associated with future stream/floodplain restoration projects

- Consider dam/pond removal and associated floodplain restoration projects in rural watersheds as a potential temperature mitigation for cold-water fisheries on a localized basis

- Update urban and forestry BMP plant lists to make sure the species we are planting are appropriate for the future hardiness zones in our warming watershed.

What more needs to be done before the workshop? The following actions could help evaluate management scenarios and appear to be doable over the summer months if someone volunteers for them.

- Add more research on the temperature impacts of agricultural, forestry and habitat restoration practices located in upland areas and the stream corridor.

- Check out the International Stormwater BMP pollutant removal database to see if there are any more urban BMP temperature "efficiency" data to analyze.

- We could derive watershed-wide or state-by-state summaries of the total treated acreage of BMPs with each temperature category, using inputs data form the Phase 6 CBWM or CAST output. Such data would be useful in constructing a back of the envelope estimate of whether or not there are more BMP heaters than BMP coolers in the watershed.

- It seems that forestry practices, especially riparian ones, have some potential to cool summer stream baseflow, which appears to be most critical to sustain cold-water fisheries. While we may not have enough data to precisely quantify the impact of forest buffers, we could (probably) calculate the total headwater stream mileage in cold-water portions of the Bay watershed that potentially could be reforested.

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