Synthesis Element 7/8:
Final Draft

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

At a Glance:

- BMPs can impact stream water temperature through multiple pathways, including modifying air temperature, surface runoff temperature and surface/groundwater interactions.
- Many Urban BMPs are "heaters", while tree planting and buffers show cooling promise over time.
- There are many BMPs that are unlikely to influence water temperature and others that have uncertain water temperature impacts, including agricultural BMPs, stream restoration and wetlands BMPs.
- Over time, the use of "heating" BMPs has grown relative to "cooling" BMPs in the Chesapeake Bay Watershed.
- Additional emphasis is needed to promote the use of cooling BMPs over heating BMPs, especially in watersheds that may be particularly vulnerable to climate change or where there is valuable cold-water habitat.

A. Contributors

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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) indicates 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.

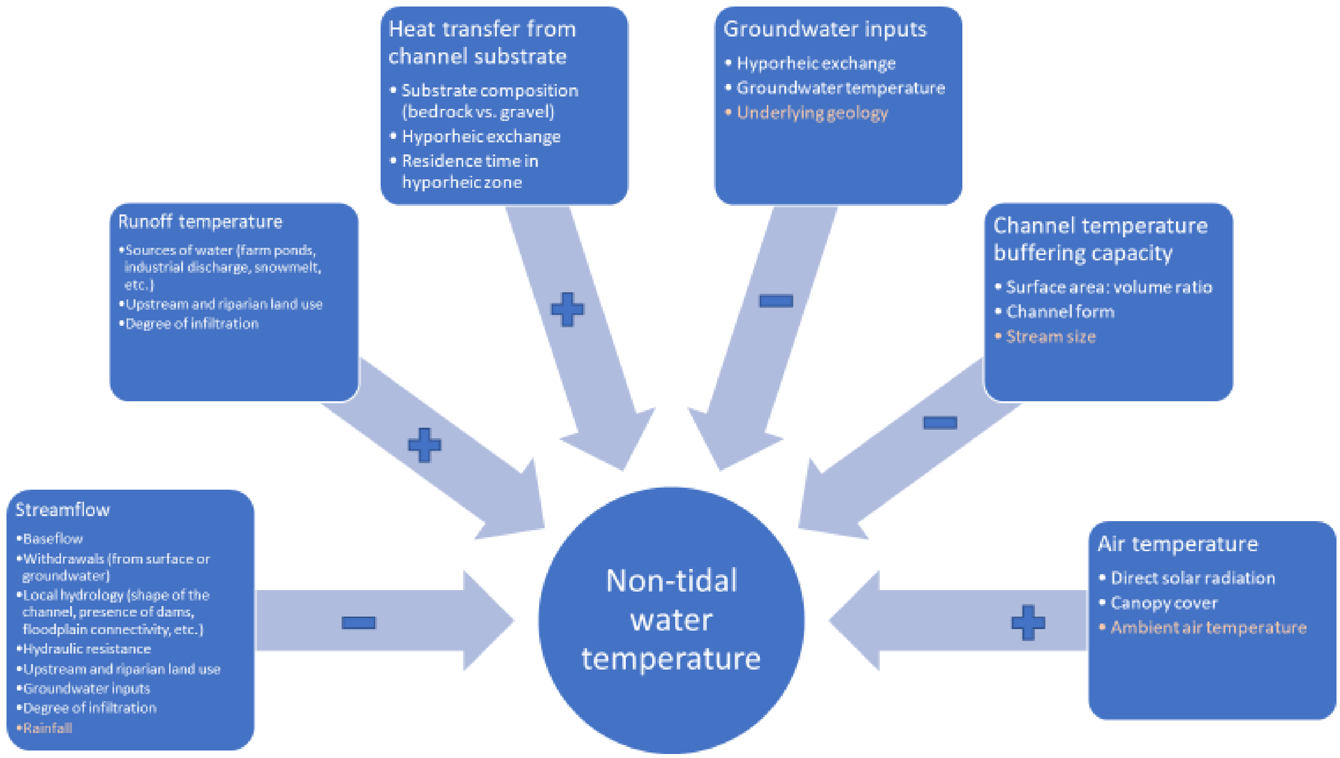
For stream temperature, the group discussed a simple model for assessing the impact of historic and future BMPs on rising stream temperatures using a basic watershed BMP delta-T equation, as follows:

[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 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 <u>require underdrains</u>. Other suspected coolers might include green roofs and floating treatment wetlands?

7. Thermally Neutral: A range of urban of and agricultural 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 agriculture 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 impacts on 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. It also addresses any lag time needed for the temperature impact to occur, and whether that impact can be enhanced (cooling) or mitigated (warming).

Table 1: Initial classification of BMPs based on ability to influence stream and sub watershed temperatures

Category	**BMP types**	**Available research**	**Strength of BMP temp effect**			**Lag Time to Change Temp?**	**Can Impact be Enhanced or Mitigated?**
			Baseflow	**Runoff**	**G/W**		
Known Heaters	Wet ponds, created wetlands, dry ED ponds, farm ponds, CAFO lagoon	Strong	+++	++	?	None	Limited ability to mitigate, unless deeper than 10 ft
Suspected Heaters	Sand filters, MTDs,	Weak	++	+	-	None	Limited ability to mitigate
Shaders/ Interceptors	Upland and stream corridor forestry practices. Ag and urban forest buffers	Strong	- -	?	?	10 to 15 yrs	Enhanced by practices that accelerate tree canopy
Shade Removers	Land clearing, some channel restoration practices, open channels ag ditches	Weak	++	+	?	None, unless the site is reforested	Can be mitigated in headwater streams (e.g., forest buffer)
Known Coolers	Bioretention, porous pavement, infiltration, w/o underdrains	Strong	-	-	-	Weeks	Limited ability to enhance w/ urban soils
Suspected Coolers	LID practices w/ under-drains, floodplain habitat restoration	Weak	-	-	-	Hours	Need more data about GW & hyporheic exchange
Uncertain/ Unknown	Stream and floodplain restoration, Ag practices, Wetlands restoration	Weak	??	??	??	??	N/A
Thermally Neutral	Street cleaning, ag & urban NMPs, IDDE	Weak	?	?	?	??	No evident mechanism to change temps

Known and Suspected Heaters

Many urban BMPs used historically have been shown to 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 & 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. While stormwater ponds were extremely common before 2010, they are not widely used today, and are often restricted or prohibited in cold-water watersheds.

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 without 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; UNHSC, 2010; Winston et al., 2009; and Long & 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 & 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 temperature increases caused by the impervious surfaces they replace.

Shaders and Shade Removers

Stream 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 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. Forests can transpire more water than most other cover types, but also have higher infiltration rates that aid groundwater recharge important for summer low flows. The net effect is not readily quantified but in the well-watered East, the potential for groundwater recharge is significant. Monitoring of infiltration rates of newly planting buffers in Maryland found small but significant increases in rates within 15 years.

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). Newly planted trees will not provide any of these benefits immediately, but will grow as the trees do. 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 fully detected by aerial imagery, at which point, the trees would also provide significant shading benefits.

Stream temperature monitoring of newly planted buffers in Maryland found significant reductions in maximum daily temperatures during the summer after 15 years, confirming the temperature benefits after tree canopy closure, even though trees were not yet fully mature. These results confirm the value of expanding riparian reforestation to ameliorate temperature stressors and potentially reconnect isolated populations of cold-water species. However, the time lag needed for young trees to grow to crown closure emphasizes the need to conserve 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 or 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 (2020). 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, 2020).

Agricultural BMPs: Forest buffers are a key agricultural practice that are known to provide cooling benefits. However, less is known about the water temperature impacts of other agricultural land management BMPs. Some agricultural BMPs, including saturated buffers for drainage systems, horse and livestock pasture management, and high residue tillage management systems, are known to improve surface vegetative cover and water infiltration, which may provide downstream cooling benefits by diverting surface runoff into the soil profile and to groundwater. Likewise, although grass buffers do not provide the shade function of trees, they can provide infiltration benefits. The conversion of agricultural row crop fields to pasture, forest, or to open space represent land use BMPs with possible water temperature impacts.

There is uncertainty about the extent to which these agricultural practices impact water temperature, especially in comparison with the broader effects of non-agricultural land use on water temperature. Nonetheless, considering the prevalence of agricultural lands in the watershed and the relatively large number of acres implementing these practices, the cumulative impacts may be significant. Further research into the water temperature impacts of these agricultural BMPs is merited.

Wetlands BMPs:

Wetlands act like a sponge, soaking up stormwater and dampening storm surges. Wetlands in the Chesapeake Bay watershed develop into familiar forms that include marshes, swamps and bogs dependent on the level, frequency, and duration of water inundation. Multiple studies have examined the potential heater aspects of created wetlands (Galli, 1990; Schueler, 2000; Jones & Hunt, 2010; and UNHSC, 2010). However, wetlands also have cooling potential. Wetlands are usually comprised of suites of vegetative cover types with varying evapotranspiration rates. Gleick (2000) reported that because of high soil moisture, surface roughness, and large areas of foliage, wetlands are usually characterized by higher evaporation rates in relation to an open water surface. Surface temperatures at wetlands with open water were up to 5.1 degrees C cooler than a crop field during the daytime.

Stannard et al.(2013) compared the evapotranspiration rates of two wetland sites selected to typify vegetation communities and hydrologic conditions with an alfalfa field and a pasture. Alfalfa had the highest annual ET due to its leaf structure, providing multiple layers and flat surfaces for efficient evaporation to occur, whereas bulrush is more grass-like with a thin, smooth structure and single needles side by side that are not conducive for efficient evaporation. However, the wetlands had higher annual ET than the pasture. This suggests that vegetation types and structure play a significant role in determining ET and the potential cooling benefits of wetlands. ET expectations would be lower for a wetland with a high percentage of open water as opposed to a high percentage of mixed vegetation.

Forested wetlands likely provide additional cooling benefits due to the amount of evapotranspiration that takes place in forested areas compared to wetlands without trees. Large trees can transpire as much as 100 gallons of water a day (Gkatsopoulos, 2017), but older trees do not cycle as much water as younger trees (Dawson & Elheringer, 1991). This would make a case for retaining older trees along waterways because of their more limited uptake of water from within the wetland system. The size of leaves, and their stomatal aperture also control transpiration which indicates that the selection of species used in created forested wetlands is important (Gkatsopoulos, 2017).

Although research does present evidence that wetlands have the potential to have a cooling effect, future research may present a more exact picture of the features of wetlands that provide cooling benefits and whether wetlands can help cool stream water temperatures. Given the significant variability in created wetlands, there is still uncertainty about whether these BMPs generate a net cooling or heating effect. However, we suspect that that the restoration, enhancement and rehabilitation of existing wetlands is likely to have a net cooling effect to the extent these BMPs help increase ET by enhancing vegetation abundance and diversity within existing wetlands, reducing the amount of open water.

Historic BMP implementation in the Chesapeake Bay Watershed

Estimates of historic BMP implementation using the Chesapeake Assessment Scenario Tool (CAST), reveals that watershed-wide, there has been substantially greater implementation of “heater” BMPs as compared with “cooler” BMPs. In many years, there has been approximately three times as much implementation of heaters as coolers. There has been comparatively less implementation of stream restoration practices.

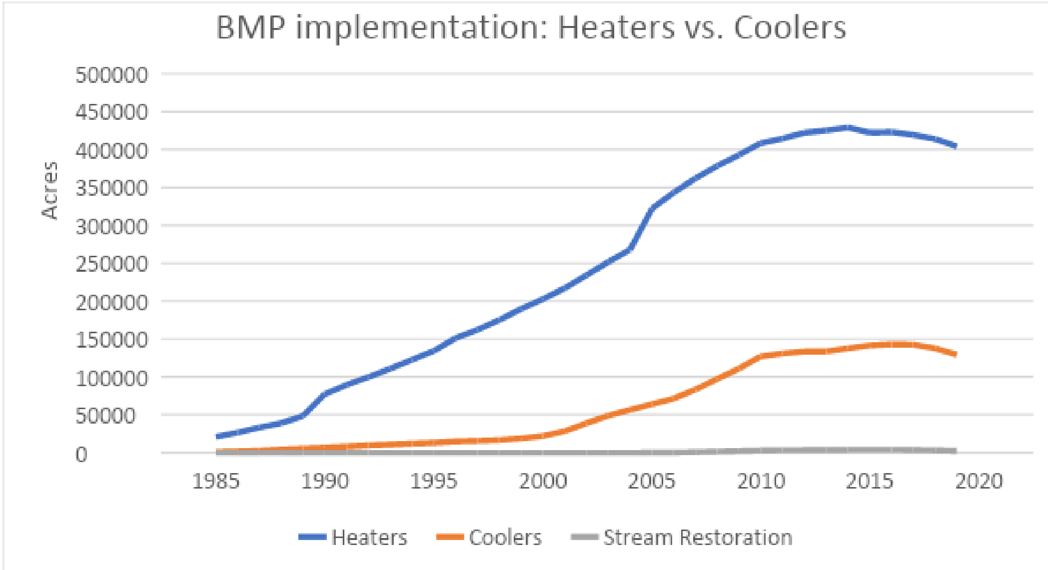


Figure 1: Historic implementation of heater and cooler BMPs in the Chesapeake Bay Watershed. Refer to Appendix A for a full list of BMPs included in each category

There is still significant uncertainty about the temperature impacts of agricultural BMPs. However, even looking at a subset of practices that have the potential to influence water temperature by increasing infiltration reveals the magnitude at which these practices these are implemented and underscores the importance of further considering their cumulative impacts.

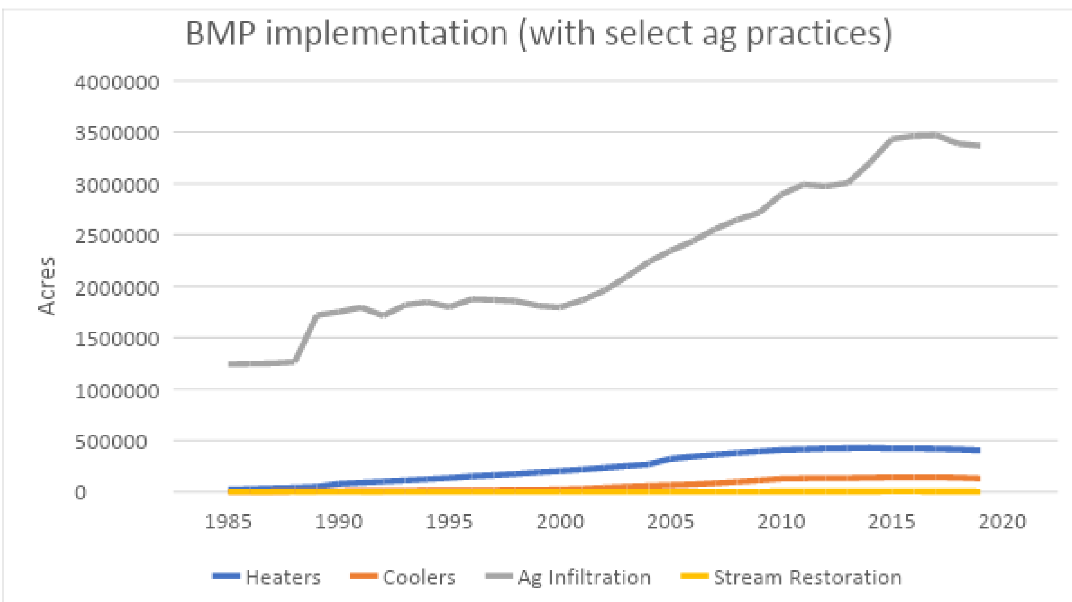


Figure 2: Historic implementation of BMPs with Ag BMPs that may influence temperature. Refer to Appendix A for a full list of BMPs included in each category

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. Our level of certainty in categorizing BMPs as heaters and coolers is built into classification system, where we identify practices in which we have lower confidence as suspected heaters and coolers. Although we can hypothesize about the mechanisms through which some agricultural BMPs may influence water temperature, at this time, there is insufficient existing research demonstrating the stream temperature impacts of agricultural and habitat restoration practices. We do not expect that our level of certainty will change significantly in the coming 3-5 years given the incremental nature of scientific research.

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 historically, 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.

Forestry tree planting BMPs, especially in the riparian corridor, can effectively lower stream temperatures once established. These practices may be particularly valuable in lowering maximum temperatures in the summer, when relatively high temperatures put aquatic biota at particular risk. In urban areas, 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. Additional synthesis efforts are needed to further evaluate the relative role of BMPs in influencing water temperature relative to broader land use and climatic trends.

What we can take action on now based on what we know:

Some potential management 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. Encourage diversity in plant selection to hedge against potential losses to invasive pests and plants. Consider large and tall trees where space permits to maximize benefits from tree planting spaces.

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 (if it exists) on the temperature impacts of agricultural 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.

- Investigate potential overlays with other datasets to evaluate where there are opportunities for BMPs to provide additional cooling benefits. For example, calculating the total headwater stream mileage in cold-water portions of the Bay watershed that potentially could be reforested.

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Appendix A: BMPs included in the historic BMP implementation analysis

Heaters (includes known and suspected heaters)

- Dry ponds
- Extended dry ponds
- Floating treatment wetlands
- Wet ponds & wetlands
- Vegetated open channel

Coolers (includes known coolers, suspected coolers, and shaders)

- Agricultural tree planting
- Bioretention
- Bioswale
- Forest buffers
- Forest buffers on fenced pasture corridor
- Impervious surface reduction
- Infiltration practices
- Permeable pavement
- Urban filter strips
- Urban forest buffers
- Urban forest planting
- Urban tree planting
- Wetland enhancement and rehabilitation
- Wetlands restoration

Agricultural infiltration practices (included in the unknown/uncertain category)

- Conservation tillage
- Grass buffers
- Grass buffers on fenced pasture corridor
- High residue tillage
- Horse pasture management
- Land retirement
- Pasture alternative watering
- Prescribed grazing

Stream restoration practices

**Note: Practices converted from linear feet to acres assuming a 100 ft average width*

- Non-urban stream restoration

- Urban stream restoration