Management Approaches to Reduce Stressors of Stream Health

Final Synthesis Report

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Executive Summary

Millions of dollars are spent annually to reduce nutrient and sediment loads to the Chesapeake Bay; however, water resource managers need better information to direct these investments toward strategies that not only help to restore the Chesapeake Bay but also have a positive impact on the health of the more than 100,000 streams, creeks, and rivers within the Chesapeake Bay watershed. An extensive body of knowledge exists on the capacity of best management practices (BMPs) to reduce certain target pollutants, providing valuable information to support Chesapeake Bay restoration efforts. To help restore streams throughout the watershed, water resource managers require an improved understanding of the factors affecting stream health and the extent to which BMPs may alleviate these stressors beyond their intended goal of nutrient and sediment reduction.

This study contributes to a three-part research program envisioned by the EPA's Chesapeake Bay Program (CBP) Stream Health Workgroup and the United States Geological Survey (USGS). The first part of the research program, conducted by the USGS, identified the key stressors (e.g., salinity, toxic contaminants, geomorphology) most affecting stream health—defined as ***the health and integrity of the benthic macroinvertebrate community***. The second component, led by the Center for Watershed Protection (CWP) and funded by the CBP through the Chesapeake Bay Trust (CBT), focused on the capacity for BMPs to affect those stressors. The third component will build upon the first two research elements and inform monitoring efforts to effectively track and characterize stream response to management efforts.

Fulfilling the second component of the three-part research program, the present study sought to answer the following research question: ***What capacity do management activities being implemented by jurisdictions to meet total maximum daily load (TMDL) goals have to address key stressors affecting stream health in the Chesapeake Bay watershed?*** This research examined the co-benefits to stream health that can be expected from implementation of BMPs primarily targeted at reducing sediment and nutrient loading to the Chesapeake Bay.

CWP worked with the CBP Habitat Goal Implementation Team and a Technical Advisory Group to develop the methods and approach for this project. First, the USGS research findings were used to select the stressors most important to stream health in urban and agricultural settings, based on their identification as important in over 50% of studies reviewed. These stressors included pesticides, geomorphology, other toxics, flow, and salinity. Next, a subset of BMPs from the Chesapeake Assessment and Scenario Tool (CAST) were selected as the focus of the literature review. The 12 selected BMPs have: 1) wide applicability in urban or agricultural areas across the Chesapeake, 2) significant implementation in the Chesapeake Bay watershed, 3) discrete physical components that can be monitored (versus programmatic BMPs), 4) sufficient research available to assess effectiveness, and 5) the potential to provide co-benefits to stream health.

CWP led a comprehensive literature search for studies evaluating the effectiveness of the selected BMPs, reviewed 125 papers, and compiled key information from each study into a database. Effectiveness values of high, medium, and low were assigned based on the literature results (Figure E - 1). Where possible, BMP effectiveness was determined by calculating a weighted median efficiency from data points extracted from the literature reviewed, and with weighting based on the study type and number of data points supporting the reported efficiency. Data from 47 papers were used to

calculate efficiencies for flow, other toxics and pesticides using this method. The Geomorphology stressor was divided into two categories: habitat and sediment. The Impact of BMPs on the habitat stressor was characterized based on a review of literature and estimated solely based on the ability of a practice to physically modify the stream. The sediment geomorphology impact was assessed using a "by proxy" method, where the effectiveness was estimated using sediment efficiencies derived from the Chesapeake Bay CAST model, combined with weighting factors based on the setting (agricultural vs urban) and the sediment source (in-stream vs upland). Finally, the salinity stressor was too complex to be represented by a single efficiency, due to the multiple parameters used to represent the stressor, such as conductivity, sodium, chloride, sulfate, calcium, magnesium, and potassium. A qualitative approach was used to characterize BMP effects on salinity, wherein papers were reviewed to characterize the potential of BMP groups to reduce in-stream salinity.

The confidence level for the effectiveness results is high for some BMP/stressor combinations (e.g., vegetated buffer and wetland effects on pesticides), while less so for others due to a very limited number of studies (e.g., effect of wet ponds and wetlands on flow) and, in some cases, high variability across studies. For example, the data for no-till and cover crops was very widely distributed, with values ranking from -800% to almost 100%. There were some BMP-Stressor combinations for which no information was available. These cells are blank in Figure E - 1.

BMP Type		**Stressors Important to Stream Health**					
Setting	**BMP Name**	Other Toxics	Flow	Salinity	Pesticides	Geomorphology: Habitat	Geomorphology: Sediment
Urban	Wet Ponds and Wetlands	high	medium	low	high	low	medium
	Dry Ponds	medium	medium	low	low	low	low
	Bioinfiltration	high	high	low	high	low	medium
	Urban Forest Buffers	medium	low	low	medium	low	low
	Urban Tree Planting		high	low		low	low
	Urban Stream Restoration			low		high	high
Agricultural	No Till and Cover Crops	Not key stressors in agricultural settings			low	low	low
	Pasture Management				low	low	low
	Vegetated Buffers				high	low	medium
	Agricultural Drainage Management				medium	low	low
	Agricultural Stream Restoration					high	high
	Wetlands				high	low	low

Legend

Effectiveness
- ★ high
- ⯪ medium
- ☆ low

Figure E - 1. Effectiveness[1] of urban and agricultural BMPs on stressors important to stream health.

At least two BMPs were found to be highly effective for each of the pesticides, geomorphology, other toxics, and flow stressors. With the exception of no-till and cover crops, the confidence intervals (where they could be calculated) were positive for all BMPs.

[1] A detailed explanation of how the effectiveness ratings (high, medium, and low) were assigned and the thresholds for efficiency that define them can be found in the Methods section of the report under Data Analysis. Efficiency values are found in Tables 2 & 3.

The results show that bioinfiltration and wet ponds and wetlands have the highest capacity of the urban BMPs to address multiple stressors, with high effectiveness for other toxins and pesticides, and high (bioinfiltration) and medium (wet ponds and wetlands) effectiveness for flow. The success of these BMPs is not surprising, since both BMP types reduce flow and capture sediment, two of the best mechanisms for removing pollutants from runoff. Urban tree planting and urban stream restoration were determined to have high effectiveness for at least one stressor. As expected, dry ponds have relatively poor pollutant removal and flow reduction compared with other urban BMPs.

In the agricultural sector, vegetated buffers, agricultural stream restoration, and wetland BMPs have high effectiveness for at least one stressor. For vegetated buffers and wetlands, this was pesticides. For stream restoration it was geomorphology.

The qualitative review showed strong support for the agricultural and urban stream restoration BMPs having high effectiveness for improving the geomorphology stressors. The studies reviewed showed that stream restoration can have positive impacts on geomorphic stressors impacted by localized physical stream conditions—such as water velocity and transient storage.

All BMPs included in this study were determined to have low effectiveness for reducing salinity in streams. BMPs were found to temporarily detain high-salinity spikes, but consistently re-release them slowly over an extended period of time or in subsequent high salinity pulses. The effect of this phenomenon is that high salinity peaks can be reduced to some degree by BMPs; however, elevated salinity persists for extended periods in the discharges. Salts were also found to be temporarily stored in the shallow groundwater. This effect of "smoothing" salinity peaks may not be better for biotic health when the effect is prolonged periods of high salinity.

This study's findings are qualified by several caveats, including:

- This study emphasized evaluating the effect of individual BMPs on one or more stressors. It is unknown if the cumulative impact of a suite of BMPs on these stressors or the effect of BMPs at the catchment scale can be extrapolated from the assessed impact from individual BMPs alone.

- Variation in BMP design was not captured in this study. This could be further teased out with the addition of more studies and a more detailed parsing of the data at a finer resolution of BMP grouping. Example variables include the design storm, whether an underdrain is used for bioinfiltration BMPs and the restoration approach used for stream restoration.

- The studies reviewed used a variety of metrics to measure flow, which were lumped and compared using percent reduction as the common metric. Adding more studies and analyzing at a finer resolution would allow for a more targeted analysis that evaluates different measures of flow separately.

- While pollutant removal rates may be high for some BMPs, these compounds are not necessarily removed from the ecosystem. For example, flow reduction often occurs through infiltration which can transport pollutants to streams through groundwater, and pesticides and other toxics can be removed from runoff through sedimentation, but removal and proper disposal of these contaminated sediments may still be needed.

- The studies on salinity were limited to the subset of structural BMPs identified for this project. Although the qualitative review showed low effectiveness of these BMPs to reduce salinity in streams, best practices to prevent the introduction of chloride from road salt and other sources such as water softeners, should not be discounted.

This report consolidates research from a literature review to provide an improved understanding of the effect of BMPs on key stressors to stream health in the Chesapeake Bay watershed. An additional goal of this project is to highlight the need to acknowledge other stressors to stream health – beyond sediment and nutrients. This report is meant to help facilitate conversations with management leaders by providing information on which practices may be most effectively used to address stressors of concern.

Introduction

Driven by the Chesapeake Bay total maximum daily load (TMDL) for sediment and nutrients, watershed implementation plan actions are prioritized, in large part, based on their effectiveness to reduce sediment and nutrient loads to the Chesapeake Bay. While the success of these restoration efforts is generally determined based on the overall health of the Bay, it is implied that local ecosystem improvements will also result. However, despite the millions of dollars spent annually to reduce pollution to the Chesapeake Bay, there is a need for improved understanding of how stream health (Box 1) is responding to these management efforts. Currently, federal, state and local agencies along with non-governmental organizations across the Chesapeake Bay watershed conduct monitoring of local stream health to address a variety of programmatic goals and regulatory requirements. The resulting data serves as one metric for the effectiveness of restoration efforts.

This study contributes to a three-part research program envisioned by the EPA's Chesapeake Bay Program (CBP) Stream Health Workgroup (SHWG) and the United States Geological Survey (USGS). The first part of the research program, conducted by the USGS, identified the key stressors (e.g., salinity, toxic contaminants, geomorphology) most affecting stream health. The second component, led by the Center for Watershed Protection (CWP) and funded by the CBP through the Chesapeake Bay Trust (CBT), focuses on the capacity for best management practices (BMPs) to affect those stressors identified as most important. The third component will build on the first two research elements and inform monitoring efforts to effectively track and characterize stream response to management efforts.

Box 1. Stream Health
Stream health, for the purposes of the present study, is defined as the health and integrity of the benthic macroinvertebrate community. Many metrics are used to characterize benthic macroinvertebrate community conditions. These commonly include measures of sensitive taxa and indices of biological integrity. For more, see Fanelli et al. (2022).

Fulfilling the second component of the three-part research program, the present study seeks to answer the following research question: What capacity do management activities being implemented by jurisdictions to meet TMDL goals have to address key stressors affecting stream health in the Chesapeake Bay watershed? This research examines the co-benefits to stream health that can be expected from implementation of BMPs primarily targeted at reducing sediment and nutrient loading to the Chesapeake Bay.

Prior research has examined the capacity of many of the BMPs under consideration in the present study to reduce certain target pollutants. For example, Schueler and Youngk (2015 and 2016) examined removal of toxins by urban and agricultural BMPs targeting sediment and nutrient removal. The study provided valuable information about twelve classes of toxins and the potential for load reduction to the Chesapeake Bay; however, it did not specifically address stream health or examine BMPs comparatively. Paakh (2016) produced a reference guide linking common stressors to aquatic biota with a rating of the effectiveness of 62 BMP types to reduce each stressor. This guide is the first known effort to systematically evaluate the effect of BMPs across a range of stressors to stream biology but was based on work in the Midwest and did not include an exhaustive literature search.

An extensive body of knowledge exists on BMP effectiveness for pollutant reduction across a wide swath of BMPs and pollutants. The present report consolidates this research through a literature review and synthesizes findings to provide a comprehensive understanding of the effect of BMPs on key stressors to stream health. An additional goal of this project is to highlight the need to acknowledge other stressors to stream health – beyond sediment and nutrients. This report is meant to help facilitate conversations with management leaders by providing information on which practices may be most effectively used to address stressors of concern and have a positive impact on stream health.

Methods

CWP worked with the CBP Habitat Goal Implementation Team – Stream Health Workgroup to establish a Technical Advisory Group (TAG) to help develop the methods and approach for this project. First, the USGS research findings (Fanelli et al. 2022) were used to select the stressors most important to stream health in urban and agricultural settings, based on their identification as important in over 50% of studies reviewed. Next, a subset of BMPs from the Chesapeake Assessment and Scenario Tool (CAST) were selected as the focus of the literature review based on the following factors: 1) widely applicable in urban or agricultural areas across the Chesapeake, to align with the USGS findings, 2) implemented in the Chesapeake Bay, based on recent implementation statistics, 3) physical BMPs versus programs and therefore easier to study their effectiveness, 4) have a relatively large number and/or high quality studies available to assess effectiveness, and 5) potential to provide co-benefits to stream health. A comprehensive literature search was conducted and 125 papers reviewed, with key information compiled into a database. Data analysis methods included quantitative analysis of BMP effectiveness, an effect-by-proxy analysis for BMPs that indirectly affect the stressor in question, and qualitative analysis for studies where quantitative methods could not be applied.

BMP & Stressor Selection

In the first part of the three-part research program, researchers with the USGS identified the key stressors affecting stream health in the Chesapeake Bay watershed (Fanelli et al. 2022). Fanelli et al.'s findings reported the percentage of studies reviewed that reported each stressor as important to explaining biological response patterns. The stressors were assessed for importance to stream health in two geographical settings: 1) urban and 2) agricultural. The scope of the current study was narrowed by including only those stressors reported as important in over 50% of the studies reviewed by the USGS in each setting (Figure 1 and Figure 2). The stressors exceeding the 50% threshold, and therefore deemed key stressors, in the urban setting were flow, geomorphology (habitat), other toxics, pesticides, and salinity. In the agricultural setting the key stressors were pesticides and geomorphology (habitat). While nutrient load was found to be a key stressor, it was excluded from the present study because of its focus on ancillary benefits from BMP implementation, beyond nutrient reduction. Although dissolved oxygen (DO) and riparian condition were reported as important in preliminary findings provided by USGS researchers, they did not exceed the 50% threshold in the final results. Consequently, these stressors are not included in the BMP-Stressor matrix (Figure 3) and full assessments of BMP effectiveness for improving DO and riparian condition were not performed. Preliminary research was conducted, however, and the findings are included as appropriate throughout the results and discussion presented herein.

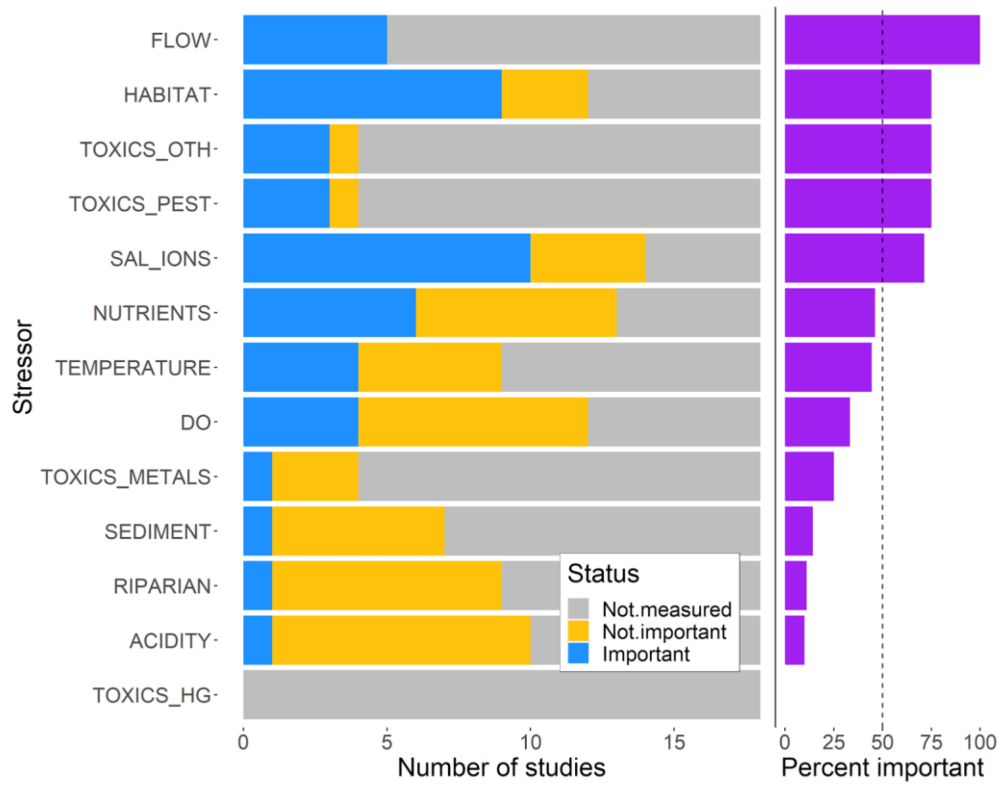

Figure 1. Stressors important to stream health in urban settings (Fanelli et al. 2022).

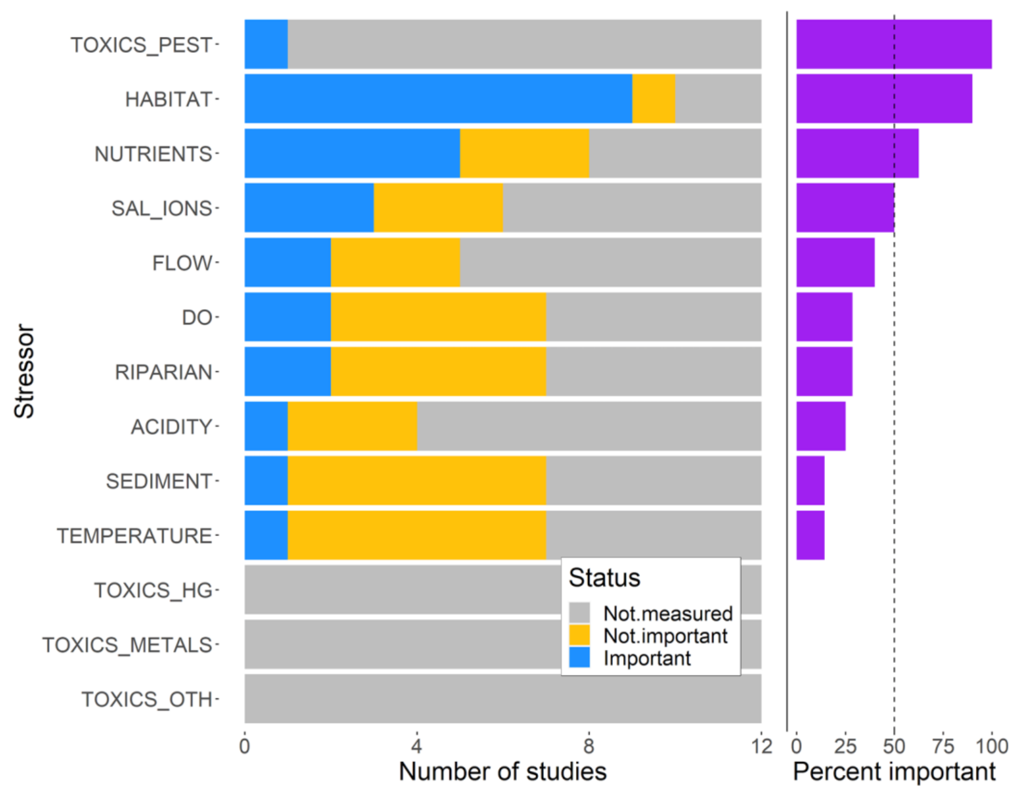

Figure 2. Stressors important to stream health in agricultural settings (Fanelli et al. 2022).

A subset of BMPs from CAST (CBP 2020) were selected for inclusion in the current study. The criteria for inclusion included the potential to provide co-benefits to stream health, significant implementation in the Chesapeake Bay watershed based on acres/units implemented, and applicability in urban or agricultural areas, as the research priorities identified by the technical advisory group (TAG) were to examine the potential of BMPs to improve key stressors identified in these two settings. BMPs assessed to have low potential for ancillary improvements for key stressors, beyond nutrient or sediment reduction, were excluded from the study. Examples of such BMPs include septic connections and dairy precision feeding. Many BMP types had no record of implementation in the CAST database in the period 2015-2019, for example, broiler mortality freezers and storm drain cleanout. Others had relatively low implementation extent or areal coverage, for example, permeable pavement. The research priorities were to examine the potential of BMPs to improve key stressors identified in urban and agricultural settings. BMPs considered resource practices, for example, abandoned mine reclamation, were therefore excluded. See Appendix A Table A-1 for details on the BMPs that were excluded.

Selection and Classification of Papers

A total of 125 papers were reviewed out of an initial 188 found in a literature search (Supplemental Materials). Only peer reviewed studies that addressed the target BMPs and key stressors of interest were reviewed. Results from some of the studies that were excluded were ultimately included as a part of a larger review paper. Review papers and larger studies examining multiple stressors or BMP types were prioritized to reduce the papers to a manageable number for evaluation and inclusion in this report. Journal Impact Factor – a measure of the number of times an average paper in a journal is cited during a year – was a criterion used to initially filter studies to this end. Additionally, targeted searches for literature focused on BMPs/stressors with low data availability following the initial screening. Journal impact factor was disregarded in these targeted searches.

Of the 125 papers reviewed, 47 contained data on key stressors and evaluated parameters capable of being compared quantitatively across studies. In these papers, the effect of treatment could be quantified as a percent reduction from some baseline (e.g., a "before" or "control" condition) or as a reduction from an inflow (an "In" vs "Out") comparison. The remaining papers were included for qualitative analysis and as reference studies where the study design or data did not lend itself to direct comparison between studies. Many studies examined the mechanisms of treatment and influence of relevant factors. For example, a study on no-till practices examined the role of rainfall timing following pesticide application but did not compare no-till to conventional tillage as a control (Shipitalo and Owens 2003). The review of

Box 2. Key Information Compiled in Literature Review Database
Authors
Publication Year
Title
Document Type
Journal Name
Journal Impact Factor
Volume
Issue
Pages
DOI
Coarse BMP
Fine BMP
BMP Size
BMP Treatment Volume
BMP Age
BMP Design Notes
Coarse Stressor
Fine Stressor
Stressor Notes
Stressor Phase
City
State
Sector
Study Type & Notes
Methods Description
Treatment Mechanism(s)
Treatment Effectiveness
Reviewer Notes
Conclusion Metrics

selected literature extracted key information from each study (Box 2) documented in a database (Supplemental Materials).

Data Analysis

Effectiveness Ratings

Effectiveness ratings were determined for each BMP-stressor intersection based on the results of the literature review. The primary method for assigning effectiveness ratings was through calculated efficiencies, as described below. The efficiencies of all BMP-stressor intersections were grouped into three percentile ranges and BMPs were deemed to have low effectiveness at efficiencies below the 33^{rd} percentile, medium effectiveness if between the 33^{rd} and 67^{th} percentiles, and high effectiveness above the 67^{th} percentile. This was applied to the other toxics, flow, and pesticides stressors using data from 47 papers.

For the salinity and geomorphology stressors, this method was found to be too reductive, as it did not adequately describe the complexity. Salinity was described in the literature by parameters including conductivity, sodium, chloride, sulfate, calcium, magnesium, and potassium. Due to retention and re-release of various constituents, either through interactions of the constituents or in subsequent runoff events, combining retention efficiencies for disparate measurements was not possible. A qualitative assessment, based on professional judgement and research findings, was used to assign effectiveness ratings in these cases. Support for these determinations is provided in the results and discussion section.

BMP effectiveness for the geomorphology stressor was assessed through a modified version of the efficiency-based rating method. Geomorphology results from interactions between local-scale conditions within a stream reach and is described in Fanelli et al. (2022) by a range of metrics. Many of these metrics are measures of in-stream habitat quality, such as riffle quality. Geomorphology is also driven by at least two proxy stressors, flow and sediment delivery. Because flow was addressed through a separate stressor, geomorphology was partitioned into a habitat component and a sediment component. Habitat can be affected through direct physical modification. Since the only BMP assessed capable of such direct modification was stream restoration, all BMPs except stream restoration were assigned an efficiency of zero for the habitat component. Stream restoration was assessed qualitatively for the habitat stressor. BMP capacity to improve the sediment component focused on sediment removal efficiency as a proxy process. It should be noted that there is interaction between the two geomorphology sub-components. For example, sediment delivery to a stream reach affects fine sediment deposition within that reach.

A further distinction was necessary because a relatively small portion of total sediment load delivered to stream reaches is from upland sources, where all BMPs except stream restoration are implemented. Cashman et al. (2018) found only 2% of bed sediment and 9% of suspended sediment originated from upland sources in an urban/suburban watershed. Gellis and Gorman Sanisaca (2018) found a higher, but still minor, 24-30% of suspended sediment to have originated from upland sources in an agricultural and forested watershed. Most sediment in both studies was from stream bank erosion. Noe et al. (2020) provided a summary of studies conducted in eight different watersheds within the Chesapeake Bay watershed, in which the sources of sediment are apportioned between upland and in-stream sources. Using this data, a method to weight BMP effectiveness for sediment removal was developed to account for the sources of sediment. For BMPs in the urban sector, weights of 0.26 and 0.75 were used to modify the sediment removal efficiencies assigned to each BMP for upland and in-stream sources, respectively. This reflects analysis of the data from Noe et al. (2020) showing 26% of sediment on average originated from upland sources in urban watersheds and 75% originated from bank erosion. The weights used for agricultural settings were 0.42 and 0.53 for upland and in-stream sediment sources, respectively. BMP efficiencies for sediment removal from in-stream sources were summarized from data obtained from literature reviewed and for upland sources the sediment efficiencies assigned to BMPs in the CAST database were utilized. These efficiencies were multiplied by the corresponding weights to obtain a weighted efficiency for sediment removal, which was used to assign an effectiveness rating, as described above, for the sediment component of the geomorphology stressor.

Measures of Efficiency

The papers combined in this study measured or reported efficiency using a variety of metrics or measures. To combine data from these various methodologies, efficiency (measured as a percent), was used as the measure of success, since it can be used as a common measure across multiple study types, and was calculated using the following equation:

$$E = \frac{(B - A)}{B} X100$$

Where:

E	=	Efficiency (%)
B	=	Metric measured before the BMP
A	=	Metric measured after the BMP

In this equation, “Before” (B) and “After” (A) can have different meanings depending on the data reported for a particular study:

- Some studies evaluate loads or concentrations using a pre-post calculation, so that the efficiency is calculated by calculating the difference in load or concentration before the BMP is installed versus after it is installed.
- For other studies, loads or concentrations are compared to a control condition (without BMPs installed). For example, Conservation Tillage practices are often compared to a plot without these practices in place. In these studies, B is equal to the Control condition, while A is equal to the Treatment condition (practice in place).
- Most urban stormwater BMPs (e.g., bioinfiltration) report an “In” versus “Out” measure, either measured as a concentration or load. In these cases, B is the value entering the and A is the value exiting the BMP.
- Finally, some studies (particularly literature reviews), reported a single efficiency value. In these cases, the reported efficiency is used, regardless of the specific method used to arrive at this efficiency, effectively assigning 100% to the value for B and (100-E)% to the value of A.

Lumping of Units, Fine Stressors and Fine BMPs

The studies included in the database presented different measures, both in terms of the stressor parameters measured and the units (mass load, concentration, or loading rate). The median values and statistical measures reported in the results lump all of these measures together, with the result that:

- Values reported are the median across all BMP types within a coarse BMP category (e.g., “Wet Ponds and Wetlands” does not distinguish between wet ponds and wetlands nor the specific design variations within them).
- All possible metrics within a stressor are combined (e.g., “flow” represents the median efficiency at reducing both peak flows and runoff volume).
- Mass-, concentration- and loading rate-based measures of efficiency are combined to calculate a single efficiency.

Number of Points Recorded Per Paper

While only 47 papers were included in the Quantitative analysis, 300 data points were used to evaluate practice efficiency. These data points were derived as follows:

- For papers that studied multiple individual practices, efficiencies were recorded for each practice.
- For modeling studies that evaluated multiple practice options or configurations, each option was recorded separately.
- For review papers, values from each paper contributing to the review was evaluated as an individual data point.
- One review paper (Zhang et al., 2010), reported a median efficiency value from 49 studies, and also included box plots representing the 10^{th}, 25^{th}, 75^{th} and 95^{th} percentile values. For this study, 49 individual values were included in the analysis, interpolating these values to represent 49 values from the 2^{nd} to the 98^{th} percentile.
- Another review paper (Vymazal and Brezinová 2015) reported 12 efficiency values from 47 papers, with each value representing the efficiency for a different pesticide group. Each of these 12 values was included in the database.

Measure of Central Tendency and Weighting

The data that characterized each BMP efficiency was in general not normal or quite sparse. Consequently, the median (rather than the mean) value was used as an estimate of efficiency for each practice-stressor combination. In addition, both feedback from the TAG and a review of the data in the database suggested that these values should be weighted to reflect the study type, and the number of data points that informed each value in the database.

To incorporate TAG feedback regarding field versus modeling studies, we assigned weights using best professional judgement:

- 1.0 was assigned to field studies, or to values derived from review papers.
- 0.5 was assigned to modeling studies; and
- 0.75 was assigned to studies classified as “Mesocosm” (essentially laboratory studies).

In general, review papers were more heavily weighted by reporting the values from each contributing study separately, where available. In Vymazal and Brezinová (2015) the removal values from individual studies were not reported. As described above, the estimated median efficiency for each of 12 pesticide groups was reported, as was the number of values used to estimate these efficiencies. Consequently, each of these 12 estimates were weighted by the number of studies used to develop them.

Methods for Confidence Intervals

Since weighted median values do not follow a specific distribution, a different method was needed to define confidence intervals for this estimate. Consequently, we used “bootstrapping” methods, which estimate the variability by resampling and calculating the value multiple times (effectively simulating an experiment of sampling from the same data but drawing different values). Confidence intervals and weighted medians were calculated for data sets with at least three data points using the methods described in (Davidson and Hinkley 1997) and the R package “boot” (https://cran.r-project.org/web/packages/boot/boot.pdf).

Results & Discussion

BMP-Stressor Effectiveness Ratings

The priority stressors and BMPs are presented in a matrix to highlight the intersections between the stressors and the BMPs that were included in this study (Figure 3). The BMPs were grouped into coarse groupings for ease of presenting the results and to facilitate analysis. Figure 4 summarizes the effectiveness of each stressor-BMP combination.

At least two BMPs were found to be highly effective for each stressor, except for salinity. All BMPs were determined to have low effectiveness for salinity. Wet ponds/wetlands are one of the most effective urban BMPs, with high effectiveness for other toxics and pesticides, and medium effectiveness for flow. Bioinfiltration is another broadly effective urban BMP, with highly effective ratings for other toxics, flow, and pesticides. Urban stream restoration was the only BMP rated highly effective for geomorphology, with respect to both habitat and sediment components. In the agricultural setting, vegetated buffers and wetlands showed high capacity and agriculture drainage management showed medium capacity to address pesticides. Agricultural stream restoration was again the only BMP to be rated highly effective for geomorphology, though the sediment component received only a medium rating.

It should be noted that studies included in this review generally evaluated BMPs at the practice scale for improving one or more stressors. While BMP effectiveness at the practice scale may translate into stressor improvements at the catchment scale, there is a limit to the extent, placement, and capacity of BMPs and the area, or loading, they can manage. For example, Hopkins et al. (2007) found distributed BMPs resulted in lower runoff and maximum specific discharge than centralized BMPs at a watershed scale for small events, but runoff response was more similar for larger events, which likely exceeded BMP design storms. BMP design is an important factor and variations can result in a range of effectiveness. For example, full infiltration bioinfiltration practices were more effective when compared to those with underdrains. Some generalization and coarsening of BMP groupings was necessary for this evaluation.

BMP Type			Stressors Important to Stream Health					
Setting	**Coarse BMP Groups**	**Fine BMP Groups**	Other Toxics	Flow	Salinity	Pesticides	Geomorphology	
							Habitat	Sediment
Urban	Wetponds & Wetlands	Wet Ponds & Wetlands						
		Floating Treatment Wetlands						
	Dry Ponds	Dry Ponds						
		Extended Dry Ponds						
	Bioinfiltration	Infiltration Practices						
		Filtering Practices						
		BioRetention						
		BioSwale						
		Vegetated Open Channel						
	Urban Forest Buffers	Urban Forest Buffers						
	Urban Tree Planting	Urban Tree Planting						
		Urban Forest Planting						
	Urban Stream Restoration	Urban Stream Restoration						
Agricultural	No Till & Cover Crops	Conservation Tillage	Not key stressors in agricultural settings					
		High Residue Tillage						
		Low Residue Tillage						
		Cover Crop						
		Cover Crop with Fall Nutrients						
		Commodity Cover Crop						
	Pasture Management	Pasture Alternative Watering						
		Prescribed Grazing						
		Horse Pasture Management						
		Forest Buffers on Fenced Pasture Corridor						
		Grass Buffers on Fenced Pasture Corridor						
	Vegetated Buffers	Forest Buffers						
		Grass Buffers						
	Agricultural Drainage Management	Agricultural Drainage Management						
		Barnyard Runoff Control + Loafing Lot Management						
	Agricultural Stream Restoration	Non Urban Stream Restoration						
	Wetlands	Wetland Restoration						
		Wetland Creation						
		Wetland Enhancement and Rehabilitation						

Figure 3. BMPs and stressors selected for inclusion in the present study. Greyed-out intersections were excluded from the study.

BMP Type		Stressors Important to Stream Health					
						Geomorphology	
Setting	**BMP Name**	Other Toxics	Flow	Salinity	Pesticides	Habitat	Sediment
Urban	Wet Ponds and Wetlands	high	medium	low	high	low	medium
	Dry Ponds	medium	medium	low	low	low	low
	Bioinfiltration	high	high	low	high	low	medium
	Urban Forest Buffers	medium	low	low	medium	low	low
	Urban Tree Planting		high	low		low	low
	Urban Stream Restoration			low		high	high
Agricultural	No Till and Cover Crops	Not key stressors in agricultural settings			low	low	low
	Pasture Management				low	low	low
	Vegetated Buffers				high	low	medium
	Agricultural Drainage Management				medium	low	low
	Agricultural Stream Restoration					high	high
	Wetlands				high	low	low

Legend

Effectiveness

high

medium

low

Figure 4. Effectiveness[1] ratings for each BMP and stressor intersection assessed.

[1] A detailed explanation of how the effectiveness ratings (high, medium, and low) were assigned and the thresholds for efficiency that define them can be found in the Methods section of the report under Data Analysis. Efficiency values are found in Tables 2 & 3.

Other Toxics, Flow, and Pesticides

Table 1 summarizes the results of stressor-BMP combinations where quantitative data were available for other toxics, flow, and pesticides. Except for no-till agriculture, all estimates of removal included positive values, with several BMPs showing median removals of greater than 80% for other toxics and pesticides. In particular, wet ponds/wetlands and bioinfiltration in the urban sector appear to be highly effective at removing other toxics and pesticides, while agricultural wetlands and vegetated buffers have high removal rates for pesticides. As expected, dry ponds have relatively poor pollutant removal compared with other urban BMPs.

Since sediment is a vector for pesticides and other toxic contaminants (e.g., PAHs, organic compounds), sediment removal is one of the most effective mechanisms for reducing other toxics and pesticide stressors to stream health (Noe et al. 2020; Hwang and Foster 2006). Sediment-associated contaminants are effectively trapped in sediment-removing BMPs (e.g., vegetated buffers, wet ponds and wetlands, and bioinfiltration). The retained toxics are not "removed" equally, however, in all BMPs. PAH concentrations were consistently high in the sediments of urban wet ponds but were found to undergo nearly complete mineralization in bioinfiltration (LeFevre et al. 2012).

Runoff reduction, primarily through infiltration, was also found to be a highly effective mechanism for improving other toxics and pesticides because of the role of runoff in transporting pollutants to surface water. In this literature review, infiltration of runoff and associated pollutants was considered as a removal of the stressor from the system. This allowed for analysis and comparison across BMPs but constitutes a simplification of the effectiveness to only the water impacts due to overland runoff into streams. The full implications of BMPs on stream health from subsurface flows were not evaluated.

Alternative wet ponds and wetlands, bioinfiltration, and tree planting appear to reduce flow, but our methodology lumped several measures of flow and compared these data using percent reduction as the common metric. A more in-depth literature review could analyze these effects in more detail to pull out some of the nuance between flow metrics. The number of data points for wet ponds and wetlands and dry ponds was also extremely limited.

Data richness is highly variable between BMP-Stressor groups, with only one or two data points for many combinations (Table 1). Agricultural wetlands and vegetated buffers are characterized by large datasets that suggest very high pollutant removals. The authors of this report are very confident that these BMPs are highly effective at removing pesticides. Many of the BMPs, however, were represented by a very low number (3 or fewer) of data points. Although the values reported from these studies were used to characterize pollutant removal, it should be noted that we are not able to characterize how variable the reported results would be if other studies were evaluated. Consequently, we are less confident in efficiencies reported for flow stressor impacts from dry ponds and wet ponds and wetlands; other toxics stressor impacts from urban forest buffers; and pesticide stressor impacts from dry ponds, pasture management, urban forest buffers, and wet ponds and wetlands.

The data distributions are generally not normally distributed for BMP-Stressor combinations with a large number of data points. Figure 5 shows the distribution of removal efficiencies for all coarse BMPs except no-till and cover crops related to the flow, other toxics, and pesticides stressors. As indicated in Figure 5, data for toxics and pesticides is left-skewed for vegetated buffers and wetlands, with the highest concentration at points concentrated near 100% removal. Several other BMP-stressor intersections have relatively high numbers of data points and clustered efficiencies around a median value or towards 100%. The authors are confident in the effectiveness assigned based on the available data for these BMP-stressor intersections. These include wet ponds and wetlands and other toxics, bioinfiltration and other toxics, bioinfiltration and flow, agricultural drainage management and pesticides. The distribution for no-till and cover crops is displayed separately in Figure 6, as the range of efficiencies extends from -800% to almost 100%. Efficiencies for this practice were calculated based on percent mass lost, mass load, or mass loading rates (Mass/Area), where extremely negative values resulted from higher export of applied pesticides from conservation tillage or no-till practices than for conventional-tilled control plots. Although the median removal for this BMP is moderate, the wide range is evidence of extreme variability. Due to this variability and the potential for worsening the pesticide stressor, the authors' applied our professional judgement in assigning no-till and cover crops a low effectiveness rating. This stressor-BMP combination could possibly be better characterized with more information about the effects of specific tillage types, storms experienced in each study, and effects of pesticide type. A more accurate characterization of the effectiveness of no-till and cover crop practices on the toxics and pesticides stressor might result from separating the no-till and cover crop BMPs into separate categories, if possible.

Insufficient research was available to determine the effectiveness of stream restoration on other toxics and pesticides. Stream restoration has shown successful improvement to flow regimes through floodplain reconnection and increased channel complexity. For example, Langland et al. (2020) showed additional storage of 10,000 cubic meters was made available following a stream restoration project. Thompson et al. (2018) examined the effects from a regenerative stormwater conveyance (RSC) restoration designed to increase the residence time of water. After restoration, runoff reduction was observed as flows were being sustained for longer periods at the inlet than at the outlet. Pool habitat and channel complexity improvements observed by Larson et al. (2001) and created by additions of large woody debris (LWD) had positive effects on flow conditions. Bukaveckas et al. (2007) observed positive impacts on water velocity and transient storage through improved physical conditions within streams. No effectiveness rating was assigned to the flow stressor, however, because the long-term sustainability of these flow improvements was not sufficiently demonstrated in the literature reviewed. Watershed hydrology, particularly storm events, was shown to be the major structuring force in streams (Violin et al. 2011). For example, Larson et al. (2001) found that watershed conditions and their influence on physical channel response via flow regime in many cases overwhelmed any potential benefits of LWD additions. Because of the high potential for the flow stressor itself to undo the very stream restoration components responsible for flow improvements, it was deemed too uncertain to assign an effectiveness rating.

Table 1. Quantitative data showing removal efficiency for BMPs to reduce stressors.

Coarse Stressor	Coarse BMP	Number of Data Points	Average Weight	Median (%)	Lower Estimate (%)	Upper Estimate (%)	Notes
Flow	Bioinfiltration	30	0.95	86.0	75.0	91.0	For these stressor-BMP combinations, the lower and upper estimates represent 90th percentile confidence intervals using bootstrapping techniques.
	Urban Forest Buffers	6	0.5	7.0	4.6	8.8	
	Urban Tree Planting	10	0.90	57.0	36.9	68.2	
Other Toxics	Bioinfiltration	13	0.79	87.8	73.5	92.7	
	Dry Ponds	4	1.0	16.0	13.0	34.0	
	Wet Ponds and Wetlands	12	1.0	58.0	50.0	63.0	
Pesticides	Ag Drainage Management	17	0.65	40.9	30.5	55.0	
	Bioinfiltration	4	0.75	46.0	22.0	72.5	
	No-Till and Cover Crops	38	0.99	51.5	-4.1	61.4	
	Vegetated Buffers	123	0.96	85.7	78.0	89.7	
	Wetlands	40	1.9	83.2	57.5	93.4	
Flow	Dry Ponds	2	0.75	22.2	0.3	44.0	These studies have very low n-values, so that the lower and upper values represent the minimum/maxim recorded, except that none are reported for n=1
	Wet Ponds and Wetlands	1	1.0	44.0	N/A	N/A	
Other Toxics	Urban Forest Buffers	1	1.0	40.0	N/A	N/A	
Pesticides	Dry Ponds	1	1.0	12.0	N/A	N/A	
	Pasture Management	1	1.0	10.0	N/A	N/A	
	Urban Forest Buffers	1	1.0	25.0	N/A	N/A	
	Wet Ponds and Wetlands	3	1.0	54.0	51.0	60.0	

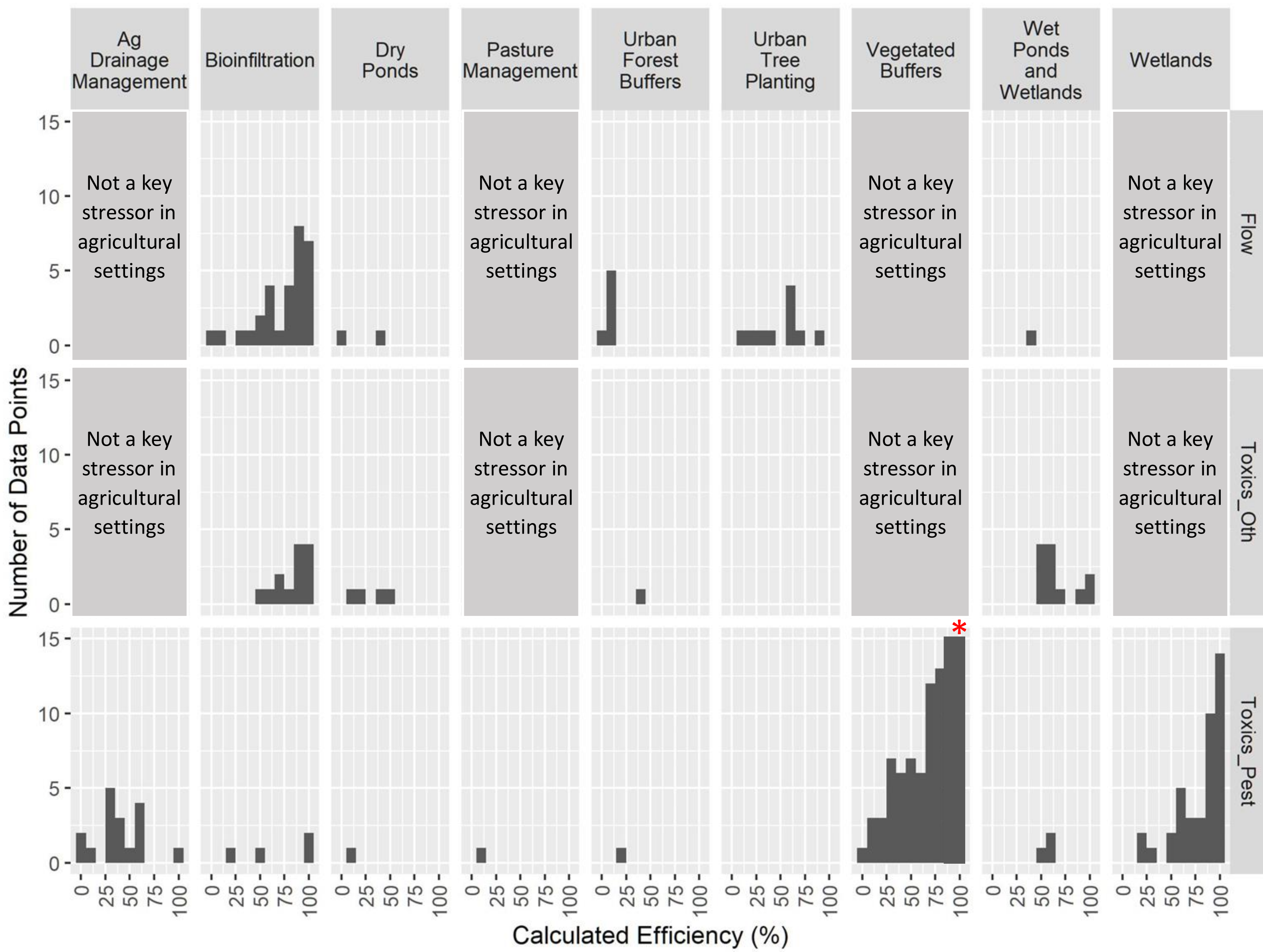

Figure 5. Histograms for all coarse BMPs except No-Till and Cover Crops and three stressors (Flow, Other Toxics, and Pesticides). (indicates 35 data points not shown for the 95-100% bins.)*

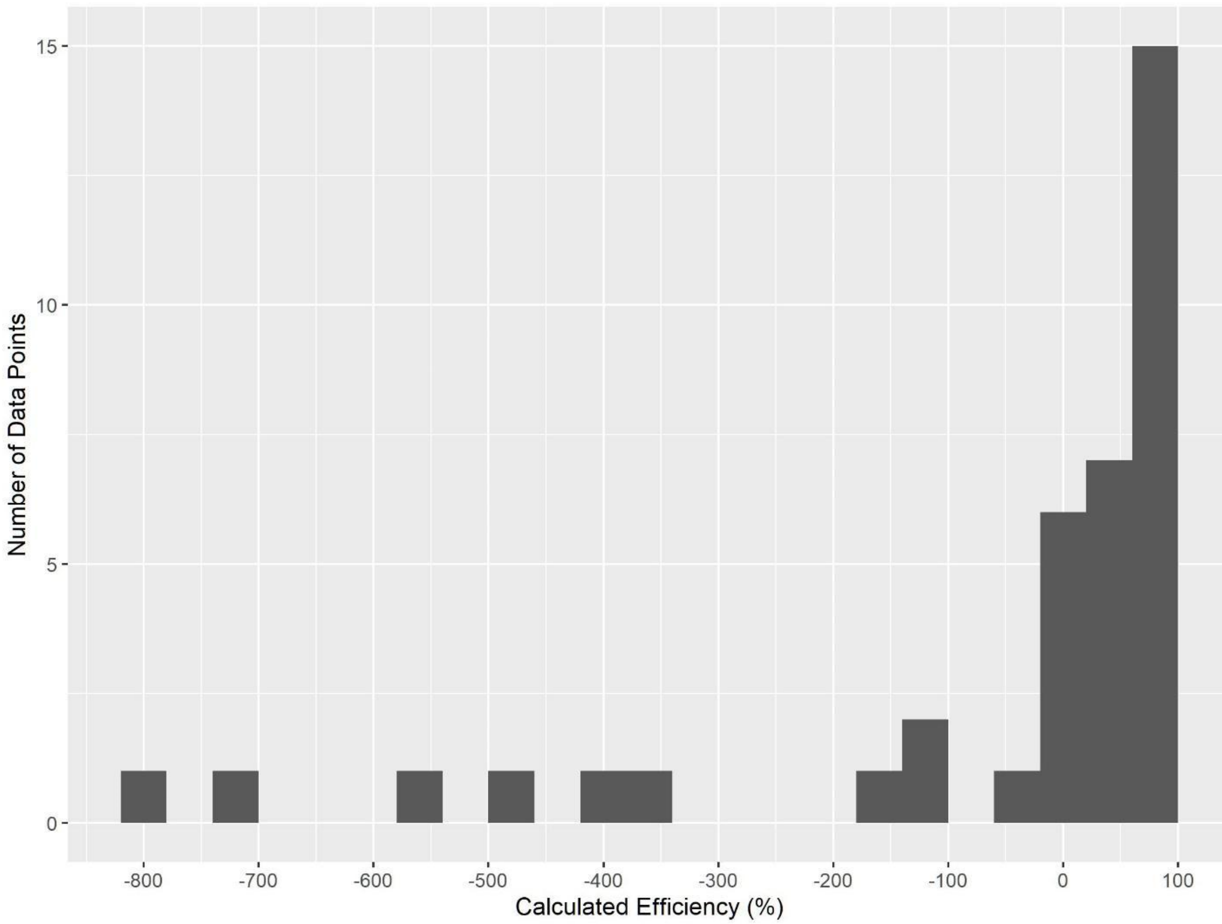

Figure 6. Histogram for No-Till and Cover Crops and the Pesticides stressor

Salinity

All BMPs included in this study were evaluated to have low effectiveness for reducing salinity in streams. This determination is based on analysis of multiple studies in which BMPs demonstrated variations of three phenomena. First, salinity in detained runoff volumes or in soil, sediments, or filter media was observed to be flushed out over longer temporal scales. Second, where BMPs removed salts from surface runoff via infiltration, the infiltrated salts were shown to migrate to streams via shallow groundwater. Third, retention of some salt ions (e.g., Na^{+}) resulted in mobilization of others (e.g., Ca^{2+} and Mg^{2+}) through ion exchange or increased solubility.

Re-release of captured salts occurred, in some cases, slowly over extended temporal scales or as high-salinity pulses in subsequent flushes, depending on BMP hydraulics. For example, Semadeni-Davies (2005), in a study of urban wet ponds, reported up to 80% of Cl^{-} retained by the pond. Continuous conductivity measurements showed, however, that Cl^{-} levels remained elevated in the outflow during the hydrograph tail or was exported from the pond during low-salinity runoff events. Denser saline water sinks to the bottom of stormwater ponds, where the highly soluble salts can be easily remobilized and serve as long-term stores of salinity (Marsalek 2003). Kozlowski (1997) and Bryson and Barker (2002) documented road salt spray accumulating on plants near roadways. This retention, however, was temporary and detrimental to the plants.

Salts were also found to be temporarily stored in shallow groundwater and migrate to streams over longer temporal scales (Marsalek 2003). Casey et al. (2013) found that Cl^- concentrations in dry and wet ponds and adjacent groundwater were regularly above 250 mg/L, which was correlated with elevated salinity in receiving streams. The study suggested that stormwater ponds were the dominant source of salinity in shallow groundwater. Due to the time lag in delivery of groundwater to streams, the ponds served as year-round sources of elevated Cl^- in stream baseflow. This agrees with previous results from groundwater and stream monitoring showing persistent effects from road salts (Kelly et al. 2008; Ostendorf et al. 2009; Cooper et al. 2014).

Where salt ions are retained in soil or filter media, ion exchange and increased solubility may offset potential gains. Cooper et al. (2014) monitored salinity at multiple points along a restored urban stream, including above, below, and within restored sections. The authors do not make any conclusions regarding overall salt retention within the restored streams, however, using monitoring within stream banks they showed possible effects of floodplain reconnection where Na^+ and Cl^- may be retained when interactions with soil are enabled. This retention, however, was associated with increased mobilization of Ca^{2+} and Mg^{2+} ions. This ion exchange process and resulting export of Ca^{2+} and Mg^{2+} has been previously observed in stream monitoring studies (Shanley 1994; Mason et al. 1999). Kakuturu and Clark (2015) showed that bioinfiltration filter media can retain Na+, when subjected to NaCl-laden runoff. Soil Na^+ increased by 555% and 3,321% following application of runoff to bioinfiltration field sites at 150 mg/L and 1,200 mg/L NaCl, respectively. This came at the expense of K, Ca, Mg, organic matter, P, S, total N, total C, and Zn retention, all of which were flushed from the media as Na^+ displaced these constituents through ion exchange. Complexation of ions as dissolved ligands with Cl^- also increases mobilization of metals and toxic compounds, as observed by Mayer et al. (2008). These and associated mechanisms can lead to release of what Kaushal et al. (2019) has termed “chemical cocktails,” or suites of metals, toxics, and other retained stormwater constituents because of elevated salinity in stormwater and freshwaters.

The cumulative effect of these phenomena is a general trend toward limited detention of salinity with some reduction of high salinity peaks during periods of road salt use followed by extended periods of elevated salinity, and additional mobilized constituents, reaching streams. It is beyond the scope of the present study to determine if high-salinity events or prolonged elevated salt levels is more detrimental to stream health or if Na^+ or Cl^- reductions coupled with mobilization of other salts, not to mention chemical cocktails, constitutes a net positive effect. It is clear, however, that calculating a single efficiency value based on the data does not provide clarity. The low effectiveness values were, therefore, assigned based on the assessment that the BMPs have capacity to alter the salinity stressor, but evidence was insufficient to demonstrate a clear effectiveness to improve the stressor.

Geomorphology

Urban and agricultural stream restoration were determined to be the only BMPs with high effectiveness for geomorphology. Urban stream restoration received a high rating for the habitat and sediment components of geomorphology, while agricultural stream restoration received high and medium ratings for habitat and sediment, respectively. Stream restoration is the only BMP capable of directly affecting the habitat component of geomorphology because it is the only BMP implemented within the stream. It is also the only BMP with capacity to affect in-stream sources of sediment. Wet ponds and wetlands, bioinfiltration, pasture management, and vegetated buffers were rated as medium effective for sediment due to their efficiency at reducing sediment transport to streams from upland sources.

Due to the inability to directly affect geomorphology-habitat, all BMPs except urban and agricultural stream restoration were deemed to have low effectiveness for this stressor sub-component. Stream restoration was assigned an effectiveness rating based on a qualitative assessment of the literature. The diversity of approaches and methods of assessment were so broad that quantitative comparison of metrics and attempts to merge disparate data into a single efficiency masked complexity. For example, stream restoration approaches targeted at improving channel stability may not improve riffle quality. The discussion of geomorphology stressors and improvements from the literature highlighted the importance of the chosen restoration type for the degraded stream reach. For example, Larson et al. (2001) found addition of large woody debris increased pool habitat and channel complexity, both measures of geomorphology-habitat, but did not result in improved sediment retention. In Gothe et al. (2016), regression analyses strongly suggested that the type of restoration measure applied was a more important determinant of restoration outcomes than restoration extent. Lumping results for different metrics into a single efficiency value, therefore, did not accurately describe the efficacy of stream restoration.

Despite this, there was adequate support in the literature for high efficacy of stream restoration to improve geomorphology-habitat when considering the restoration goal. Gothe et al. (2016) observed increased plant species and trait diversity following stream restoration. Many of the biological indices used showed significant responses to measures affecting connectivity with the floodplain, especially, projects aiming to widen the stream channel. This was indicative of new habitat creation and increased habitat variability (e.g., through temporary flooding). Bukaveckas et al. (2007) measured dispersion values that suggested the flow conditions within a restored channel had greater complexity after restoration. Larson et al. (2001) found that adding LWD improved physical conditions and increased the number of pools in a reach. Bain et al. (2014) observed floodplain reconnection and removal of pollutant sources and obstructions to fish passage resulted in improvements to fish and macroinvertebrate populations.

It should be noted, however, that while many studies found improved habitat conditions, others noted lower than expected improvements. For example, Kasse et al. (2012) found that the stream restoration projects studied did not resemble reference conditions. They suggest that that the stream restoration may not be a failure but may be indicative of the creation of a “novel anthropogenic ecosystem.” Such results highlight the motivation for the present study, that is, the importance of multiple stressors to stream health and a need to address multiple key stressors to achieve restoration success. While Kasse et al. (2012) and others conjecture that restored sites may become more similar to reference conditions as restored stream reaches mature, Violin et al. (2011) caution that habitat improvements may actually decrease over time if stressors driving degradation, particularly flow, are not mitigated. Much of the literature about urban stream restoration also emphasizes that the restoration effort is not likely to succeed if the goal of the restoration is not addressing the causes of the system’s degradation.

The second component of geomorphology, sediment, was evaluated using a weighted efficiency accounting for in-stream and upland sediment sources (Table 2). All BMPs except urban and agricultural stream restoration were assigned an efficiency of zero for in-stream sediment because they are implemented at upland locations and therefore incapable of directly affecting in-stream sediment. The efficiency of stream restoration for in-stream sediment reduction is based on measurements by Langland et al. (2020) which calculated an 85% reduction in sediment load following legacy sediment removal in a stream restoration. Further data from additional literature sources may be available and are needed to improve confidence in this value.

For upland sources, multiple urban BMPs showed high efficiencies including wet ponds and wetlands, bioinfiltration, and urban forest buffers. Vegetated buffers had the highest efficiency for upland sediment in the agricultural setting, followed by pasture management. The impact of these efficiencies was diluted, however, by the upland sediment source weighting factor, particularly in the urban setting, where a weight of 0.26 was applied. The total sediment efficiency was highest for urban and agricultural stream restoration, at 64 and 45%, respectively. The higher total efficiency for stream restoration in the urban setting was due to the relatively higher importance of in-stream sediment sources in that setting. In the agricultural setting, upland sediment was assigned a weight of 0.42 based on analysis of data from Noe et al. (2020). These results align with Gregoire et al.'s (2009) statement that "while one [BMP] may show great potential for pollutant removal, its potential to impact overall pollutant loading may be very limited."

Table 2. Sediment removal efficiencies and weighting factors used to determine BMP effectiveness ratings for geomorphology-sediment.

		Total	Upland		In-Stream	
Setting	**BMP Name**	**Efficiency (%)[1]**	**Efficiency (%)[2,7]**	**Weight[3]**	**Efficiency (%)[4,7]**	**Weight[3]**
Urban	Wet Ponds and Wetlands	17	66	0.26	0	0.75
	Dry Ponds	9	35	0.26	0	0.75
	Bioinfiltration	21	82	0.26	0	0.75
	Urban Forest Buffers	13	50	0.26	0	0.75
	Urban Tree Planting	2	6	0.26	0	0.75
	Urban Stream Restoration	64	0	0.26	85[5]	0.75
Agricultural	No Till and Cover Crops	2	6	0.42	0	0.53
	Pasture Management	15	37	0.42	0	0.53
	Vegetated Buffers	22	51	0.42	0	0.53
	Agricultural Drainage Management	9	22	0.42	0	0.53
	Agricultural Stream Restoration	45	0	0.42	85[6]	0.53
	Wetlands	6	15	0.42	0	0.53

[1] Total Efficiency = Upland Efficiency x Weight + In-Stream Efficiency x Weight

[2] Calculated as the mean of efficiencies for each BMP type in CAST.

[3] Weighting by portion of total sediment load to streams from upland or in-stream sources. Based on data from Noe et al. (2020). Weights do not sum to 1 due to sediment from other sources (e.g., forest).

[4] Calculated as the median of efficiencies from literature data sources.

[5] n= 1

[6] n= 1

[7] Zero values indicate no potential to affect sediment source.

BMP Detailed Discussions

Urban & Suburban BMPs

Wet Ponds and Wetlands

A wet pond and/or wetland under this category is defined as a water impoundment structure that intercepts stormwater runoff then releases it to an open water system at a specified flow rate (CBP 2020). These structures retain a permanent pool and usually have retention times sufficient to allow settlement of some portion of the intercepted sediments and attached nutrients/toxics. There is little or no vegetation living within the pooled area, except for ponds equipped with floating treatment wetlands (FTWs).

Effectiveness & Treatment Mechanisms

Pesticides and Other Toxics

Page et al. (2010) conducted a study of a stormwater reuse wetland, with steady flows from a large holding tank that receives diverted stormwater. Consequently, the flows to this system were relatively constant compared with typical stormwater wetlands. All removals were significant. There was an almost 50% reduction in diuron, and approximately 60% of atrazine and triazine were removed before outflow to a waterbody.

Crane et al. (2014) used environmental forensics techniques to determine sources of polycyclic aromatic hydrocarbons (PAHs) in the bed sediments of 15 stormwater ponds. Multiple samples of the upper 15 cm of sediment were collected from each pond. Samples were analyzed for total organic carbon (TOC), black carbon, particle size, a suite of 34 PAHs – a set of 18 parent and 16 alkylated PAHs, and other chemical parameters (Crane et al. 2014). They found that CT-sealants comprised the major source of PAHs – in the 15 stormwater ponds studied – followed by vehicle emissions, and wood combustion. Log ΣPAH34 showed a significant correlation with black carbon which increases the sorption of PAHs, and this sorption can affect the bioavailability and toxicity of PAHs in stormwater ponds. Another study examined three wet ponds with enhancements such as planted sand filters at the outflow, aluminum salts dosing, or iron enhanced sediment (Istenic et al. 2011). The enhancements resulted in an ~100% concentration reduction for total of 15 PAHs.

Flow

Few studies were found on the effect of urban wet ponds and wetlands on flow. Where wetlands are employed to intercept runoff en route to streams, runoff volume reduction is minimal. As wetlands are defined by a stable water balance, the flashy nature of urban runoff can be detrimental to wetland structure – scour and plant failure can result (Mitsch and Wilson 1996). The single study found on stormwater wetland hydrology, Pennino et al. (2016), found shallow marsh wetlands to be significantly correlated with peak runoff and calculated an overall peak runoff reduction of 44% for a watershed with dense BMP implementation, including marsh wetlands, as compared to a traditionally developed watershed.

Treatment Mechanisms

1. Sedimentation
2. Adsorption
3. Plant Uptake

4. Biodegradation/Volatilization

Other Management Strategies, Research Gaps, and Potential for Future Studies

Real-time control of wet ponds and wetlands holds potential for reducing stressors to stream health beyond those found from traditional designs and should be further explored (Kerkez et al. 2016; Vijayaraghavan et al. 2021).

BMP Name	Other Toxics	Flow	Salinity	Pesticides	Geomorphology	
					Habitat	Sediment
Wet Ponds and Wetlands	★	⯪	☆	★	☆	⯪

Figure 7. Effectiveness ratings for wet ponds and wetlands and each stressor intersection. See Figure 4 for Legend.

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Dry Ponds

Dry ponds, or dry detention basins, are depressions created by excavation or berm construction that temporarily store runoff and release it slowly via surface flow or groundwater infiltration following storms (CBP 2020). Dry detention basins are designed to dry out between storm events, in contrast with wet ponds, which contain standing water permanently. Dry ponds often include hydrodynamic structures, which are devices designed to improve quality of stormwater using features such as swirl concentrators, grit chambers, oil barriers, baffles, micropools, and absorbent pads that are designed to remove sediments, nutrients, metals, organic chemicals, or oil and grease from urban runoff (CBP 2020).

Effectiveness & Treatment Mechanisms

Salinity

Dry pond BMPs showed very little effectiveness in mitigating the salinity stressor. Stormwater pond surface and ground waters had some of the highest specific conductance values and chloride concentrations in the literature reviewed. Dry ponds seemed to serve as road salt hotpots in suburban and urban landscapes and acted as a year-round source of chloride to adjacent groundwater and surface water resources (Casey et al. 2013). Mayer et al. (2008) evaluated the increasing salinity trend in a restored stream where chronic salinity levels may have been high enough to damage vegetation and salinity peaks potentially impacted other in-stream biota. The restoration reconnected the stream to the floodplain, hyporheic, and groundwater flow paths, which can affect pollutant attenuation (Mayer et al. 2008).

Pesticides and Other Toxics

Crabtree et al. (2006) monitored influent and effluent of highway runoff stormwater ponds (2 wet and 1 dry). They found low PAH concentrations in the highway runoff. All ponds had some sort of oil pretreatment devices, but all were shown to achieve minimal PAH removal. Excluding the effects of the oil separator, the dry pond had a 16% removal efficiency for PAHs (Crabtree et al. 2006). A relationship exists between treatment efficiency of pollutants attached to suspended sediments and the retention time of highway runoff within the drainage device/system. Another study’s findings suggest that dry ponds are less effective given the pesticide degradation/transformation and subsequent export of degradation products indicative of minimal retention of pesticides by the BMP (Sebastian et al. 2014).

Flow

Two studies reviewed analyzed the effects of implemented BMPs on stormwater runoff flows. Pennino et al. (2016) analyzed the effect of stormwater BMP prevalence on flow and nutrient metrics in streams as measured at stream gauges. This analysis calculated an overall watershed effect of 44% peak runoff reduction because of BMP, and dry ponds were found to be significantly correlated with peak runoff.

Emerson et al. (2005) manually surveyed 82 detention ponds included in their model of valley creek watershed (Philadelphia, PA) with and without detention ponds. Their model predicted 0.3% peak flow reduction with dry ponds compared to no dry ponds. Emerson et al.’s (2005) study showed that attenuation of peak flows through a single dry pond may not result in watershed scale flow reduction because the cumulative watershed runoff remained essentially unchanged, with high flows through the detention ponds delayed and prolonged.

Treatment Mechanisms

1. Flow attenuation

2. Sedimentation

Other Management Strategies, Research Gaps, and Potential for Future Studies
Real-time control of dry ponds holds potential for reducing stressors to stream health beyond those found from traditional designs and should be further explored (Kerkez et al. 2016; Vijayaraghavan et al. 2021).

BMP Name	Other Toxics	Flow	Salinity	Pesticides	Geomorphology	
					Habitat	Sediment
Dry Ponds	⯪	⯪	☆	☆	☆	☆

Figure 8. Effectiveness ratings for dry ponds and each stressor intersection. See Figure 4 for Legend.

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Bioinfiltration

Bioinfiltration BMPs are a category of BMPs typically used in the treatment of stormwater that work to reduce loading to streams through the mechanisms of biological and biochemical reactions, retention, infiltration, and/or filtration. Common BMPs discussed in this section include bioswales, bioretention practices, and infiltration basins.

Bioretention/Raingardens – An excavated pit backfilled with engineered media, topsoil, mulch, and vegetation. These are planting areas installed in shallow basins in which the storm water runoff is temporarily ponded and then treated by filtering through the bed components, and through biological and biochemical reactions within the soil matrix and around the root zones of the plants (CBP 2020). Bioretention practices can be built with or without an underdrain connection which may be a requirement based on the site's soil type.

Bioswale – A bioswale is designed to function as a bioretention with a generally narrow, linear flow configuration.

Infiltration Practices – From CAST an infiltration practice is defined as "a depression to form an infiltration basin where sediment is trapped, and water infiltrates the soil" (CBP 2020). No underdrains are associated with infiltration basins and trenches because these systems provide complete infiltration. CBP design specifications require infiltration basins and trenches to be built in A or B soil types. The BMP can be built with or without sand layers and vegetation.

Filtering Practices – Practices that capture and temporarily store runoff and pass it through a filter bed of either sand or an organic media (CBP 2020). There are various sand filter designs, such as above ground, below ground, and perimeter. An organic media filter uses a medium besides sand to enhance pollutant removal for many compounds due to the increased cation exchange capacity achieved by increasing the organic matter.

Effectiveness & Treatment Mechanisms

Bioretention/raingardens

In a study of small raingardens with a capacity for 1.27 to 2.54 cm of runoff, Dietz and Clause (2005) reported 98.8% of inflow left the garden as subsurface flow, and the rain garden was effective at reducing the peak flow rate and increased the lag time of influent water. A rain garden could be an effective BMP in reducing flow and pollutant loads if an underdrain were not connected to the stormwater system due to the high retention of flow shown in this study.

Burns et al. (2012) modeled the effect of adding non-infiltrating bioretention and infiltrating bioretention to 500 m^2 parcels of forested and developed land use areas in Melbourne, Australia. The best modeled reductions to flow for developed areas used infiltrating bioretention and rainwater harvesting. This combination of BMPs predicted an annual runoff of 14 mm/yr compared to the 436 mm/yr and 456 mm/yr with non-infiltrating bioretention or no bioretention, respectively. Because the bioretention was underdrained and lined for no infiltration, the only loss of water was through evapotranspiration, therefore the effect on annual flow was minor. Much more substantial effect was seen from the infiltrating practices, but this also included a component of rainwater harvest and reuse, which was modeled by just removing that volume from the parcel and is possibly responsible for the largest share of the reduction rather than infiltration through the bioretention

Soil samples collected from 58 raingardens within a catchment area were measured for total petroleum hydrocarbons (TPH) in LeFevre et al.'s (2012) study. All of the samples collected reported less than 3 ug/kg of TPH, which was significantly greater than upland control samples but far below the regulatory level requiring remediation, 10,000 ug/kg. The TPH levels did not correlate with any differences in site conditions (LeFevre et al. 2012). Because TPH is trapped via sorption in bioretention media and then degraded via biodegradation, raingardens serve as sustainable treatment mechanism. This contrasts with retention ponds where Kamalakkannan et al. (2004) found PAH levels in pond sediment of 37.8 to 64.5 mg/kg, showing that while sedimentation of hydrocarbons in wet ponds is an effective mechanism for decreasing loading to streams, there are long term challenges to managing the trapped pollution.

PAHs were examined in sediment cores collected from a bioretention BMP in Diblasi et al.'s (2009) study. Nearly all PAH accumulation occurred in surface sediment and the top layer of media near the runoff entry point. This study also investigated partitioning in the total suspended solids (TSS) and found 74% of PAH in particulate for influent samples and 56% for effluent samples. The percentage of PAHs in particulate form that were high molecular weight (HMW) PAHs was higher than the percentage of HMW PAHs in dissolved form.

Bioswale

One study compared the performance of a pilot filtering swale with a standard swale design for treating zinc, pyrene, phenanthrene, and glyphosate from roof runoff. This study conducted by Fardel et al. (2020) compare pollutant removals by the 2 water quality swale types, to compare the concentration reductions between the overflow and the infiltrated water in the case of the standard swale, and to examine how the inflow pathway influences the removal of the selected micropollutants. The filtering swale – which includes a sand and drainage layer – was more effective at filtering the selected micropollutants (Zn, pyrene, phenanthrene, and glyphosate) out of stormwater runoff compared to a standard swale composed of just one type of soil throughout. The study also found that the directionality of the stormwater inflow into the swale played a role in the BMP's effectiveness. Lateral inflows were more effective for both the standard and filtering swales.

Infiltration Practices

To examine the immediate effect of living trees on the hydraulic conductivity of an infiltration BMP using structural soils, Bartens et al. (2008) conducted two experiments simulating the potential impacts of tree growth in urban subsoil. There was strong evidence that the presence of black oak and red maple trees increased the infiltration rate through the subsoil relative to containers that did not have trees. Trees increased the infiltration rate by an average of 63% when compared to the no-tree containers. For the severely compacted soil treatment, trees increased the infiltration rate by an average of 153%. Infiltration rates did not increase over time for the containers with trees. Decrease in infiltration rate over the course of the experiment was consistent in compaction level 1, in compaction level 2 the decrease was greatest for no-tree followed by red maple, and black oak. For compaction level 2 the difference between tree and no-tree treatments strengthened over time – the presence of tree roots helped maintain infiltration rates (Bartens et al. 2008). The study did not capture the transition time during which the roots grew into the compacted soil (tree establishment). Roots clearly grew throughout the soil profile – showing the potential for tree roots to penetrate compacted soils. Saturated hydraulic conductivity was very low for pots with no trees; all pots with trees drained more rapidly than those without. Trees increased drainage by a factor of 27 on average (Bartens et al. 2008).

BMP age is a concern for infiltration practices. Emerson et al. (2010) examined how an infiltration trench with an artificially accelerated aging process performs over time from a hydrologic and water quality perspective. They found that removal efficiency of TSS was related to the volume of rainfall that was captured on an individual storm basis. The capacity of the storage bed was frequently exceeded during the study, and the tendency to overflow increased as the BMP aged. The authors point out the infiltration BMPs should be designed, constructed, and maintained such that deteriorating processes are balanced by physical processes that can maintain and increase the soil's hydraulic properties relative to infiltration. Small drainage areas and low suspended sediment runoff are recommended for infiltration trench longevity (Emerson et al. 2010).

Another study that takes into account the age of an infiltration BMP on performance, Bork et al. (2021) investigated the influence of preferential flow paths on the transport of biocides for three stormwater infiltration systems (SIS) of different ages (3, 10, and 18 years old). For fungicides/biocides, like diuron or terbutryn, the study reported that the SIS can retain biocides by adsorption when the substances have sufficient contact with the soil matrix, but there is also a decrease in biocide retention capacity in urban SIS due to preferential flow pathways caused by increasing biological activity and changing soil properties after 10 -18 years of operation. This study shows a correlation between SIS age and macropore/preferential flow pathways, which are often a result of macrofauna like ants and worms (Bork et al. 2021). Therefore, the factors supporting higher activity of macrofauna in an SIS may also lead to faster solute breakthrough. The authors recommend regular monitoring of the pollutant retention capacity of SIS to detect its reduction over time, and to avoid biocide groundwater pollution.

Filtering Practices

Hatt et al. (2008) examined hydraulic performance of fine media infiltration practices using different media ranging from sand only to sand and various mixes of organic material and soil amendments. Because it is a lab study the results are not very informative of the effect such practices have on reducing flow to streams (e.g., it only examined the hydraulics of flow through the media with the assumption that all volume passing through the media was infiltrated). However, the study did show the effect of sediment loading and clogging on the surface layer of the fine media, indicating the importance of maintenance and differences in media composition on long-term hydraulic conductivity of the filter media. It also speaks some to the interaction between removing sediment and other pollutants from runoff, thereby reducing pollution to streams, while at the same time reducing the hydraulic conductivity and therefore the flow reduction capacity of the infiltration practice.

Treatment Mechanisms

1. Filtration
2. Infiltration
3. Sedimentation
4. Evapotranspiration
5. Vegetative uptake
6. Microbial activity/respiration
7. Sorption
8. Mineralization/biodegradation
9. Phytoremediation
10. Tree root growth

Other Management Strategies & Research Gaps

Many of the studies reviewed in this report highlight the potential effects of bioinfiltration practices on groundwater. In this literature review, we view the infiltration of any stream health stressor into soil as a removal of the stressor from the system, or as a measure of the BMP's effectiveness. This allows us to simplify the complex system of stream health impacts to address only the surface water impacts due to overland runoff into streams. This does not capture the full effects or impacts of BMPs on stream health from subsurface or groundwater flows that are affected by BMPs. The following highlights key findings from the studies reviewed that address groundwater impacts.

All treatment mechanisms are not created equal, and the ultimate fate of the pollutant being treated must also be considered. For example, a BMP may reduce pesticides as a stressor to streams through infiltration, but we clearly do not want to direct pesticides into the groundwater, and we must also consider shallow groundwater flow dynamics to account for potential subsurface loading from infiltrated pollutants. We cannot consider infiltration (or any other treatment mechanism) as a simple mechanism to make the pollutant go away (Bucheli 1998).

The high metallic load of stormwater sediment is a concern because changes in pH could result in downward migration of heavy metals. In addition, the sediment layer was found to be a source of ammonium, phosphate, and DOC. The occurrence of preferential flow paths may have reduced the release of solutes by stormwater sediment during rainfall events. The authors emphasize the need to incorporate sampling of percolating water in stormwater infiltration basin monitoring programs, and to clean the infiltration bed on a regular basis (Datry et al. 2003).

Examining specific conductance and salinity, Datry et al. (2004) reports that "rainfall events produced a plume of low-salinity stormwater in the first 2m below the groundwater table, generating steep vertical physico-chemical gradients that resorbed during dry weather." Additionally, Ostendorf et al. (2009) found that more dissolved contamination infiltrates into the aquifer from the infiltration basin than runs off into the infiltration basin during the summer and fall months. These modeled findings imply a slow, seasonal dissolution of deicing agent solids deposited in the infiltration basin during winter. 13% of applied deicing agent, according to a model, is carried in suspension and deposited in the infiltration basin where it slowly dissolves (Ostendorf et al. 2009).

BMP Name	Other Toxics	Flow	Salinity	Pesticides	Geomorphology	
					Habitat	Sediment
Bioinfiltration	★	★	☆	★	☆	⯪

Figure 9. Effectiveness ratings for bioinfiltration and each stressor intersection. See Figure 4 for Legend.

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Urban Forest Buffers

An urban forest buffer is a linear wooded area that helps to filter nutrients, sediment, and other pollutants from runoff (CBP 2018). From an examination of 115 peer-reviewed papers, only two address the efficacy of urban forest buffers on stream health stressors. Guardian et al. (2021) examined the efficiency of current BMPs in the Potomac watershed at reducing transport of micropollutants. For urban BMPs, the purchase of underdeveloped land along the stream to shaded habitat and leaf litter inputs were considered forest buffers. Matteo et al. (2006) modeled the effectiveness of ten-foot roadside tree buffers in rural, suburban, and urban environments within the Mill River Watershed in central Massachusetts. This brief review of urban forest buffers addresses their impacts on stream health stressors such as habitat, toxics and pesticides, salinity and ions, flow, and other toxic substances found in stream water.

Stressors Important to Stream Health

Habitat

Neither study discussed specific impacts on habitat from the use of urban forest buffer BMPs in terms of efficiency or effectiveness. Matteo et al. (2006) did emphasize the importance of tree selection in urban environments. The trees selected need to withstand many stressors, and Matteo et al. (2006) suggests that the following be taken into consideration during the tree selection process: "climate, soil conditions—texture, pH, drainage/compaction, exposure—sun and wind, human activity, drainage, pest problems, space constraints, above- and belowground growing space, utility wires and other infrastructure, maintenance requirements, and temperature/hardiness zone."

Toxics and Pesticides

Guardian et al. (2021) found that the total concentration for the 65 pesticides and metabolites detected during sampling was reduced by 25% with the urban forest buffer BMP.

Salinity and ions

Neither study discussed specific impacts on salinity and ions in the streams from the use of urban forest buffer BMPs.

Flow

Matteo et al. (2006) model results showed an 8.75% decrease in stormwater runoff with a roadside forest buffer BMP as well as a 33.84% increase in groundwater recharge and an increase of 2.74% in evapotranspiration (ET). This study also showed a decrease in variability from baseline for groundwater and ET when roadside forest buffers were implemented. Matteo et al. (2006) states that the effect on "variability of runoff and groundwater recharge is an indication of buffering capacity attributed to BMPs."

Other Toxic Substances

Guardian et al. (2021) studied the effectiveness of urban forest buffers on toxics and other pollutants such as pharmaceuticals and personal care products (PPCPs) and persistent industrial chemicals. From sampling, they detected 14 PPCPs, 5 hormones, 8 per- and polyfluoroalkyl substances (PFAS), and 11 other industrial chemicals. Guardian et al. (2021) attributes the total concentration reductions of ~65% of the PPCPs and ~45% of the more persistent industrial chemicals to the construction of urban BMPs along a stream with 53% adequate riparian forest buffer.

Conclusion and Policy Implications

The modeling conducted by Matteo et al.'s (2006) provides evidence that urban forest buffers can provide co-benefits like stormwater runoff reductions and increased groundwater recharge beyond the reduction of nitrogen, phosphorus, and sediment. In addition, the reduction in the variability of watershed processes from the modeled BMP "indicates that forest BMPs make the watershed more adaptive to handling adverse conditions." The study also found that roadside forest buffers are as effective as riparian buffers in reducing the effects of urbanization. By comparing rural, suburban, and urban environments within the same watershed, Matteo et al. (2006) illustrated the differences between urbanizing and urbanized subbasins where different BMPs and policies might be needed. They suggest targeting areas prone to urbanization and apply landscape planning to enhance the urbanizing areas, while urbanized areas may want to focus on increasing pervious cover by adding more street trees or reforesting riparian corridors.

Guardian et al. (2021) provides a background for the motivation that widespread BMP implementation for nitrogen, phosphorus, and sediment reductions have potential for co-benefits of reducing other stressors like micropollutants and hormones. The authors assert that their work "reveals the potential to co-manage a diverse array of micropollutants based on shared transport and transformation mechanisms in watersheds."

BMP Name	Other Toxics	Flow	Salinity	Pesticides	Geomorphology	
					Habitat	Sediment
Urban Forest Buffers						

Figure 10. Effectiveness ratings for urban forest buffers and each stressor intersection. *See Figure 4 for Legend.*

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Urban Tree Planting

According to CBP definitions and categorizations, urban tree planting encompasses a few tree planting practices in the urban setting. Since urban forest buffers are defined in their own section of this report, they will be excluded here.

Urban Tree Canopy Expansion – The planting of trees in an urban area that are not part of a riparian forest buffer, structural BMP (e.g., bioretention, tree planter) or do not conform to the definition of the Urban Forest Planting BMP. Urban tree canopy expansion would qualify as a "Tree Planting – Canopy" BMP in CAST, which is defined as tree plantings on developed land (turf or impervious) that result in an increase in tree canopy but are not intended to result in forest-like conditions (CBP 2020).

Urban Forest Planting – Tree planting projects in urban or suburban areas that are not part of a riparian buffer, structural BMP or Urban Tree Canopy Expansion BMP, with the intent of establishing forest ecosystem processes and function. This requires urban forest plantings to be documented in a planting and maintenance plan that meets state planting density and associated standards for establishing forest conditions, including no fertilization and minimal mowing as needed to aid tree and understory establishment.

Effectiveness & Treatment Mechanisms

The tree planting studies reviewed largely focused on the benefits of planting trees in urban areas as it reduces stormwater runoff flows through interception of rainfall by tree canopy and foliage.

- Sanders' (1986) study modeled that the existing trees in Dayton, Ohio curtailed potential runoff by approximately 7%.
- A study in Malaysia combining the effects of throughfall and stemflow reported that approximately 22% of rainfall was intercepted by the tree canopy, branches, and trunk (Abas et al. 1992).
- Investigating how surface type and tree cover affects surface water runoff in urban areas, plots constructed with asphalt, grass, or asphalt with a centrally located tree pit were compared (Armson & Stringer 2013). The tree pit plot saw 26% and 20% of total rainfall as runoff in winter and summer, respectively; when compared to the 62% and 53% of total rainfall that became runoff in the asphalt plot during winter and summer, respectively. The small tree canopies in the study suggest that this was mostly due to infiltration rather than any significant effects from interception.
- Livesley & Glover's (2014) study focused on the impact of bark characteristics on the initiation and magnitude of stemflow, since the two species studied had similar branching structure and canopy size. Both tree species (Sydney Blue Gum and narrow-leafed Black Peppermint) intercepted over 25% of precipitation. The narrow-leafed peppermint tree, which had rougher bark by comparison, was more effective – interception approximately 44% of precipitation.

Treatment Mechanisms

1. Canopy interception
2. Evaporation/Evapotranspiration
3. Leaf storage
4. Infiltration
5. Stemflow

Key Findings

- Certain plant species may be better performers for mitigating rainfall, we cannot rely on total values of leaf area for a given species to make decisions about the benefits of planting a certain type of tree stand on a temporary basis. Also, total evaporation per tree cannot be used as a sole indicator when making decisions on vacant land tree planting scenarios (Kirnbauer et al. 2013).
- Vegetation has a significant influence on the regulation of throughfall and potential stormwater runoff – residents can considerably affect the process. The study conducted by Inkiläinen (2013) reported that reduction of throughfall depends largely on the magnitude of the incident storm and the frequency of storms. Canopy Cover was found to be more influential in predicting throughfall than LAI, and coniferous trees were the only functional plant group found to be influential in predicting throughfall (Inkiläinen 2013).
- Livesley & Glover's (2014) paper comments on the lack of standard protocols for measuring throughfall, or canopy intercept, and stemflow. This makes comparisons amongst studies difficult. They also note that bark water storage capacity is a neglected component of tree canopy interception, and that the urban hydrological implications of measured canopy interception and stemflow depend greatly on the landscape context (pervious green space v. impervious streetscape).

Other Management Strategies, Research Gaps, and Potential for Future Studies

Using trees more effectively in urban areas is often less challenging than educating local constituents about the benefits of new practices. Therefore, Berland et al. (2017) suggests four major areas of additional research regarding urban tree planting and stormwater benefits.

1. Documented performance of trees as stormwater control by species and life stage,
2. Studies on the influence of local soil, atmospheric, and landscape conditions for trees as a stormwater BMP,
3. Situating stormwater control in the context of urban forestry goals and arboricultural challenges, and
4. Developing policy and economic mechanisms to encourage strategic tree planting on private and public land.

An assessment of structural attributes of street tree assemblages at the community scale and estimated associated stormwater interception benefits across multiple communities within a metropolitan area (Berland et al. 2014). This assessment found that Tree City USA participant communities had greater forest structure and double the estimated stormwater interception when compared to non-participant communities. Findings from this research suggest the importance of municipal intervention and management for bolstering tree abundance in public rights-of-way. Further research is warranted across community boundaries (Berland et al. 2014).

Kuehler et al.'s (2017) review highlights the limited research performed, and documents areas of need for quantifying the benefits of urban trees for stormwater management and provide a basis for providing credits for trees in stormwater designs. Research gaps identified in the Kuehler et al. (2017) review include:

- Fundamental research related to urban trees and their contribution to interception and runoff delays,

- How tree canopy cover affects runoff coefficients,
- Studies scaling local urban tree effects to the larger watershed,
- Evaluating the potential to use trees to transpire water from urban stormwater controls, and
- Policy analyses for urban tree canopy to be integrated into stormwater management decisions and credited by regulators.

Another suggestion for future research from Inkiläinen et al. (2013) is for urban stand-scale studies in different climate zones, and the societal effects from resident landscape preferences and/or ownership structures.

BMP Name	Other Toxics	Flow	Salinity	Pesticides	Geomorphology	
					Habitat	Sediment
Urban Tree Planting		★	☆		☆	☆

Figure 11. Effectiveness ratings for urban tree planting and each stressor intersection. See Figure 4 for Legend.

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Urban Stream Restoration

Generally, urban stream restoration is the practice of "attempting to restore some of the function of a river ecosystem" in a heavily populated and urbanized area (Lammers and Day 2018). However, stream restoration can mean many things. As part of this report, we want to emphasize that not all stream restoration approaches are going to show improvements for all stream health stressor parameters. Nine papers in this review address the impacts of urban stream restoration on stream health stressors. This brief review of urban stream restoration BMPs addresses their impacts on stream health stressors such as habitat, toxics and pesticides, salinity and ions, flow, and other toxic substances found in stream water. Note that toxics and pesticide stressors were not addressed by the literature reviewed below, and this may signify a gap in research. This review of urban stream restoration shows that the complexity of stream systems and the countless reasons for the project's implementation make it difficult to quantitatively determine the effectiveness of this BMP.

Effectiveness

The success of urban stream restoration projects depends on the purpose of the restoration and the metrics used to measure success after project completion. Measures of success in the literature from this review largely focused on the improvements of habitat – both in-stream and riparian. There was also a significant emphasis on nutrient and energy dynamics related to biogeochemical processes related to denitrification and the role of carbon and nitrogen (e.g., Gift et al. 2010; Newcomer et al. 2012). This not surprising as most urban stream restoration projects are implemented to address water quality degradation from nutrient and sediment loading.

The discussion of habitat stressors and improvements from the literature highlighted the importance of the chosen restoration type for the degraded stream reach. In Gothe et al. (2016), their regression analyses strongly suggested that the type of restoration measure applied was a far more important determinant of restoration outcomes than restoration extent, and that the main determinants of plant community responses to restoration are discharge, altitude, and the type of restoration. Their results indicate that widening the stream channel has the strongest effect on plant community response. Gothe et al. (2016) addresses the riparian and plant community aspects of restoration type, whereas Larson et al. (2001) explores the efficacy of using LWD as the primary restoration strategy. They found that adding LWD can improve physical conditions in a channel and increase the number of pools in a reach, but "it cannot be expected to increase sediment retention or to stabilize in-channel sediment over the time frames observed" in their study. In addition, Larson et al. (2001) note that the addition of LWD to the stream will only improve conditions if the LWD affects conditions that were significant causes of the initial degradation.

Much of the literature about urban stream restoration clearly emphasizes that the restoration effort is not likely to succeed if the goal of the restoration is not addressing the causes of the systems degradation rather than the symptoms. For instance, Cooper et al.'s (2014) research on a restored urban stream reach suggests that "stream salinization in urban watersheds may limit the ability to manage streams for nutrients, wildlife, and other ecosystem services" as well as reduce the benefits of restoration efforts. Violin et al.'s (2011) findings, similarly, indicate that "habitat restoration will prove ineffective if urban stormwaters rapidly rehomogenize restored stream segments, as seen in previous urban restorations." The structural integrity and impaired macroinvertebrate communities in their study signify that "habitat complexity on its own is insufficient to support the recovery of biotic communities." Their analysis of long-term data from one restored reach, while limited, "does not provide evidence that waiting longer prior to evaluating a restoration project is likely to yield different conclusions." This conclusion is in opposition to other literature that often use their monitoring timeframe as a reason for less successful metrics after completing a stream restoration.

Policy Implications & Suggestions

Bain et al.'s (2014) project highlights the fundamental importance of hydrologic and geomorphic characterization as a part of the stream restoration planning stages, and the need to adapt as the surrounding urban area evolves. They assert that "examining interactions between biology, hydrology, and geomorphology seem essential for separating ephemeral species and dynamics from long-term system improvements and making sure that in-stream challenges are met." Violin et al. (2011) notes that hydrological differences, particularly storm events, are the major habitat structuring force in the urban stream channels they studied. If stormwater is rarely addressed by natural channel design restorations, then restoration type decisions may be a significant barrier to urban stream restoration success. On a similar vein, Gothe et al.'s (2016) findings emphasize the importance of considering how the specific environmental setting of river reaches can affect the outcome of restoration, and the importance in choosing relevant restoration measures for the target organism groups or ecosystem parameters in restoration planning. Additionally, Larson et al. (2001) emphasizes that "it is critical to identify the primary factors causing degradation in a reach, to evaluate existing channel conditions, and to determine which, if any, objectives could be met with in-stream enhancement projects."

Stressors Important to Stream Health – Additional Information

Habitat

Restoration Types & Efficacy

The study conducted by Gothe et al. (2016) evaluated restoration projects in 20 catchments across 10 European regions. The sites were classified by restoration extent and restoration type to identify the main determinants of structural and functional responses of riparian plant communities. Many of the biological indices they used showed significant responses to measures affecting connectivity with the floodplain, especially, projects aiming to widen the stream channel. Restoration type was the only significant determinant of plant community responses. Stream channel widening was the restoration type with the strongest determining effect on plant community responses.

Bain et al.'s (2014) study used a wide range of indicators to retrospectively examine the multi-million-dollar restoration of Nine Mile Run in Pittsburgh, PA. They evaluated the stream restoration at multiple scales using hydrologic, biotic, water chemistry, and local community activity characterization data. The use of floodplain reconnection and the removal of pollutant sources and obstructions to fish passage resulted in improvements to fish and macroinvertebrate populations after the restoration was completed.

Larson et al.'s (2001) study evaluated the effectiveness of LWD, or in-stream log placement, as the primary strategy for achieving urban stream restoration goals in western Washington. Effectiveness was evaluated by characterizing physical stream conditions using common metrics. They found that while LWD projects can modestly improve physical habitat in a stream reach over a two- to ten-year period, they do not achieve corresponding improvements in biological conditions. Unfortunately, the influence of watershed disturbance on physical channel response in the urban environment was evident, and, in many cases, overwhelmed any potential benefits of LWD.

Violin et al.'s (2011) study compares the physical and biological structure of urban degraded, urban restored, and forested streams in North Carolina to quantify the ability of reach scale stream restoration to restore physical and biological structure to urban streams and to examine the assumption that providing habitat is sufficient for biological recovery. They focused on Natural Channel Design restoration projects and postulated that "successful restoration ought to lead to stream habitat and biological communities that are distinguishable from unrestored urban streams." Violin et al. (2011) found that urban restored streams differed significantly from their unrestored urban counterparts in only a single metric - having reduced canopy cover as a direct result of project implementation. The restored streams did not have improved habitat complexity or detectable changes in their macroinvertebrate communities. The restored streams more closely resembled urban rather than forested streams – both structurally and biologically. This suggests that restoration activities have not yet led to the recovery of habitat conditions nor sensitive macroinvertebrate taxa in these streams.

Salinity and Ions

Cooper et al. (2014) studied groundwater-surface interactions of sodium chloride and other ions in an urbanized stream basin in Maryland. Minebank Run was restored in 2005 and all data for the study was collected after the restoration was complete. They found "increasing trends in specific conductivity over time suggest[ing] a persistent source of salts in the basin - perhaps accumulations in soils and groundwater." The authors suggest that "Salinization of streams in urban watersheds may reduce the benefits of restoration and limit the ability to manage streams for nutrient management, wildlife and other ecosystem services."

Flow

Stream restoration has been shown to retain excess flow through legacy sediment removal and floodplain reconnection. For example, Langland et al. (2020) documented 10,000 cubic meters of additional storage following a stream restoration project in Pennsylvania. Adding LWD to the urban streams in the Larson et al. (2001) study produced more physical channel characteristics typical of undisturbed streams. They noticed flow attenuation through increased pool habitat and channel complexity in most of the project reaches studied.

Gift et al.'s (2010) data supports the idea that low water table levels inhibit interaction of groundwater-borne nitrate with the active denitrification zone at the top of the soil profile. Gothe et al. (2016) found that "discharge explained a substantial proportion of the variation in the response ratio of Shannon diversity," and they suggest that "the probability of encountering a diverse plant community may increase with increasing discharge, provided that suitable habitats are available for colonization and establishment."

BMP Name	Other Toxics	Flow	Salinity	Pesticides	Geomorphology	
					Habitat	Sediment
Urban Stream Restoration			☆		★	★

Figure 12. Effectiveness ratings urban stream restoration and each stressor intersection. See Figure 4 for Legend.

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Agricultural BMPs

No-Till and Cover Crops

Agricultural tillage practices used as BMPs to reduce sediment and nutrient flow to streams are often referred to as "no-till." The tillage management practices that can be included under the use of the term, no-till, are "low residue," "conservation," and "continuous high residue" or "high residue, minimum soil disturbance." The practices studied and discussed in this literature review under the "No-Till and Cover Crop" BMP include a mix of the above tillage practices and implemented cover crops. However, the discussion mainly focuses on tillage practices as the researchers and reviewers did not consistently differentiate between the effects of tillage and the cover crops planted. Cover crops are short term crops grown after the main cropping season to reduce nutrient and sediment losses from the farm field (CBP 2018). Many of the studies provide a comparison between a combination of no-till and cover crop practices with conventional, or any tillage routine that does not achieve 15% crop residue coverage immediately after planting. Conventional tillage does not qualify as a BMP.

Low Residue Tillage – Low residue tillage in CAST requires 15 – 29% cover, strip till or no-till, and less than 40% soil disturbance. The CBP defines low residue tillage as a tillage practice "that involves the planting, growing, and harvesting of crops with minimal disturbance to the soil in an effort to maintain 15 to 29% crop residue coverage immediately after planting each crop" (CBP 2018).

Conservation Tillage – Conservation tillage in CAST requires a minimum of 30% residue coverage at the time of planting and a non-inversion tillage method. The CBP defines conservation tillage as a tillage practice "that involves the planting, growing, and harvesting of crops with minimal disturbance to the soil in an effort to maintain 30 to 59% crop residue coverage immediately after planting each crop" (CBP 2018).

High Residue Tillage – Continuous, high residue, minimum soil disturbance tillage (HRTill) management eliminates soil disturbance by plows and implements intended to invert residue. In CAST, this practice requires a minimum of 60% crop residue cover remaining on the soil surface as measured after planting. The practice involves all crops in a multi-crop, multi-year rotation and the crop residue cover requirements are to be met immediately after planting each crop.

Effectiveness & Treatment Mechanisms

Studies addressing the impacts of no-till and cover crop practices on stream health were overwhelmingly focused on the pesticides stressor. Most of the studies included in our literature review looked at how effective no-till and/or cover crops were at reducing the movement of pesticides and herbicides off agricultural land. Runoff plays a role in this movement as does the movement of sediment. A study by Clausen (1996) found that a reduced tillage practice not only reduced runoff by 64% but also reduced the mass export of atrazine and cyanazine pesticides through the runoff and sediment reductions. Using the paired watershed technique to determine the effect of conversion from conventional tillage to conservation tillage in New England, Clausen (1996) found that pesticide export was primarily in the dissolved phase with the use of reduced tillage practices.

The study conducted by Locke et al. (2008) compared the percentage of applied pesticide lost in runoff from conventional tillage and no-till treatment. The effectiveness of the no-till treatment in this small plot mesocosm study varied by the pesticide studied. The percentage of chlorimuron in runoff during the study increased from 1.5 to 12%, while the percentage of alachlor decreased from 4.5 to 2.3%. This was a common result amongst the studies.

No-till, or conservation tillage, techniques can be effective as reducing toxics and pesticides from washing off into streams and other surface water bodies because the crop residue acts a physical barrier that slows the flow of runoff. This mechanism is particularly useful to reduce sediment loss, so the primary containment of pesticides and other toxic substances is related to their chemical characteristics and reactions. Substances that are more likely to sorb to soil or plant materials are more likely to be reduced by no-till, or conservation tillage, practices. Substances that are less likely to sorb to soil or plant material still present a challenge.

A 2-year natural rainfall study conducted by Mickelson et al. (2001) evaluated the effect of tillage and herbicide application methods on crop residue cover, surface runoff volume, erosion, and herbicide loss with sediment and runoff water. This study found that while no-till had the lowest annual runoff volume and soil loss, it also had the highest runoff concentrations of herbicides (atrazine, metolachlor, and cyanazine). Mickelson et al. (2001) reported that less than 2% of applied pesticides were lost with runoff water, but that 95% of the total loss was in solution. When applying herbicides using a broadcasted spray on a no-till field, some of the toxic compounds land on crop residue only to be washed off during the next storm event.

The main mechanisms leveraged using no-till, or conservation tillage practices, are:

1. The use of physical barriers (surface residue) to reduce and slow surface runoff flows,
2. Soil adsorption,
3. Plant uptake, and
4. Infiltration and/or leaching

Key Findings

- A tillage practice's effectiveness at reducing toxics and pesticide runoff may be affected by the differences in the chemical characteristics and reactions of the compounds used (Locke et al. 2008; Warnemuende et al. 2007; Shipitalo and Owens 2011).
- A 6-year study conducted by Shipitalo and Owens (2003) on fields in 7 watersheds with varied tillage practices and cover crop routines concluded that "rainfall timing following atrazine application had a larger effect on runoff losses of atrazine and metabolites than tillage practices." In Shipitalo and Owens (2006), a few events caused most of the herbicide loss for all watersheds in the study. The top 5 transport events for each herbicide and watershed accounted for 60 to 99% of the herbicide losses for the 9-yr period. These runoff events generally had high herbicide concentrations rather than high runoff volumes.
- Studies reported that no-till practices resulted in increased herbicide losses with runoff when compared to other conservation tillage techniques. Shipitalo and Owens (2006) found that both flow-weighted yearly average concentrations and average herbicide losses were greater for no-till than for the watersheds when chisel or disk tillage practices were used. No-till can result in increased herbicide losses and concentrations compared with instances where greater amounts of tillage are used. Similar findings were reported in Shipitalo and Owens (2011) and Warnemuende et al. (2007).

- The method of herbicide application plays an important role in herbicide loss with sediment and runoff water. Mickelson et al. (2001) results show that applications before disking and incorporation with the Mulch Master significantly reduced herbicide concentrations and losses in runoff. Toxicity persistence between no-till and conventional tillage practice and varied pesticide application timing, conducted by Mugni et al. (2015), suggests that no-till practices may be preferable to conventional tillage. The late application performed in the study remains effective for longer during the soy growing season with a shorter toxicity persistence in runoff.

No-till and other conservation tillage practices are effective at reducing pesticide and sediment loading in agricultural runoff. However, it is common practice to remove cover crops before spring planting using herbicides, so effectiveness ratings may need to be adjusted separately from tillage practices. The choice and use of tillage practice should be determined with the characteristics of the pesticides, herbicides, and other toxic substances used on the land as well as the application method and timing to maximize the reduction of these substances in our surface waters.

Other Management Strategies, Research Gaps, and Potential for Future Studies

In this literature review, we view the infiltration of any stream health stressor into soil as a removal of the stressor from the system, or as a measure of the BMP's effectiveness. This allows us to simplify the complex system of stream health impacts to address only the surface water impacts due to overland runoff into streams. This does not capture the full effects or impacts of BMPs on stream health from subsurface or groundwater flows that are impacted by BMPs, such as no-till or conservation tillage practices. A few studies in our literature address concerns about the leaching of pesticides, herbicides, and other toxic substances into subsurface flows or groundwater reservoirs.

Watts & Hall (1996) conducted a study comparing leaching and runoff losses for herbicides on conventionally tilled and mulch-tilled, or single disked, land. Their study reported that the minimum tillage practice had "little effect on reducing the volume of percolate" and that herbicide leachate availability was greater for the mulch-tilled land over the three-year period under study. The authors also noted that the incorporation of "spray herbicides preplant[ing] within the mulch-tilled system appeared to reduce the transport of chemicals in root zone leachates when compared to pre-emergence applications in a no-till system.

Another study from the 1990s, by Isenee et al. (1990) reported that "much more atrazine leached into groundwater in a no-till system than a conventional till system." Their findings also supported the conclusion that atrazine persists in shallow groundwater and slowly leaches from residue in the soil. In this study groundwater was sampled under three fields over three study years. A limited number of samples collected contained pesticide residues above the detection limit. At the 5% level of significance, they found no verifiable difference between the no-till and conventional practices. Isensee et al. (1990) states that "the unusually rapid pesticide leaching to depths beyond those predicted by classical transport theory" provides "strong presumptive evidence for a macropore flow mechanism, especially in no-till fields."

A related study by Malone et al. (2003) conducted an analysis of data from Granovsky et al. (1993). The results from the analysis showed "no significant difference in the number of percolate-producing macropores between no-till and conventional tillage practices," and that the percolate may have a faster breakthrough time, or move more quickly through the soil, depending on the soil type. The breakthrough time and number of percolate-producing macropores in the soil can significantly affect pesticide concentrations. The model used in the study predicted that an increase in breakthrough time or an increase in percolate-producing macropores would reduce the concentrations of pesticides in the percolate. This study provides evidence that the number of percolate-producing macropores “does not change between tilled and no-till soil and that time of percolate breakthrough is a key reason for higher pesticides transport on no-till soil.

Another related study on this topic – by Elliot et al. (2000) – conducted a comparison between a conventional tillage plot and a no-till plot. The experiment monitored herbicide concentrations in tile drain effluent to compare the leaching characteristics of 8 herbicides. They found “direct evidence of preferential flow in both plots as the applied herbicides all leached at the same rate and were present in quantifiable concentrations in the first water reaching the drainage tile.” They also evaluated the effectiveness of a single tillage pass on reducing herbicide transport for the annual barley crop. Elliot et al. (2000) notes that “the tillage pass caused only a slight reduction in water flow to the tile drain but resulted in a substantial reduction in the amount of herbicide transported.” The transport of herbicides to the tile drains was greater in the no-till plot than for conventional till. The authors hypothesize that the tillage pass disrupted water entry into preferential flow paths at the soil surface of the conventionally tilled plot. This perhaps allowed more opportunities for soil adsorption.

BMP Name	Other Toxics	Flow	Salinity	Pesticides	Geomorphology	
					Habitat	Sediment
No Till and Cover Crops	Not key stressors in ag. setting			☆	☆	☆

Figure 13. Effectiveness ratings for no till and cover crops and each stressor intersection. See Figure 4 for Legend.

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Pasture Management

Pasture management BMPs includes precision intensive rotational/prescribed grazing and horse pasture management. Horse pasture management is defined as maintaining a 50% pasture cover with managed species and managing high traffic areas by CBP. Our review includes only one paper that addressed the effects of pasture management on stressors important to stream health. The study compared agricultural, or rural, watersheds where one watershed has implemented BMPs and the other has not. Conducted by Guardian et al. (2021), the study assesses the impact of BMPs in reducing micropollutant transport in the Potomac River watershed.

The agricultural BMPs implemented in the BMP watershed are pasture management (improvements to heavy use areas and plantings of over nine acres of cool season grasses), pasture alternative watering (three spring developments to replace in-stream cattle watering and improving two stream crossings), and grass buffer on 8,800 feet of fenced pasture corridor. These BMPs resulted in a 10% reduction in the total concentration of pesticides and metabolites.

This is just one study, but it does show potential for additional research into the effects of agricultural pasture management on stream health stressors like pesticides, emerging contaminants, and especially micropollutants. The BMPs studied by Guardian et al. (2021) were implemented for nitrogen, phosphorus, and sediment reductions, but provided co-benefits by reducing other pollutant stressors as well. The potential for co-benefits from this BMP is limited, however, by the fact that pasture management addresses pollutant sources from livestock pasture, which is not a particularly high source of the key stressors examined.

BMP Name	Other Toxics	Flow	Salinity	Pesticides	Geomorphology	
					Habitat	Sediment
Pasture Management	Not key stressors in ag. setting			☆	☆	☆

Figure 14. Effectiveness ratings for pasture management and each stressor intersection. See Figure 4 for Legend.

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Vegetated Buffers

Vegetated buffer BMPs includes grass and forest buffers with and without exclusion fencing. According to CBP, these types of vegetated buffers typically are associated with agricultural lands. This literature reviewed under the vegetated buffer classification in this study excludes urban and suburban forest buffers. All other types of vegetated buffers regardless of sector are discussed in this section. CAST defines grass buffers as "linear strips of grass or other non-woody vegetation maintained to help filter nutrients, sediment and other pollutants from runoff." CBP requires a 35-foot buffer width, but a 100-foot buffer width is recommended.

Effectiveness & Treatment Mechanisms

Pesticides

Mickelson et al. (2003) compared influent with sediment added and influent without added sediment for total atrazine concentrations after runoff passed through a buffer vegetated with 59% smooth brome, 35% Kentucky bluegrass, and 6% Kentucky tall fescue. The study reported overall reductions in pesticide for all treatments. The most effective treatment was the 9.1 m vegetated buffer length and influent without sediment added which had an 83.5% reduction in atrazine when compared to the 36.3% reduction with the 4.6m long buffer. The study found no statistically significant difference between the treatment with sediment or without sediment. Length of vegetative filter strip was found to be a significant parameter in reducing transport of pollutants with surface runoff water.

A study conducted in California assessed reductions in water toxicity associated with reduced pesticides in agricultural runoff on a working industrial-scale row crop operation (Anderson et al. 2010). Study was designed to evaluate the effectiveness of an integrated vegetated treatment system (VTS) incorporating a sedimentation basin (33m long), a vegetated ditch (233m), and a Landguard organophosphate-A (OP-A) dosing system (33m). The vegetated reach was planted with rushes, pennywort, creeping wild rye, and red fescue. Diazinon's relatively high solubility means that high proportions of the pesticide transported in aquatic systems can be expected to remain in the aqueous phase. The VTS was effective at removing most of the organochlorine and pyrethroid pesticides from water. Most of the particles are removed through sedimentation, but the sediment contains toxic concentrations of pyrethroids and chlorpyrifos. The combination of sedimentation, vegetation, and Landguard OP-A treatment sections in the VTS were effective at reducing water column pesticide concentration and toxicity associated with ag tailwater from organophosphates, pyrethroid, diazinon, and organochlorine.

In a field rainfall simulation study conducted to test the ability of different vegetated buffer designs to mitigate herbicide and antibiotic transport in surface runoff, Lin et al. (2011) assessed the effectiveness of 3 buffer strip designs compared with a cultivated fallow control. The vegetated buffers in this study were planted with tall fescue or tall fescue with a 1m wide switchgrass hedge at the upslope end of the buffer, and native warm season grasses/eastern gamagrass. All treatments significantly reduced the load of atrazine, s-metolachlor, and glyphosate in surface runoff. 4 meters of vegetated buffer strips removed about 58 – 72% of atrazine and metolachlor, and 60-71% of glyphosate in surface runoff. Sulfamethazine loads in surface runoff were significantly reduced by more than 70%. Native vegetation had the greatest effectiveness at the reducing the transport of metolachlor, while the tall fescue and switchgrass hedge enhanced the reduction of atrazine, metolachlor, and glyphosate loads by 10-30% compared with tall fescue alone.

To reduce metolachlor, atrazine, and DEA dissolved masses exported in runoff, Lafrance et al. (2012) studied the efficiency of 3-, 6-, and 9-meter grass filter strips compared with a control with no buffer strip at the experimental plot scale under natural rainfall conditions. The grass filter strips – seeded with a mix of creeping red fescue, bent grass, and perennial rye-grass – were very efficient at reducing masses of dissolved metolachlor, atrazine, and DEA exported in runoff during most rainfalls in the four-season study (1998 – 2001). The presence of grass filters strips influenced the dissipation of parent compounds in the field. A follow up study was conducted in 2003 to investigate the impact of grass filter strips less than 3m on herbicide loss. This study found that exported herbicide mass reductions increased linearly for 1-m to 3-m strips (Lafrance et al. 2012).

Moore et al. (2014) reports the findings from a one-time, simulated 5-hour runoff event (with added mixtures of diazinon and permethrin) in two experimental plots at the University of Mississippi Field Station - one unvegetated control plot, and one grass-wetland experimental plot. Their results show that both control and experimental plots were equally ineffective at retaining diazinon with a mean of 9.6% retention for both plots. The grass-wetland buffer experimental plot was more effective with cis- and trans-permethrin insecticides, retaining 83% and 85% of masses, respectively. The control plot retained only 39% of cis- and 44% of trans-permethrin masses. The distance required to decrease pesticide concentrations by one half, or a half distance, for both permethrin isomers were 26% to 30% shorter in grass buffers (22 m – 23 m) than in the control (32 m). This study highlights another instance where the chemical characteristics of the pesticide play a major role in the effectiveness of the treatment BMP.

Models

The studies included in this subsection on models differentiates the effectiveness values reported by field and experiment studies from those predicted through modeling.

Zhang et al. (2010) used quantitative results from 73 studies published in peer-reviewed journals to perform meta-analyses for buffer design factors: width, slope, vegetation type, and soil drainage type. The model's results found buffer width to be a significant factor in the removal of all pollutants, explaining 37%, 60%, 44%, and 35% of the total variance in removal efficacy for sediment, pesticides, N, and P, respectively. Buffer slope was found to be significantly associated with sediment removal efficacy, with optimal slopes ranging between 8.14 to 11.72%. The final model was built based on the independent variables that were found to be statistically significant and selected by their goodness-of-fit. The low goodness-of-fit (R^2) values for sediment (0.654), Nitrogen (0.492), Phosphorus (0.475), Pesticide (0.597) reinforces the fact that there are other factors at play for buffer efficacy measures (Zhang et al. 2010). Buffers composed of trees had higher efficiency than those composed of grasses or a mix of grasses and trees. Soil drainage type did not show a significant effect on efficacy.

To model the effectiveness of buffer strips and vegetated ditches on pesticides, Dunn et al. (2011) collected runoff samples from 44 operational farming locations over a 6-year period. The study focused on fields in agricultural potato production with at least 10m wide buffer. The buffers were planted with dense stands made of primarily white clover, meadow fescue, and timothy grasses. Buffer strip effectiveness was based on buffer width, so a 25m buffer strip was found to be more effective than a 5m buffer strip

The Zhang & Zhang (2011) study addresses the challenge of simulating performance of agricultural BMPs in reducing organophosphates in runoff at the watershed scale. They used the Soil and Water Assessment Tool (SWAT) and watershed data collected between 2000 – 2006 to model the effectiveness of sediment ponds, vegetated ditches, buffer strips, pesticide use reduction. The model successfully simulated the expected watershed conditions and pesticide concentrations when compared to real world data. The authors' note the limitations of their simulation due to the flaws inherent in the algorithms used to calculate/represent mechanisms in the system. Similar to the Zhang et al. (2010) model discussed earlier, the buffer strip effectiveness was based primarily on buffer width. Zhang & Zhang (2011) shows that the SWAT model is an effective means of simulating the effectiveness of BMPs at a watershed scale.

Flow & Pesticides

The flow stressor can have an impact on the effectiveness of a vegetated buffer strip to capture pesticides and other toxics in runoff. Poletika et al. (2009) study found that the vegetated filter strip (VFS) performed well when flow across the strips was uniform. Flow uniformity showed a highly significant effect with concentrated flow reducing infiltration. Chemical residues in the outflow water and sediment tended to increase with greater flow volume and with concentrated flow (Poletika et al. 2009). The increased flow volume had a minor impact on removal efficiency.

Treatment Mechanisms

1. Reduction of runoff velocity/Increased hydraulic retention time
2. Filtration
3. Particulate Deposition; sedimentation
4. Infiltration
5. Sorption – plants and soil
6. Enhanced microbial activity and chemical degradation

Key Findings

- The effectiveness for water quality control on a catchment basis seems to depend on the physical attributes of buffer zones (width, slope, soil type, vegetative structure), types of pollutants, and general proximity of buffer zone to source of surface water pollution. Failure of buffer zones have generally been attributed to inadequate buffer zone structure or to a variation in pollution type, dissolved vs particulate pollutants (Norris et al. 1993).

- The herbicide trapping efficiency of VBS was determined by the buffer width, species composition, and chemical properties of the herbicide. The source to buffer area ratios of 8:1 or greater can still effectively reduce herbicide transport in surface runoff (Lin et al. 2011).

- Appropriate management of riparian buffers can enhance the delivery of multiple ecosystem services along with improving the ecological value of the riparian zones and the adjacent aquatic habitat. In addition, collective findings highlight the merits of targeted, designed buffers that support multiple benefits – enhancing diversity in topography, soil moisture and carbon, vegetation, and habitat (Stutter et al. 2019).

- Literature data from Prosser et al. (2020) suggests that VBS are particularly important and effective at capturing pesticides that pose a greater risk of movement into surface water (i.e., higher solubility in water and low sorption capacity to soil) and pesticides that are likely to be bound to sediment (i.e., lower solubility in water and high sorption capacity).

Other Management Strategies, Research Gaps, and Potential for Future Studies

The review of existing regulations circa 2018 regarding vegetated buffers by Gene et al. (2019) shows an inconsistent use of width distances required between jurisdictions across North America, regardless of stated protection goals. This study highlights the need to harmonize vegetated buffer size for maximum effectiveness in similar ecological, climatic, and agricultural conditions. Additionally, another study addresses the potential for catchment-wide strategies to make a larger influence on aquatic and riparian ecology over localized riparian management. Stutter et al. (2019) reviewed 16 recent papers to combine evidence of emerging designs of enhanced structural elements in riparian buffers. The review states that "there is a movement away from traditional vegetated buffer strips toward designed riparian buffer zones constructed to intercept agricultural surface and subsurface runoff." Highlighting an area for future research, the review notes "low evidence levels for channel morphological benefits from riparian buffers." Prosser et al. (2020) also conducted a review of current literature on regarding vegetated buffers. Their review outlines the observed influence of different factors (e.g., buffer width, slope, runoff intensity, soil composition, plant community) that can influence the efficacy of vegetated buffers in pesticide and nutrient retention. This review acknowledges the consensus that there is a positive relationship between buffer width and efficacy but emphasizes that the ratio of source area to buffer area – which is rarely reported – may be a more effective method of buffer efficacy (Prosser et al. 2020). They also state that vegetated buffer strips (VBS) should be managed to remove accumulated nutrients. The removal of plant material may encourage growth and increase nutrient uptake.

BMP Name	Other Toxics	Flow	Salinity	Pesticides	Geomorphology	
					Habitat	Sediment
Vegetated Buffers	Not key stressors in ag. setting					

Figure 15. Effectiveness ratings for vegetated buffers and each stressor intersection. See Figure 4 for Legend.

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Agricultural Drainage Management

The agricultural drainage management BMP is defined by CAST as "the process of managing water discharges from surface and/or subsurface agricultural drainage systems, to raise and lower the water level within the soil profile throughout the year following an operation and maintenance (O&M) plan." This review includes only two papers that discuss the impacts of agricultural drainage management on stressors important to stream health.

The first study in this discussion was published in 2001, Rice et al. conducted a field study designed to quantitatively compare the off-site movement of soil and agrochemicals from conventional polyethylene mulch and vegetative mulch (hairy vetch residue) plots over three complete growing seasons. Significantly greater volumes of runoff water and loads of soil and pesticides were collected from plots containing polyethylene mulch. Rice et al.'s results show that vegetative mulch reduced both sediment-bound and dissolved chemical loads in agricultural runoff.

The second study in this discussion of agricultural drainage management, Penn et al. (2020) is a review of blind inlets with an in-depth discussion of a new study that sampled accumulated sediment from layers of a 12-year-old blind inlet. Blind inlets are constructed by backfilling a subsurface drainage pipe with gravel. Other types of back fill materials (limestone sand, steel slag, and biochar) may be used to improve pollutant removal. The use of an oak-derived biochar alternative media saw 99% atrazine removal (Gonzalez et al. 2016a). Pollutants are removed through sedimentation, filtration, degradation, and sorption mechanisms.

When compared to tile risers, blind inlets load reductions of 57% for atrazine, 58% for 2,4 D, 53% for metolachlor, and 11% for glyphosate (Gonzalez et al. 2016b). Accumulated pesticide concentrations from the study of the 12-year-old blind inlet showed the highest accumulation for atrazine and the lowest accumulation for 2,4-D because of 1) low and high water solubility, 2) high and low octanol-water partition coefficient (K_{ow}), and 3) long and short half-lives of the pesticides, respectively. Pesticide concentrations were higher in the blind inlet layers than surrounding soil indicating the blind inlet is a sink.

BMP Name	Other Toxics	Flow	Salinity	Pesticides	Geomorphology	
					Habitat	Sediment
Agricultural Drainage Management	Not key stressors in ag. setting			★	☆	☆

Figure 16. Effectiveness ratings for agricultural drainage management and each stressor intersection. See Figure 4 for Legend.

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Agricultural Stream Restoration

Agricultural, or nonurban, stream restoration is the practice of "attempting to restore some of the function of a river ecosystem" in an agricultural or nonurban area (Lammers and Day 2018). Five studies reviewed addressed the impacts of agricultural stream restoration on stream health stressors such as riparian area, DO, habitat, and toxics and pesticides. Much of the literature discussed flow which is not included as a stressor of concern for agricultural stream restoration for our study. Literature discussions about flow from the reviewed papers have been included under the habitat stressor, because flow can be considered part of the in-stream habitat. Note that the DO and toxics and pesticides stressors were not addressed by the literature reviewed below, and this may signify a gap in research.

Effectiveness

Findings from Bukaveckas et al. (2007) suggest that stream restoration is a useful management strategy in the context of basin-wide effort to mitigate downstream transport. Transient storage might potentially be a useful metric for assessing restoration success. Their study only represents the short-term (2 year) effects of restoration which may or may not be suggestive of long-term response.

Gothe et al.'s (2016) result that altitude and discharge were the "most strongly and frequently related environmental variables to the response of both plant species and trait diversity to restoration" could indicate that "new, open habitats were created after the restoration and that more variable habitats were established over time (e.g., through temporary flooding)." These findings emphasize the importance of both choosing relevant restoration measures that affect environmental conditions of importance and considering the environmental settings of river reaches in restoration planning. Those two considerations for agricultural stream restorations would maximize the likelihood of restoration success.

According to Kasse et al. (2012), "restoration success depends on changing successional pathways to support restored conditions." Kasse et al.'s (2012) study found that their stream restoration projects did not resemble reference conditions. They propose that this may be due to a disparity in vegetation age between reference and restored sites and suggest that the sites compositional and structural conditions may become more similar over time. Kasse et al.'s (2012) results indicate "possible reassembly of degraded site species composition at restored sites after project completion." The authors might call this a "restoration failure," or they suggest that it "could indicate that the stream restoration revegetation resulted in the creation of a novel anthropogenic ecosystem." Considering the challenges associated with selecting appropriate reference sites to compare against restored stream reaches, the latter may be a more appropriate description for the reality of stream restoration impacts.

The results from McMahon et al. (2021) on restoration were difficult to interpret and were largely inconclusive because of a very high variability in flows, with the "post-construction" years being very wet. Although there were differences between upstream and downstream reaches after restoration, similar effects were noticed before the restoration. The authors suggest that the effects of the restoration may take a few years to become evident, especially in agricultural applications, and the projects examined in McMahon et al. (2021) were recently completed.

Thompson et al. (2018) found that no significant reductions resulting from the restoration were apparent at the watershed scale when comparing the treatment and reference watersheds. Even though results show that stream restoration can enhance water quality by removing nutrients from the water column, these changes were "not of a magnitude large enough to allow detectable changes due to the restoration 0.6 km farther downstream."

Stressors Important to Stream Health – Additional Information

Flow

Stream restoration has been shown to retain excess flow through legacy sediment removal and floodplain reconnection. For example, Langland et al. (2020) documented 10,000 cubic meters of additional storage following a stream restoration project in Pennsylvania.

Riparian

The Gothe et al. (2016) study evaluated restoration projects in 20 catchments across 10 European regions and classified by restoration extent and type to identify the main determinants of structural and functional responses of riparian plant communities. The main determinants were found to be discharge, altitude, and restoration type. Restoration type was the only significant determinant and widening the stream channel had the strongest determining effect on plant community responses. Their study also examined land use on plant community responses to restoration. Catchment land use was a weak predictor of plant community response. The strongest relationship was found between agricultural land use and the response ratios of geophyte-community weighted mean (CWM). The geophyte response ratios decreased with increasing agricultural land use which indicates a "negative geophyte response to grazing and especially phosphorus availability" (Gothe et al. 2016).

Kasse et al. (2012) compared channel environment metrics and riparian vegetation metrics among reference, restored, and degraded sites in nine rural headwater streams. Riparian vegetation metrics of species richness, basal area, and canopy cover indicated treatment effects. The effect of site treatment (i.e., reference, restored, or degraded) on species richness was significant. The most fundamental difference between degraded and restored sites was the dominance of planted species at restored sites. Channel width, channel bed canopy cover, riparian stem density, and percentage canopy cover did not differ between restored and degraded sites, while species richness and basal area were marginally different.

Habitat

Bukaveckas et al. (2007) conducted a 4-year study that "measured water velocity, transient storage, and nutrient uptake in channelized (pre-restoration) and naturalized (post-restoration) reaches of a stream to assess the effects of restoration on mechanisms of nutrient retention." The difference between the higher transient storage value for the restored reach when compared to the channelized reach was significant. Reduced water velocity was the primary mechanism enhancing nutrient uptake in the restored channel compared to the channelized segment. This finding was "most apparent in the subreach of the restored channel connected to a backwater area." Dispersion values also suggest that the flow conditions within the restored channel have greater complexity after restoration.

Kasse et al.'s (2012) results show that stream channel width and canopy cover indicate treatment (i.e., reference, restored, and degraded) effects. There were significant effects of site treatment on channel width and canopy cover. The reference site channel width and channel canopy cover were significantly different from that of both degraded and restored site types. Both channel width and canopy cover were similar for the degraded and restored sites.

McMahon et al. (2021) studied six legacy sediment removal and floodplain reconnection restoration projects for water quality impacts, measuring upstream and downstream loads and concentrations. They did not find significant removal of nitrogen in baseflow. In agricultural settings there was not enough carbon to achieve denitrification, but the forested reference site consistently had plenty of total organic carbon (TOC).

Thompson et al. (2018) examined the effects on water quality from a regenerative stormwater conveyance (RSC) restoration designed to increase the residence time of water and encourage frequent floodplain inundation to increase sediment deposition and nutrient removal through biological uptake. They observed large changes in flow weighted mean concentration (FWMC) between the periods before and after restoration and observed sustained flow in the treatment watershed relative to the reference after restoration. In addition, there was a “noticeable divergence between the inflowing and outflowing “Flow Duration Curves (FDCs)” at low flows. After restoration, they saw a reversal where flows were being sustained for longer periods at the inlet than at the outlet.

BMP Name	Other Toxics	Flow	Salinity	Pesticides	Geomorphology	
					Habitat	Sediment
Agricultural Stream Restoration	Not key stressors in ag. setting				★	⯪

Figure 17. Effectiveness ratings for agricultural stream restoration and each stressor intersection. See Figure 4 for Legend.

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Wetlands

There is a wide range of wetland practices used in the Chesapeake Bay Watershed. To differentiate the practices, the CBP has establish four categories for wetland practices based on key differences. These categories are restoration, rehabilitation, enhancement, and creation. Each category involves the manipulation of the physical, chemical, or biological characteristics of a site. The only difference between the wetland practices is the end goal or purpose of the manipulations, or actions, taken in the site area. The goal of Wetland Restoration is to repair the natural/historic functions to a former wetland. Wetland Rehabilitation's goal is to repair the natural/historic functions to a degraded wetland. Wetland Enhancement seeks to heighten, intensify, or improve a specific function in an existing wetland. Lastly, Wetland Creation (Establishment) develops a new wetland that did not previously exist.

Effectiveness & Treatment Mechanisms

A study evaluating created wetlands in California's Central Valley (Budd et al. 2009), saw a decrease in all seven of the pesticides monitored by both wetlands in the study. It's important to note the highly permeable soils in the area of study – California's Central Valley – lead to high infiltration rates which had a large effect on flow reduction and therefore pollutant reduction. Flow was also present only in the irrigation season, May-Sept. Higher flow events also showed lower sediment and pesticide removal. Removals would likely be lower in Chesapeake Bay conditions due to year-round precipitation and conditions with less permeable soil and higher groundwater.

Vymazal & Brezinová (2015) reviews 47 studies evaluating the use of constructed wetlands to remove pesticides from agricultural runoff. The most common constructed wetland type used in agriculture is the free water surface (FWS) constructed wetland (CW). Other types of constructed wetlands include subsurface flow (SF), vertical flow (VF), and hybrid constructed wetlands. The review studied 87 different pesticides, and effectiveness of the BMP is calculated as the average of load reduction values reported across all studies reviewed where the pesticides was evaluated in at least two studies. This review by Vymazal & Brezinová (2015) highlights that we can only remove pesticides from runoff and erosion (which are generally the major sources), not from spray-drift (generally a secondary source), leaching, drain flows, or atmospheric transport (volatilized or wind eroded soil).

A study by Toner & Keddy (1997) created a simple model of the limits of wooded wetland based on three variables that capture the impacts of flooding. They identified 1) the best predictors of the lower limit of wooded wetland, 2) the range of the predictors in which there is a low probability of dominance by woody plants, and 3) the period of time over which these variables would be effective. Changes in flow from dam construction and water diversion projects was the main stressor on the limits of wooded wetland in this study. Their best model combined variables for the last day of the first flood and the time of the second flood - a simple testable model that could provide a tool for maintaining wetland area and diversity. Time of the second flood is one of the best single predictors. This study focused on the effects of altered hydrology on riparian wetlands, specifically vegetation conditions. It is helpful to show how one stressor on stream health (flow) can affect another stressor (riparian area) as well as a BMP (wetland).

The mechanisms used by constructed wetlands to treat stressors to stream health, like pesticides, include sedimentation of pesticide-bound particles, photolysis, hydrolysis, adsorption, microbial degradation, plant absorption and metabolism. Budd et al. 2009 noted increased removal with increased hydraulic residence time and vegetation density as well as increased removal with increased sorption to sediment particles. Vymazal & Brezinová (2015) highlights the following factors for influencing treatment effectiveness: pesticide characteristics, pesticide distribution, organic carbon-water partition coefficient (K_{oc}), K_{ow}, half-life on soil, half-life in water, and soil and water photolysis. The Vymazal & Brezinová (2015) study also found that removal was highest for pesticides with: low solubility, very high K_{oc}, very high K_{ow}. Treatment mechanisms, pesticide, and treatment conditions are combined and connected in complex processes that make singling out particular mechanisms difficult. Designs with multiple zones (e.g., open water and vegetated) and/or hybrid constructed wetlands are encouraged to increase potential for multiple treatment mechanisms.

BMP Name	Other Toxics	Flow	Salinity	Pesticides	Geomorphology	
					Habitat	Sediment
Wetlands	Not key stressors in ag. setting			★	★	☆

Figure 18. Effectiveness ratings for wetlands and each stressor intersection. See Figure 4 for Legend.

References

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Research Gaps and Challenges

The results, conclusions and implications drawn from the literature reviewed in this study are based on the availability of research on how recommended BMPs in urban and agricultural settings affect important stream health stressors. Challenges encountered in this study are highlighted below and gaps in existing research are identified where they were apparent.

Data Richness

The breadth of the present study made providing sufficient depth of investigation challenging. There were at least 48 intersections between key stressors and priority BMPs (coarsely grouped) to be studied (Figure 3). In preliminary iterations, this number was even higher. At least 240 papers would need to be reviewed to have five sources for each BMP-Stressor intersection. Availability of time and funding constrained the search and review of literature, making even this conservative number difficult for the present project. To account for this, review papers and larger studies examining multiple stressors or BMP types were prioritized. Journal impact factor was one means by which these studies were identified. This reduced the number of studies to a manageable number for evaluation and inclusion in this report, however, the use of this metric likely excluded studies that may have benefitted this literature review. A secondary literature search targeting BMP and stressor intersections with too few quantitative data sources would improve the study. Figure 19 highlights BMP-stressor intersections where additional research and data sources would be most beneficial. This additional research could be added to strengthen the data richness and confidence of conclusions presented in this report. It is possible that for some of the intersections highlighted, insufficient research has been conducted and data gaps exist in the literature. The difficulty in finding these sources in the literature search and review indicates that this may be the case.

BMP Type		**Stressors Important to Stream Health**					
Setting	**BMP Name**	Other Toxics	Flow	Salinity	Pesticides	Geomorphology	
						Habitat	Sediment
Urban	Wet Ponds and Wetlands						
	Dry Ponds						
	Bioinfiltration						
	Urban Forest Buffers						
	Urban Tree Planting						
	Urban Stream Restoration						
Agricultural	No Till and Cover Crops	Not key stressors in agricultural settings					
	Pasture Management						
	Vegetated Buffers						
	Agricultural Drainage Management						
	Agricultural Stream Restoration						
	Wetlands						

Figure 19. BMP-stressor intersections highlighted for which additional data sources could be targeted to improve data richness.

Salinity

The structural BMPs and management practices included in this study were found to have a low effectiveness for reducing the salinity stressor. Stormwater BMPs (e.g., bioinfiltration, wet ponds and wetlands, and dry ponds) were shown to slow pulses of salts and release them slowly – reducing peaks in the discharges. Salts were also found to “hide” in stream groundwater, hyporheic zone, and streambanks. Smoothing salinity peaks may or may not be better for biotic health when the overall effect is prolonged periods of high salinity. The effects of these alterations to the salinity regime through BMP implementation could be further investigated. Some evidence of salt retention in BMPs was found in the literature but questions remain regarding the impact at larger spatial and temporal scales. Watershed-scale and long-term monitoring studies could advance the understanding of BMP influence on salinity. The body of knowledge on performance of individual BMPs could also be increased. Few studies were found evaluating BMPs by monitoring the input, storage, and discharge of salts, thereby enabling a mass balance approach to understanding salt fate and transport.

A key caveat should also be noted. This study only examined a select set of structural BMPs and research primarily focused on road salt as a salinity source. Salinity challenges are mainly due to the practice of road salting to prevent icing during the winter, but there are other sources that can be significant (e.g., agriculture). Management practices, unrelated to the recommended sediment- and nutrient-targeted BMPs included in this study, have been shown to be effective in addressing sources of salinity (CWP 2019). The conclusions in this report only apply to the subset of structural BMPs and management practices reviewed and does not consider other management approaches for reducing salt that were not included in this research.

Geomorphology-Habitat

The complexity of stream geomorphology and habitat made it difficult to quantitatively summarize the effectiveness of BMPs on this stream health stressor through a single descriptive statistic. The main challenge is quantitatively providing a comparison between research studies where different metrics were measured, or monitored, and integrating these disparate metrics through a comprehensive, quantitative assessment approach. It may be possible to quantitatively evaluate and combine disparate metrics for geomorphology-habitat, but science-based weighting factors or some other method beyond the scope of this study would be required. This challenge is compounded by the fact that the only BMP in this study capable of directly affecting in-stream habitat was stream restoration, which is a BMP that includes numerous design approaches, motivations, and objectives for project implementation. Outcomes for various geomorphology-habitat metrics were found to vary by stream restoration approach. While stream restoration BMPs showed positive impacts on a variety of geomorphology-habitat metrics (e.g., Larson et al. 2001; Bukaveckas et al. 2007; Bain et al. 2014; Gothe et al. 2016), it should be noted the results may not hold true for all stream restoration techniques (e.g., Natural Channel Design, Legacy Sediment Removal, Regenerative Stormwater Conveyance, Large Woody Debris, Beaver Dam Analog, Floodplain Reconnection, etc.). In addition to the use of effective restoration approaches, improving stream geomorphological stressors over long time scales requires addressing the cause(s) of the system's degradation both upstream and upland. Violin et al. (2011) commented that rebuilding habitat may not be enough to support the recovery of biotic communities stating that "habitat restoration will prove ineffective if urban stormwaters rapidly rehomogenize restored stream segments, as seen in previous urban restorations."

Potential for Future Studies

In addition to limited resources for certain BMPs and stream health stressors, specific knowledge gaps were noted within studies. Some of these are highlighted below:

- The use of the ratio of source area to buffer area is suggested as a more effective method for measuring the efficacy of vegetated buffers that is rarely reported when compared to buffer width (Prosser et al. 2020).

- A 2017 conference session survey (n = 14) of an international group of experts showed that they thought channel morphological improvements and terrestrial biodiversity to be the primary benefits actively sought and managed for through buffer strip implementation. This same group rated the evidence levels for channel morphological benefits from riparian buffers as "low" (Stutter et al. 2019).
- Berland et al. (2017) mentions the need for documented performance of trees as stormwater control by species and life stage as well as situating stormwater control in the context of urban forestry goals and arboricultural challenges.
- Policy analyses for urban tree canopy to be integrated into stormwater management decisions and credited by regulators (Kuehler et al. 2017).
- A standardized measurement process for throughfall, or canopy intercept, and stemflow would be beneficial for comparing the effectiveness of tree planting on stormwater benefits or runoff reductions (Livesley & Glover 2014).

In addition, the authors of this report see a need for future studies to explore:

- The potential needs for groundwater treatment and/or soil remediation with the use of infiltration-based BMP methods used to "remove" toxics and pesticides from runoff.
- The effects of real-time control of wet ponds and wetlands and dry ponds on BMP effectiveness.
- Elements of flow regimes most responsible for stream health and BMP effects on these key elements.
- Impacts of cover crops herbicide use on the overall effectiveness of the no-till and cover crops BMP.
- The role of soil health, water storage, and infiltration capacity in the stormwater benefits of trees and the impact of trees at larger spatial scales.
- The co-benefits from and the effectiveness of Stream Restoration BMPs on the stream health stressors included in this study. The complexity and diversity of this BMP warrants a separate study.
- Guidance on the appropriate maintenance of vegetated buffers should be explored to maximize BMP effectiveness.

Conclusion

Sediment removal and flow reduction are two of the most effective mechanisms for reducing other toxics and pesticide stressors. Sediment-associated contaminants are effectively trapped in sediment-removing BMPs (e.g., vegetated buffers, wet ponds and wetlands, and bioinfiltration). Flow reduction reduces the transport of pollutants to streams. BMPs effective at reducing flow are bioinfiltration and urban tree planting. It should be noted that reduction of overland flow is typically achieved via infiltration to shallow groundwater, which can potentially be a transport vector of pollutants to streams. These two vectors – flow and sediment – are the main reason why some BMPs are more effective than others at reducing pesticides and other toxics stressors from entering streams as well as benefiting stream geomorphology.

For agricultural settings – since the most important stream health stressors are pesticides and geomorphology – agricultural wetlands and vegetated buffer can effectively reduce pesticides in runoff and stream restoration can improve geomorphology. Reduced pesticide usage is also important for the agricultural sector.

For urban settings – where the most important stream health stressors are flow, geomorphology, other toxics, pesticides, and salinity – bioinfiltration and urban tree planting can help manage altered flow regimes. Bioinfiltration also provides co-benefits for pesticide and other toxics stressors, as does wet ponds and wetlands. Stream restoration can improve geomorphology. None of the structural BMPs studies is expected to improve salinity.

Effectiveness was assessed at the practice level. Therefore, it is important to consider the potential extent of BMP implementation and effects along with the effectiveness ratings. It is also important to pursue a broad implementation strategy. Because multiple stressors are responsible for degradation of stream biological health and no BMP is effective at all key stressors, a multi-BMP approach is necessary to address multi-stressor degradation to stream health.

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Appendix A

Table A-1. BMPs from full list of CAST BMPs excluded from the study and justifications for removal (CBP 2020).

Sector	Fine BMP Group	Justification for Removal
Urban BMPs	Runoff Reduction Performance Standard	not a "BMP"
	Storm Water Treatment Performance Standard	not a "BMP"
	Conservation Landscaping Practices	no BMPs of this type were reported in 2015-2019
	Erosion and Sediment Control	Research showed obvious impact of sediment reduction, but not co-benefits
	Grey Infrastructure (IDDE)	Literature consisted of guidance manuals with little available on impacts
	Urban Grass Buffers	no BMPs of this type were reported in 2015-2019
	Impervious Disconnection	Not widely practiced and difficult for jurisdictions to implement
	Urban Filter Strips	Not widely practiced
	Impervious Surface Reduction	Difficult for jurisdictions to implement
	Septic Connections	Limited potential for co-benefits
	Septic Denitrification	Limited potential for co-benefits
	Septic Secondary Treatment	Limited potential for co-benefits
	Septic Effluent	Limited potential for co-benefits
	Septic Pumping	Limited potential for co-benefits
	Urban Shoreline Management	Typically found in tidal areas, not non-tidal streams
	Storm Drain Cleanout	Maintenance activity, not structural BMP or management practice
	Street Sweeping	Maintenance activity, not structural BMP or management practice
	Urban Nutrient Management	Limited potential for co-benefits
	Permeable Pavement	Limited acreage treated.
Ag BMPs	Nutrient Application Management Core Nitrogen	Not identified as a priority by TAG
	Nutrient Application Management Rate Nitrogen	Not identified as a priority by TAG
	Nutrient Application Management Placement Nitrogen	Not identified as a priority by TAG
	Nutrient Application Management Timing Nitrogen	Not identified as a priority by TAG
	Nutrient Application Management Core Phosphorus	Not identified as a priority by TAG
	Nutrient Application Management Rate Phosphorus	Not identified as a priority by TAG
	Nutrient Application Management Placement Phosphorus	Not identified as a priority by TAG
	Nutrient Application Management Timing Phosphorus	Not identified as a priority by TAG

	Manure Incorporation	Not widely practiced (MD only).
	Crop Irrigation Management	no BMPs of this type were reported in 2015-2019
	Livestock Waste Management Systems	Limited potential for co-benefits
	Poultry Waste Management Systems	Limited potential for co-benefits
	Manure Transport Out Of Area	Limited potential for co-benefits
	Manure Transport Into Area	Limited potential for co-benefits
	Poultry Mortality Composting	Limited potential for co-benefits
	Capture & Reuse	no BMPs of this type were reported in 2015-2019
	Manure Treatment Technologies Out Of Area	no BMPs of this type were reported in 2015-2019
	Manure Treatment Technologies Into Area	no BMPs of this type were reported in 2015-2019
	Ag Stormwater Management	no BMPs of this type were reported in 2015-2019
	Ammonia Emission Reductions (Litter Amendments)	Limited potential for co-benefits
	Ammonia Emission Reductions (Biofilters)	no BMPs of this type were reported in 2015-2019
	Ammonia Emission Reductions (Lagoon Covers)	no BMPs of this type were reported in 2015-2019
	Land Retirement	Not identified as a priority
	Tree Planting	Limited potential for the co-benefits considered
	Alternative Crops	Not widely practiced.
	Non-Urban Shoreline Management	Typically found in tidal areas, not non-tidal streams
	Soil and Water Conservation Plan	Components of conservation plans captured in other BMP categories.
	Livestock Mortality Composting	Not widely practiced (MD only).
	Dairy Precision Feeding	Not widely practiced (NY only).
Resource BMPs	Oyster Aquaculture	no BMPs of this type were reported in 2015-2019
	Oyster Reef Restoration	no BMPs of this type were reported in 2015-2019
	Non-Tidal Algal Flow-way	no BMPs of this type were reported in 2015-2019
	Tidal Algal Flow-way	no BMPs of this type were reported in 2015-2019
	Forest Harvesting Practices	Nature of the BMP does not fit study. Little research found in USGS stressor study.
	Abandoned Mine Reclamation	Nature of the BMP does not fit study. Little research found in USGS stressor study.
	Dirt&Gravel Road E&S	Nature of the BMP does not fit study. Little research found in USGS stressor study.