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RESEARCH ARTICLE

Modeling nonlinear edge-of-field buffers to enhance sediment trapping efficiency: Application of AgBufferBuilder in the Saginaw Bay basin

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ABSTRACT
Due to concentrated surface water runoff, edge-of-field buffers may ineffectually mitigate agricultural nonpoint source pollution. To address this challenge, we evaluated the AgBufferBuilder (ABB) tool, which designs nonlinear buffers based on hydrologic modeling. ABB was tested on 45 areas of interest (AOIs) within the Saginaw Bay basin in central Michigan (United States) to determine the effectiveness of ABB at improving sediment trapping efficiency from runoff compared to existing conditions. While ABB did not consistently achieve the target sediment trapping efficiency rate of 75% in all AOIs, it demonstrated potential for enhancing sediment retention using nonlinear buffers in 37 of 45 AOIs. Spatial reconfiguration, a process of redesigning buffer layout based on ABB results, allowed for increased sediment trapping efficiency while requiring less total area to be taken out of crop production than existing conditions in 15 cases. Despite software limitations, including an outdated platform, ABB offers an approach to nonlinear buffer design that may enhance buffer performance to protect water quality. Updates to the ABB model and increased accessibility are essential for broader adoption.

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buffer; conservation targeting; edge-of-field; filter strip; sediment loss; vegetative buffer strip

INTRODUCTION

This study investigates the potential of optimizing nonlinear edge-of-field buffer designs to enhance sediment trapping efficiency and reduce agricultural nonpoint source pollution. Agricultural practices are a primary contributor to water quality degradation in the United States, with nonpoint source pollution from agricultural fields being a significant concern (Ahearn et al. 2005; Capel et al. 2018; Coulter, Kolka, and Thompson 2004; Jabbar and Grote 2019; Logan 1993; Tong and Chen 2002; US EPA 2015). Sediment and nutrient runoff from agricultural lands enter local waterways through overland flow and subsurface tile drainage systems. Climate change is exacerbating this issue due to increased frequency and intensity of rainfall events, necessitating innovative approaches to conservation practices (Bartlett and Dedekorkut-Howes 2023; Gowda et al. 2018; Mehdi et al. 2015).

We build on Dosskey et al. (2002, 2015; Dosskey, Helmers, and Eisenhauer 2008, 2011) work, who concluded that nonlinear field-edge conservation buffers could significantly improve sediment trapping efficiency and associated nutrient dynamics. Their work showed that nonlinear buffers may increase total sediment trapping by approximately 50%, on average, compared to industry standard linear, fixed-width edge-of-field practices (Dosskey et al. 2015). Statistical models suggest that variable-width (nonlinear) buffers address one of the leading factors in pollutant (sediment, pesticides, nitrogen [N], and phosphorus [P]) removal efficacy for addressing nonpoint source pollution in agricultural fields (Zhang et al. 2010). We extend this work by exploring the following study objectives. The first objective is to evaluate the AgBufferBuilder (ABB) tool for its potential to improve water quality by supporting the design of nonlinear buffers. Focusing on sediment trapping

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efficiency rates, we expand upon previous research highlighting individual field case studies by Dosskey et al. (2002, 2015; Dosskey, Helmers, and Eisenhauer 2008, 2011) in two critical ways. First, we apply ABB to 45 systematically selected areas of interest (AOIs) within three subwatersheds of the Saginaw Bay watershed in Michigan (United States) to understand how the tool performs across multiple fields and landscape conditions. Second, our methods include assessing unfarmable areas that need removal from production due to the geometry of ABB-proposed nonlinear buffers based on the limitations of typical tractor movement in the field. The second study objective is to evaluate ABB's utility for optimizing edge-of-field buffer layouts through spatial reconfiguration, aiming to minimize the total buffer area required to meet sediment trapping efficiency goals. Spatial reconfiguration of edge-of-field buffers is a process of redesigning buffer layouts based on ABB results to determine if it can enhance water quality outcomes. We applied the ABB tool to compare the total area and sediment trapping capabilities in a given AOI between existing edge-of-field conservation practices and proposed nonlinear edge-of-field buffers, which are modeled to maximize sediment trapping efficiency.

Conservation buffers

Several strategies can address agricultural nonpoint source pollution that results from erosion-driven sediment leaching into local waterways due to stormwater runoff and snowmelt (Logan 1993; Myers et al. 1985). One approach focuses on reducing pollutant generation through on-field practices such as cover cropping, tillage, and precision agriculture (Bongiovanni and Lowenberg-Deboer 2004; Ruffatti et al. 2019; US EPA 2015). Alternatively, conservation buffers can mitigate pollutant transport (Dabney, Moore, and Locke 2006; Lovell and Sullivan 2006; Lowrance, Dabney, and Schultz 2002; Wu et al. 2023). These vegetative areas, including filter strips, riparian buffers, and field borders, slow surface runoff, reduce erosion, and trap sediment. Many of these practices are similar, with their primary distinction being their location within or along the edge of the field or their proximity to a water body (Dabney, Moore, and Locke 2006; Lowrance, Dabney, and Schultz 2002). Buffers for water quality protection incorporate vegetation to slow surface runoff, reducing rill and sheet erosion and facilitating sediment deposition.

Buffer design

Buffers are commonly designed and implemented linearly with a fixed-width strip of vegetation planted along the field or stream edge or upslope within the field perpendicular to the predominant direction of runoff flow. This uniform approach simplifies buffers' design, implementation, and maintenance by incorporating them into the customarily linear patterns of tractor movement. Typically, studies use the width of linear buffers as the primary determinant variable for buffer effectiveness to determine a standard buffer width and recommend best management practices (King et al. 2016; Lee, Smyth, and Boutin 2004; Lerch et al. 2017; Lv and Wu 2021; Mayer, Reynolds, and Canfield 2005; Mayer et al. 2007; Prosser et al. 2020).

Michigan, similar to most states in the Midwest United States, offers support to producers through a nonpoint source program that provides technical assistance, information and education, access to state and federal funding through grants to support the implementation of best management practices, and land use planning that includes monitoring water quality issues in agricultural landscapes (MI EGLE n.d.). Producers and agriculture professionals evaluating conservation programs in Michigan shared that existing conservation programs are often limited to "entry-level" conservation practices, including linear edge-of-field buffers, while lacking the capacity to implement more complex practices that are necessary to address the scope and scale of conservation challenges (Zimnicki et al. 2021). Regional efforts to increase linear buffer adoption along streams and rivers, such as those mandated by the Minnesota Buffer Law, are widely implemented to mitigate agricultural nonpoint source pollution (State of Minnesota Revisor of Statutes 2021; MN BWSR n.d.; MN BWSR 2021). While these buffers improve water quality by stabilizing banks and reducing erosion, their fixed-width requirements are unlikely to address concentrated flow runoff (Pankau et al. 2012; Shrestha et al.

2018). Not accounting for concentrated flow means that fixed-width buffers are unlikely to control some of the most significant runoff points within particular fields, translating into water quality impairments at the watershed and landscape scales. Increasing buffer widths uniformly to accommodate high-flow areas would impose undue burdens on landowners and lead to agricultural land loss. Tailored buffer designs that account for site-specific hydrological conditions and dynamically respond to changing concentrated flow conditions over time are necessary to protect water quality while minimizing negative impacts.

Controlling nonpoint source pollution requires alternative practices in areas where linear buffers are ineffective, and several approaches exist in the literature for addressing concentrated flows. The assumption of uniform, planar flow across the entire buffer leads to conventional linear buffer designs (Helmers et al. 2005a, 2005b). However, nonuniform runoff flow is prevalent in agricultural landscapes. Many site-specific factors such as slope, slope length, soil type, and surface cover roughness influence the effectiveness of a buffer and cause considerable variation in the required buffer width to trap runoff in different contexts effectively (Dillaha et al. 1989; Dosskey, Helmers, and Eisenhauer 2008; Dosskey et al. 2002; Prosser et al. 2020; Shrestha et al. 2018; Wallace et al. 2018). In the case of the Minnesota Buffer Law, the Minnesota Board of Water and Soil Resources (BWSR) responded to demands from stakeholders by amending the administrative rule to allow approved alternative practices and developing guidance on alternative practices (MN BWSR n.d.). The BWSR guides projects using critical area plantings in locations where the concentrated flow enters a water body based on the contributing upslope area, creating spatially targeted, nonlinear buffers.

MATERIALS AND METHODS

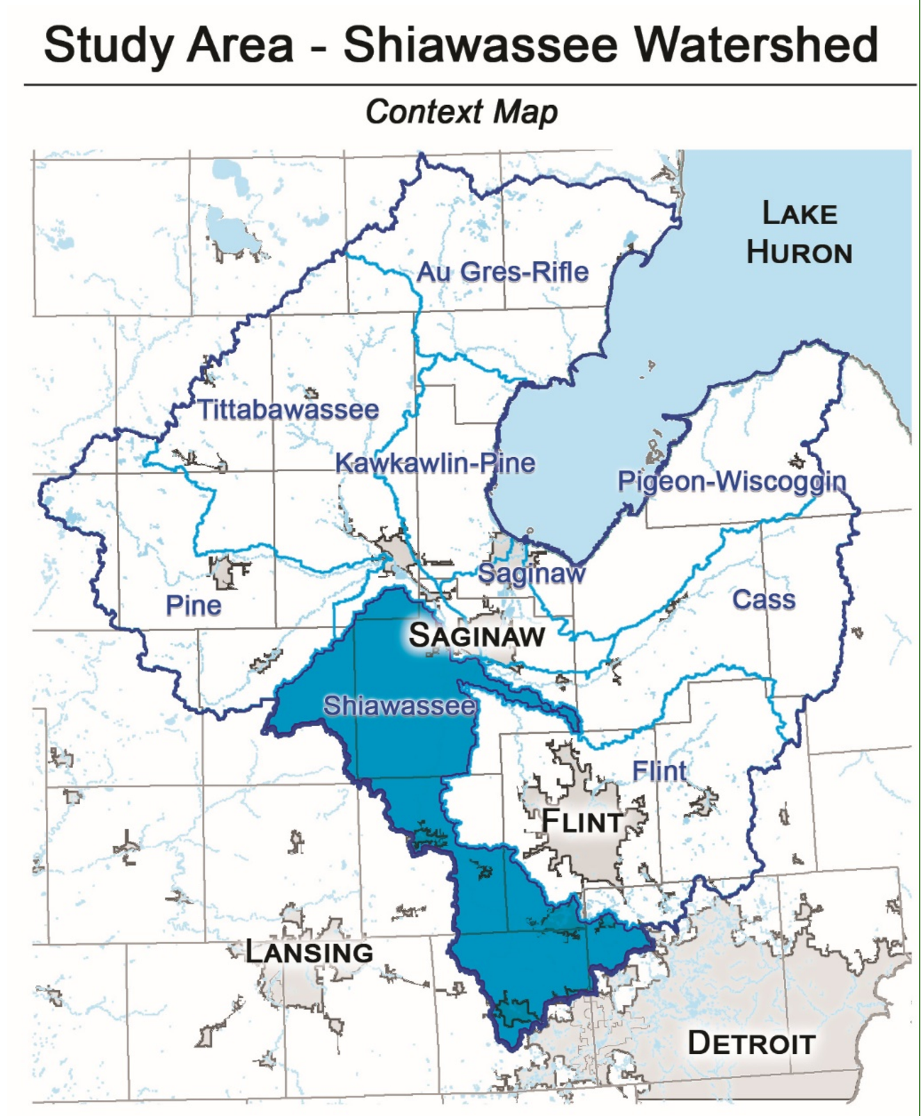
This study evaluates the ABB tool, a field-scale, buffer-to-area ratio-based GIS tool developed to address the issue of concentrated flow across fixed-width linear buffers (Dosskey et al. 2015). Buffer configurations are determined by process-based mathematical models accounting for contributing upslope area, slope, slope length, soil texture, and soil surface cover. The ABB-modeling process involves a series of steps aided by ArcGIS tools. The process begins with users drawing the field margin based on aerial photograph interpretation. Then the modeling software uses a digital elevation model (DEM) tosegment field margins and leverages the "flow accumulation" and "slope" functions in ArcMap to calculate each segment's contributing area size and slope. The process allows users to set model parameters for desired trapping efficiency, predefined soil texture, and tillage type. Finally, the modeling software calculates the required filter area for each segment. It converts the result to raster grid cells, and the modeling software recalculates the sediment trapping percentage while generating a map showing the proposed buffer and a table with statistical results. This dual design and evaluation functionality allows for scenario comparisons and can be used to estimate the water quality improvement potential for a given AOI.

Dosskey, Helmers, and Eisenhauer (2008, 2011) developed ABB as a series of models that integrate concepts derived from the Vegetative Filter Strip Model (VFSMOD) with design aids that estimate optimal buffer width based on factors like pollutant type, field length, slope, soil texture, and land cover, assuming uniform runoff distribution. To address concentrated flow, they later introduced a segmented buffer approach (Dosskey, Helmers, and Eisenhauer 2011) that determined buffer segment width based on the relationship between buffer area and sediment trapping efficiency. ABB automates these concepts, creating variable-width buffer designs based on site-specific conditions. Although initially developed for earlier ArcGIS versions, we successfully implemented ABB using ArcMap 10.8 in this study (ESRI 2019). We compared existing field-edge buffers to ABB-designed nonlinear buffers across 45 AOIs in three subwatersheds with varying sediment loads to assess ABB's utility in identifying water quality improvement potential. The following research questions guide this study based on our underlying objectives: (1) how effective are ABB-designed nonlinear buffers in capturing sediment compared to existing field-edge buffers across different agricultural landscapes, and (2) can spatial reconfiguration of buffers, as ABB facilitates, improve sediment trapping efficiency while potentially reducing overall buffer area? By addressing these questions, the study aims to evaluate the effectiveness of ABB as a tool for optimizing buffer design, which has the potential to improve water quality.

Study area

The Saginaw Bay watershed, shown in Figure 1, is a critical ecosystem encompassing 2.2 million ha (5.5 million ac) across 22 counties (The Nature Conservancy n.d.). Base map data for Figure 1 and subsequent figures were obtained from USDA NRCS Geospatial Data Gateway (2024). Renowned for its diverse habitats and rich biodiversity, the bay is a vital breeding ground for fish species like walleye (MI Sea Grant n.d.). However, designated as an Area of Concern due to severe water quality impairments, Saginaw Bay's challenges are caused primarily by nonpoint source pollution, particularly from agriculture (US EPA 2021). Nonpoint source pollution contributes roughly 75% of P loads in the watershed and significantly contributes to N loads in this basin (He et al. 2014). Reducing agricultural nonpoint source pollution continues to be a focus of ongoing restoration efforts (Fales et al. 2016; He et al. 2014; Sowa et al. 2013). Despite progress, challenges persist,

Figure 1. Regional context for the Saginaw Bay watershed basin, highlighting the study area in the Shiawassee watershed.



including eutrophication, harmful algal blooms, and fish kills (Beletsky et al. 2013).

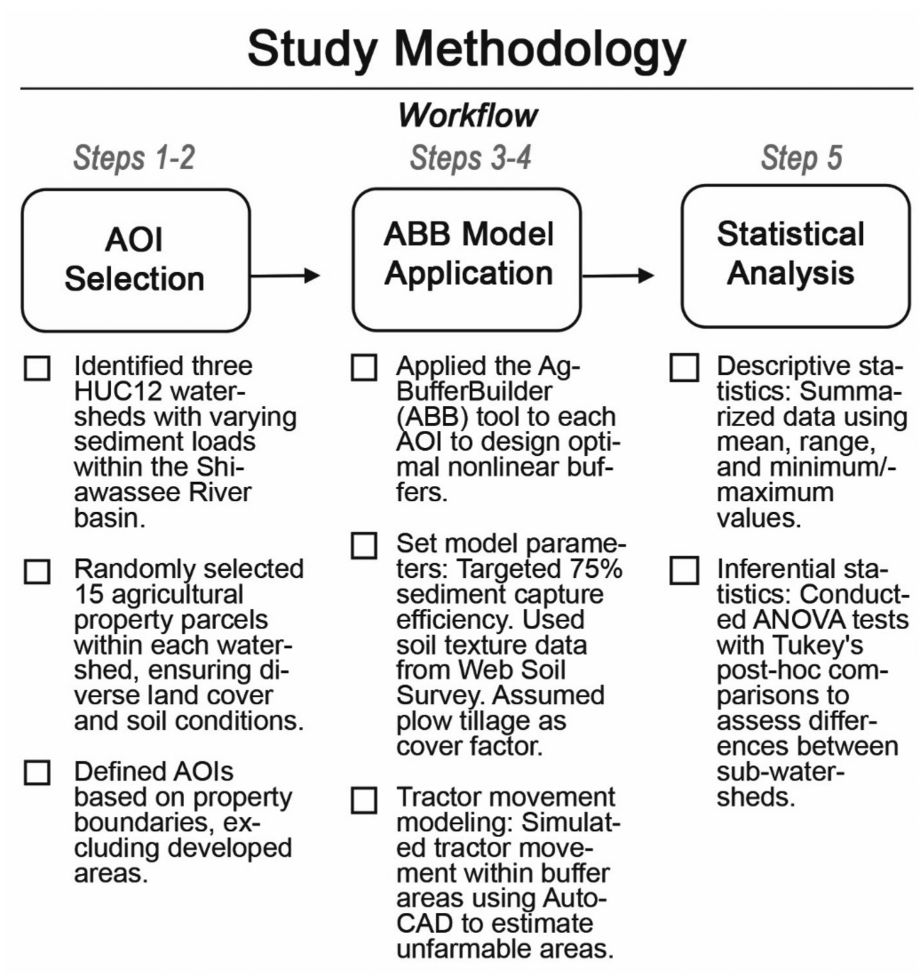
The Shiawassee River basin, selected at the Hydrologic Unit Code (HUC) 8 scale, serves as our study area within the broader Saginaw Bay watershed. We chose this basin due to its diverse land use patterns, ranging from primarily agricultural areas to subwatersheds with a mix of urban, forested, and agricultural land cover. This variety suited our goal of comparing ABB functionality across a gradient of agricultural intensity within a larger watershed.

Methods

An overview of the workflow is provided in Figure 2, highlighting key steps in our research process. To begin, we selected three watersheds within the Shiawassee River basin representing a range of sediment loading conditions to evaluate the effectiveness of nonlinear edge-of-field buffers in mitigating agricultural nonpoint source pollution. Within each of the three subwatersheds, based on land cover and soil characteristics, we selected 15 AOIs ($n = 45$). The ABB tool was applied to these AOIs to design and assess nonlinear buffer configurations.

To select study subwatersheds (step 1), we used data from the Great Lakes Watershed Monitoring System (GLWMS) to identify HUC12 watersheds within the Shiawassee River basin with varying sediment loading characteristics. GLWMS utilizes the Revised Universal Soil Loss Equation to estimate sediment loads based on tons of sediment contributed per acre per year (MSU IWR et al. 2021). We categorized HUC12

Figure 2. Research methodology workflow diagram showing a summary of key research steps. AOI is area of interest; HUC12 is Hydrologic Unit Code 12.



watersheds into low, medium, and high sediment loading classes by applying zonal statistics and natural breaks classification in ArcGIS Pro (ESRI 2023). Subsequently, we selected one watershed with a median sediment load from each class for detailed analysis: North Ore Creek (low), Bear Creek (medium), and Shad Creek (high), as shown in Figure 3.

To select AOIs (step 2), we randomly selected 15 agricultural property parcels within each watershed using the Public Land Survey System (PLSS) dataset, NLCD land cover data, and the ArcGIS Create Random Points tool (Dewitz 2023; ESRI 2023). As shown in Figure 4, we created a starting polygon shapefile by selecting only PLSS quarter-quarter sections with greater than 70% agricultural land cover. Next, we selected 15 random centroid points within the land cover-filtered, quarter-quarter section polygon file. We then used the quarter-quarter sections to select individual AOIs defined by property parcel boundaries. Property boundaries were obtained from county GIS departments and incorporated into the AOI definition (Parcel Boundaries of Michigan 2021). We drew an AOI for each field based on the legal parcel boundary. When property parcels included houses, structures, parking lots, or other developed land uses, the parcel boundary was

Figure 3. Breakdown of sediment loading within the Shiawasee watershed, highlighting the selected Hydrologic Unit Code (HUC) 12 subwatersheds.

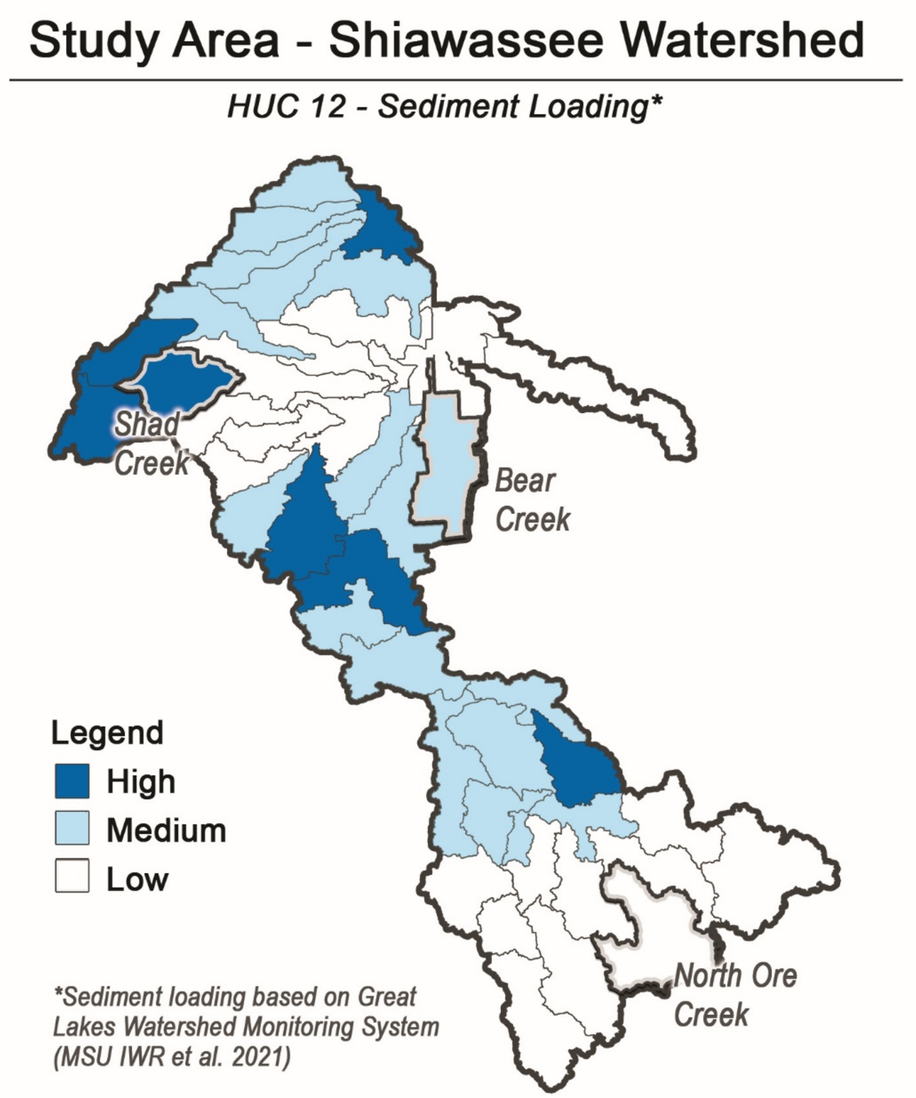
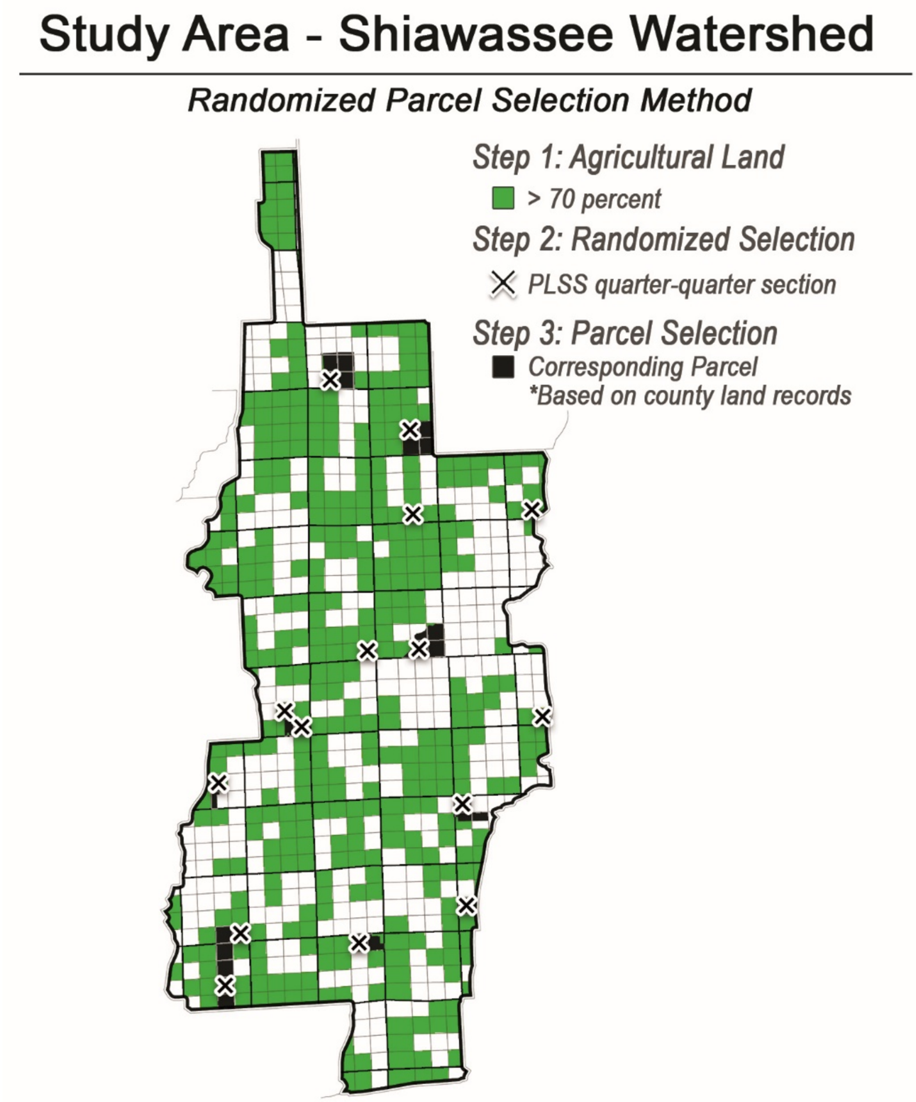


Figure 4. Breakdown of the parcel selection process for randomly selecting areas of interest for the Shiawassee watershed. PLSS is Public Land Survey System.



modified to exclude these areas based on a visual determination using 2016 orthoimagery from the National Agriculture Imagery Program (NAIP) (USDA FSA 2016). ABB required parcels intersected by streams to be split into two subsections and analyzed separately. We drew both property parcels for independent evaluation if a centroid point fell directly on a property boundary. These two types of split-parcel analysis occurred in 3 (stream splits) and 1 (centroid split) of the 45 AOIs. After initial analysis, the results for all sections of each subdivided parcel were recombined to create a single result for each parcel. This procedure resulted in 45 AOIs, with 15 each in the Shad Creek, Bear Creek, and North Ore Creek subwatersheds.

Running the ABB model (step 3), we used settings shown in Tables 1 and 2 to provide an overview of ABB input and output parameters; for a detailed explanation of model parameters, see ABB documentation (Dosskey et al. 2015). For each AOI, ABB was run with a 9 m (29.5 ft) pixel size, targeting sediment trapping with a 75% efficiency goal. Soil texture data from the Web Soil Survey informed the model, while we made a standard assumption of plow tillage as the cover factor (USDA 2022). The ABB tool's buffer assessment function evaluated existing

Table 1. List of AgBufferBuilder (ABB) main tool input parameters and user-selectable parameter options.

ABB input parameter	Input parameter options	Selected model parameter
Soil Texture Category	Class-0 (clay, silty clay, clay loam, silty clay loam, silt) Class-1 (sandy clay, silt loam, loam, very fine sandy loam) Class-2 (fine sandy loam, sandy clay loam, loamy very fine sand, sandy loam, loamy fine sand, very fine sand, coarse sandy loam, fine sand, sand, loamy coarse sand, coarse sand)	Varied by AOI. For example, in Bear Creek AOI #3, "Shiawassee gravelly sandy loam" and "Parkhill loam," identified as soil types using NRCS Web Soil Survey (2019)—model parameter set to corresponding Class-1.
USLE C-Factor	• "No-till or chisel after corn leaving good residue cover." • "Plow tillage after corn or chisel after soybeans."	• "Plow tillage after corn or chisel after soybeans." Selected to err on the side of more disturbance.
Trapping Efficiency	1% increments, 50% to 75%	Set at 75% for all AOIs

Dominant soil types by HUC12 (NRCS 2019)

North Ore Creek: (14.5%) Wawasee loam, 0% to 2% slopes; (14.4%) Conover loam, 0% to 4% slopes; (12.3%) Hillsdale-Miami loams, 2% to 6% slopes; (11.9%) Wawasee loam, 2% to 6% slopes; (5.3%) Gilford sandy loam, 0% to 2% slopes, gravelly subsoil; (5.2%) Wawasee loam, 6% to 12% slopes; (4.8%) Miami loam, 12% to 18% slopes; (4.1%) Bronson loamy sand, 0% to 2% slopes; (4.0%) Brady loamy sand, 0% to 2% slopes; (3.7%) Pewamo clay loam, 0% to 2% slopes; (2.9%) Boyer-Oshtemo loamy sands, 0% to 2% slopes; (2.3%) Hillsdale-Miami loams, 6% to 12% slopes; (2.1%) Fox-Boyer complex, 12% to 18% slopes; (2.1%) Fox-Boyer complex, 2% to 6% slopes; all other soil types less than 2% of North Ore Creek AOIs.

Bear Creek: (47.0%) Zilwaukee and Misteguay silty clays, 0% to 1% slopes, rarely flooded; (9.2%) Conover gravelly sandy loam, 0% to 3% slopes; (8.8%) Conover-Williamstown loams, 0% to 6% slopes; (8.6%) Selfridge loamy sand, 0% to 3% slopes; (7.6%) Parkhill loam, 0% to 1% slopes; (3.9%) Shiawassee gravelly sandy loam, 0% to 3% slopes;
(2.2%) Arkona sand, 0% to 4% slopes; all other soil types less than 2% of Bear Creek AOIs.

Shad Creek: (78.8%) Parkhill loam, 0% to 1% slopes; (6.7%) Metamora-Conover complex, 0% to 3% slopes; (6.4%) Selfridge loamy sand, 0% to 3% slopes; (6.0%) Corunna sandy loam; all other soil types less than 2% of Bear Creek AOIs.

Notes: HUC = Hydrologic Unit Code; AOI = area of interest; USLE = Universal Soil Loss Equation.

Table 2. Summary of AgBufferBuilder (ABB) main tool output parameters.

ABB output parameter	Parameter description	In-text references	ABB output units
AOI	Area of Interest	"AOI"	acres
Design_Area	Design Buffer Area	"proposed buffer"	acres
Assess_Area	Assessment Buffer Area	"existing buffer"	acres
Trapping Efficiency	Existing Buffer: Combined Area-Weighted Trapping Efficiency	"CAWATE"	%
Trapping Efficiency	Proposed Buffer: Combined Area-Weighted Trapping Efficiency	"CAWATE1"	%

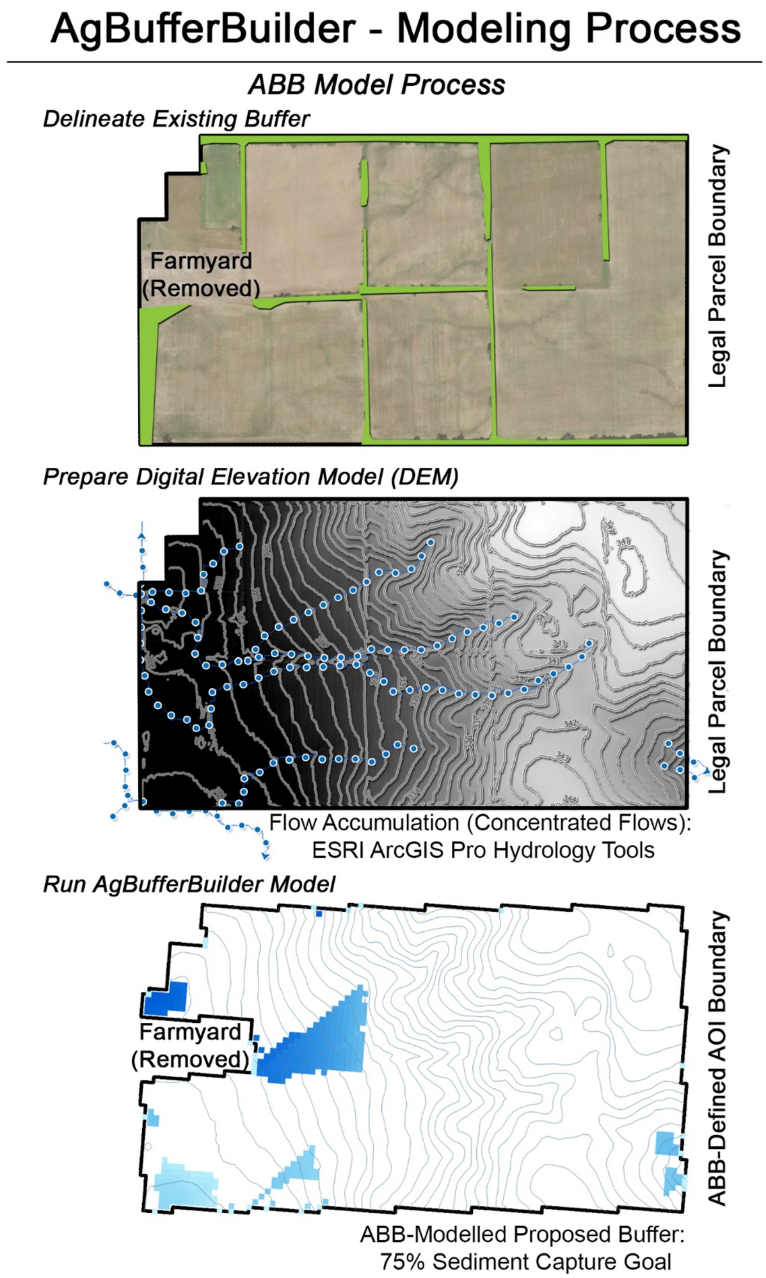
buffer performance. Although finer output resolutions are possible, we maintained a 9 m by 9 m pixel size due to software limitations of ABB that resulted in ABB crashing, exponential growth in model run time, and alignment with the methods of previous studies conducted by Dosskey et al. (2015). An example field showing existing buffer conditions, hydrological analysis developed using ArcGIS Pro for visualizing concentrated flows (not an ABB-model input), and ABB-generated model results is shown in Figure 5.

We utilized AutoCAD (step 4) to simulate real-world farming practices using a standard 9.15 m (30 ft) wide harvester to address the unfarmable areas the proposed buffer design created. By modeling tractor movements around the buffer areas, we identified and minimized irregular shapes that would hinder agricultural accessibility. This approach allowed us to refine the buffer design while prioritizing land conservation and sediment trapping efficiency. However, irregular buffer shapes often create unfarmable areas that are impractical for producers to access with farming equipment.

Existing and proposed buffer raster data were converted to a polygon format using raster to polygon, overlay analysis, and erase tools in ArcGIS. This process generated distinct polygons representing the unique areas of existing and proposed buffers. The result was three final polygon layers for each AOI: overlapping buffers, nonoverlapping existing buffer, and nonoverlapping proposed buffer. We exported these final shapefiles from ArcMap to AutoCAD.

A virtual tractor path was then designed within the farmable area, accounting for tractor

Figure 5. Field-scale analysis of existing conditions and proposed buffers in North Ore Creek.



width and turning radius. Using AutoCAD, a buffer of 4.57 m (15 ft) was created around the farmable area to represent the tractor's path. This path was adjusted to accommodate the nonlinear buffer shape, including smoothing sharp turns and accounting for areas inaccessible to the tractor. Unfarmable areas resulting from buffer shape and tractor limitations were identified and quantified. We adopted the following rules to standardize our approach to unfarmable area determinations. Rule 1 addresses when two 90-degree turns are necessary within 9 m (29.5 ft), impossible using a tractor with a 4.57 m turning radius; the path was diverted along a 45-degree path instead of following the proposed nonlinear edge, leaving the remaining area impractical to farm. Rule 2 addresses when the proposed nonlinear buffer edge created pockets; we determined that any pockets with an opening under 36 m (118 ft) wide (4 raster grid cells) were impractical to farm due to the tractor-turning radius preventing efficient entering and exiting of the space. After we outlined the unfarmable areas on their own AutoCAD layer, the Area tool calculated the total coverage of existing, proposed, overlap, and unfarmable buffer areas for each AOI.

We generated descriptive statistics and categorical comparisons (step 5) to answer our first research question to compare ABB-modeled sediment trapping efficiency for nonlinear buffers with existing, linear edge-of-field buffers across different AOIs. We used basic descriptive statistics (minimum, maximum, mean, range, and categorical descriptions of AOIs) generated using SPSS to describe our combined results across all AOIs (IBM 2021). We recognize the limitations of our study, which include small sample sizes due to the significant time required to model individual fields and non-normal distributions of several key variables. We present both descriptive statistics and ANOVA tests with Tukey's post hoc tests to evaluate the difference of means among subwatersheds for the following variables:

1. AOI size (ha): Legal parcel with any developed areas removed.
2. Existing buffer size (% of AOI): Aerial photo interpretation defining existing vegetated areas not in production.
3. Proposed buffer size (% of AOI): The nonlinear buffer design modeled by ABB.
4. Unfarmable area (% of AOI): Areas identified as impractical to farm after proposed buffers are added to the field based on the virtual tractor path and movement limitations.
5. Uncultivated area (% of AOI): The total area of the proposed buffer and any identified unfarmable field sections.
6. Change in sediment trapping efficiency (% of total sediment): The modeled results comparing Combined Area-Weighted Average Trapping Efficiency (CAWATE) (existing buffer) and CAWATE1 (proposed buffer) potential sediment trapping efficiency.

Presenting the ANOVA and descriptive statistics allows us to effectively summarize and compare data across multiple subwatersheds while acknowledging that outliers within the dataset may influence the ANOVA tests within each of the variables affecting these subwatershed comparisons.

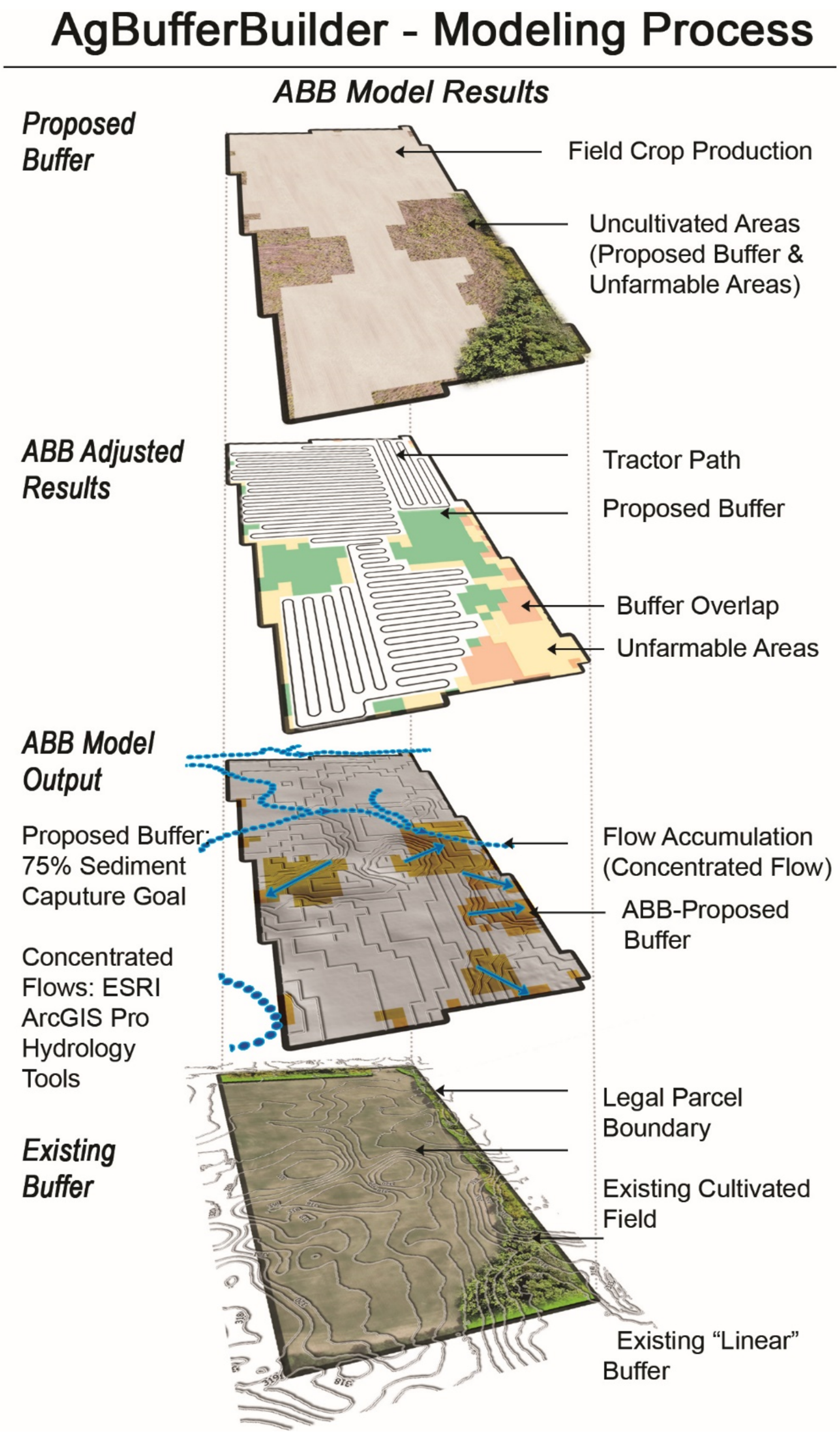
RESULTS AND DISCUSSION

We structured the analysis into five sections, beginning with research question 1, which addresses the ABB model focusing on buffer size and overlap, sediment trapping efficiency comparison, and buffer area adjustment for unfarmable areas. The overall assessment of ABB buffer performance and comparison of results from HUC12 subwatershed sections address research question 2 by considering the total area required to implement the buffer design and its sediment trapping efficiency potential.

Buffer size and overlap

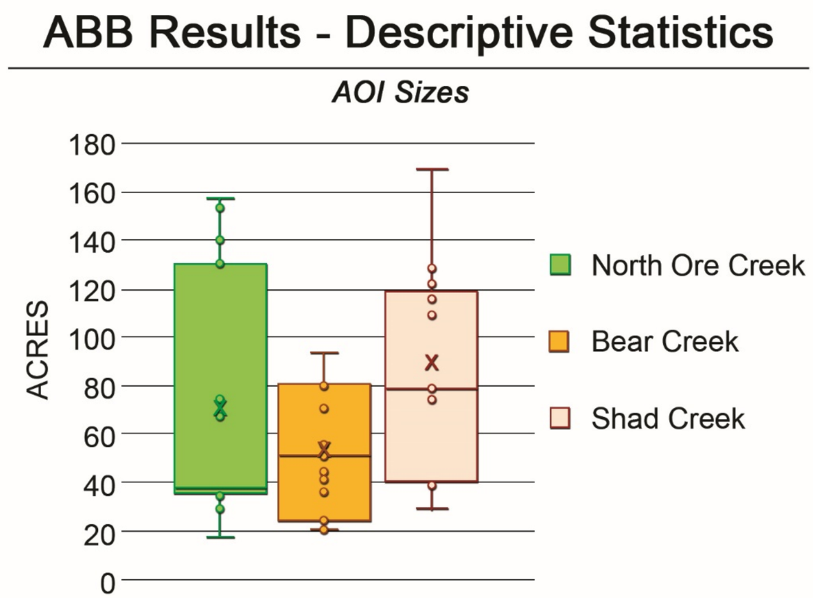
Figure 6 shows the ABB outputs, including a delineation of existing buffers, model-generated proposed buffers, overlap between proposed and existing buffers, the virtual tractor path identified in our AutoCAD analysis, and the unfarmable areas that result from limitations to tractor movement caused by the geometry of the proposed nonlinear buffers. We ran this model for each of the 45 AOIs and present key characteristics of the model results in the following sections. To begin, key buffer size and overlap characteristics of the AOIs include the following: AOI sizes ranged from 7.03 to 68.45 ha (17.38 to 169.15 ac) across the three watersheds, with a mean of 28.81 ha (71.19 ac). Figure 7 shows substantial variation in AOI size across watersheds. We report buffer sizes as a percentage of AOI to facilitate comparisons across the 45 AOIs with varying total area. Existing buffer sizes ranged from 0% to 67.75% of AOI (mean = 12.60%), while proposed buffers ranged from 0% to 22.22% (mean = 4.00%). Existing buffers cover a more significant percentage of AOIs than proposed buffers. Figure 8 shows the distribution of the proposed and existing buffer as a percentage of AOI and summarizes these results across all watersheds. Overlap between existing and

Figure 6. AgBufferBuilder (ABB) modeling process from input data to final buffer design.



proposed buffers varied significantly, with a mean of 30.24% of the proposed buffer area across all watersheds. Notably, we observed only a minimal overlap in the Shad Creek watershed. Figure 9 shows the distribution across all watersheds of overlapping proposed/existing buffer areas as a percentage of the proposed buffer for each AOI. Note that two of the AOIs in Bear Creek con-

Figure 7. Descriptive statistics for sizes of the areas of interest (AOIs). ABB is AgBufferBuilder.



Area	AOI Range	AOI Mean
All AOIs	7.03 to 68.45 hectares (17.38 to 169.15 acres)	28.81 hectares (71.19 acres)
North Ore Creek	8.43-37.96 hectares (20.84-93.79 acres)	12.89 hectares (53.75 acres)
Bear Creek	7.03-63.65 hectares (17.38-157.28 acres)	28.49 hectares (70.40 acres)
Shad Creek	11.84-68.45 hectares (29.26-169.15 acres)	36.19 hectares (89.42 acres)

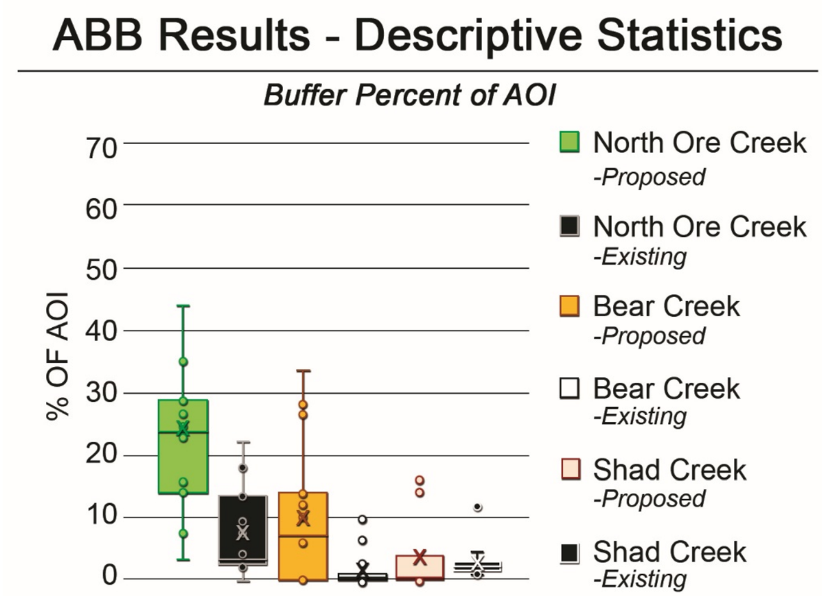
tained zero proposed buffer, leading to “DIV/0” errors when calculating the value of the overlap buffer as a percentage of the proposed buffer.

Sediment trapping efficiency comparison

ABB supports comparisons of sediment trapping capabilities of existing and proposed buffers across watersheds and subwatersheds. To assess the effectiveness of proposed buffers in capturing sediment, we compared their performance to existing buffers using the CAWATE metric. ABB reports CAWATE values to represent existing buffer sediment trapping efficiency. CAWATE1 values report the same metric for proposed buffers generated by ABB. Results indicate that proposed buffers captured significantly more sediment on average than existing buffers, with a mean increase of 24.70%. However, performance varied across watersheds, with Shad Creek demonstrating the highest improvement and Bear Creek showing the lowest. These findings highlight the potential for substantial sediment reduction through optimized buffer design. Key sediment trapping efficiency characteristics of the AOIs include the following: Across all watersheds, existing buffer CAWATE values ranged from 0% to 79.32% of estimated sediment trapping efficiency ($n = 45$, mean = 12.86%). Proposed buffer CAWATE1 values across all watersheds ranged from 0% to 68.49% of estimated sediment trapping efficiency ($n = 45$, mean = 37.56%).

Figure 10 illustrates the variation in sediment trapping efficiency improvement between proposed and existing buffers across subwatersheds. The difference in sediment trapping efficiency

Figure 8. Descriptive statistics for existing and proposed buffers as a percentage of the area of interest (AOI). ABB is AgBufferBuilder.



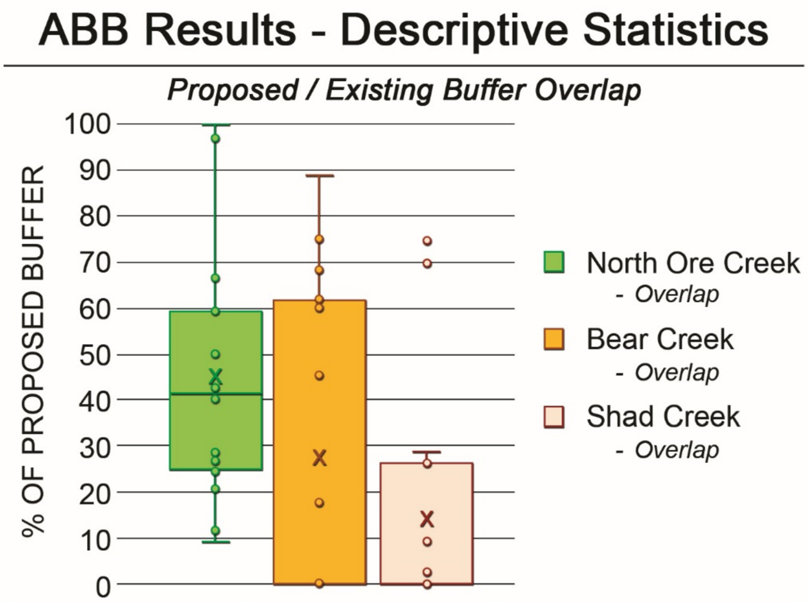
Area	% of AOI for Existing Buffers	% of AOI for Proposed Buffers
All AOIs	0% to 67.75% (mean = 12.60%)	0% to 22.22% (mean = 4.00%)
North Ore Creek	3.33% to 67.75% (mean = 24.31%)	0.09% to 22.22% (mean = 7.53%)
Bear Creek	0% to 33.60% (mean = 9.95%)	0% to 9.80% (mean = 1.50%)
Shad Creek	0% to 16.96% (mean = 3.54%)	1.00% to 11.78% (mean = 2.95%)

between proposed and existing buffers ranged from −48.14% to 66.81%, with an average increase of 24.70% for proposed buffers. Negative values indicate the existing buffer captures more sediment than the proposed buffer within a given AOI. Positive values indicate that the proposed buffer captures more sediment than the existing buffer.

Buffer area adjustment for unfarmable areas

This analysis aims to adjust buffer area calculations to account for unfarmable areas created by the proposed buffer design. Proposed buffers offer a targeted approach to buffer implementation, minimizing land out of production. However, it is crucial to understand that practical considerations related to farming operations necessitate additional land allocation for unfarmable areas, underscoring the importance of this aspect in buffer implementation. Here, we present results for buffer percentage of AOIs that account for the additional unfarmable area and compare them to existing and unmodified proposed buffers. Figure 11 shows the differences in percentage of AOI for unfarmable and uncultivated areas [(proposed + unfarmable) − existing] values. Unfarmable areas accounted for an average of 2.35% of total AOI, nearly doubling the total area required to implement proposed buffers. In five cases, adding unfarmable areas resulted in a larger total buffer area than the existing buffer, occurring once in North Ore Creek and twice in Bear and Shad Creeks. In those five cases, the maximum difference in percentage of AOI between (proposed + unfarmable) and existing buffers was very small at 1.56% of AOI.

Figure 9. Descriptive statistics for overlap between existing and proposed buffers. ABB is AgBufferBuilder; AOI is area of interest.



Area	Overlap Range	Mean Overlap
All AOIs	0% to 100%	n=43, mean = 30.24%
North Ore Creek	9.26% to 100%	n=15, mean = 44.71%
Bear Creek	0% to 88.96%	n=13, mean = 32.07%
Shad Creek	0% to 74.68%	n=15, mean = 14.20%

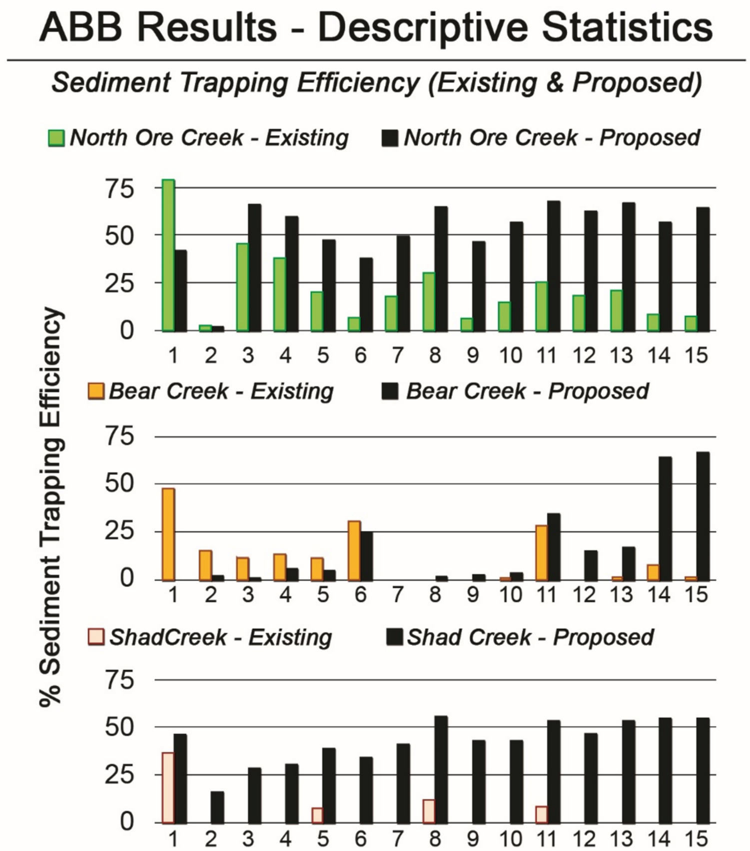
Overall assessment of AgBufferBuilder buffer performance

To address research question 2, we evaluated the feasibility and effectiveness of ABB-designed buffers considering buffer area and sediment trapping efficiency performance in order to determine if there is an opportunity for spatial reconfiguration of buffers within the field that could lead to increased adoption. Figure 12 shows the relationship between changes in the percentage of AOI [(proposed + unfarmable) – existing] plotted against changes in the percentage of sediment trapping efficiency. In 15 of 45 AOIs, ABB-designed buffers achieved increased sediment trapping efficiency while matching or reducing the total buffer area needed compared to existing conditions—see Q2 in Figure 12. This scenario represents an optimal outcome where water quality and land use efficiency are improved. It is worth noting that new CAWATE values were not calculated for unfarmable buffers when preparing Figure 12. Since ABB did not target the unfarmable areas, we made the conservative assumption that they would contribute minimal additional sediment trapping efficiency capacity. While proposed buffers generally outperformed existing buffers, there were eight cases where existing buffers captured more sediment than the proposed ABB-supported buffer design. As shown in Figure 12 (Q3), except for one outlier where existing conditions included nearly 70% buffer coverage, the superior sediment trapping efficiency of these existing buffers is generally small.

Comparing results from HUC12 subwatersheds

The ANOVA analysis compares mean values for the three subwatersheds for key characteristics and the performance of proposed buffers. In the following list, we summarize key findings from the ANOVA tests shown in Table 3:

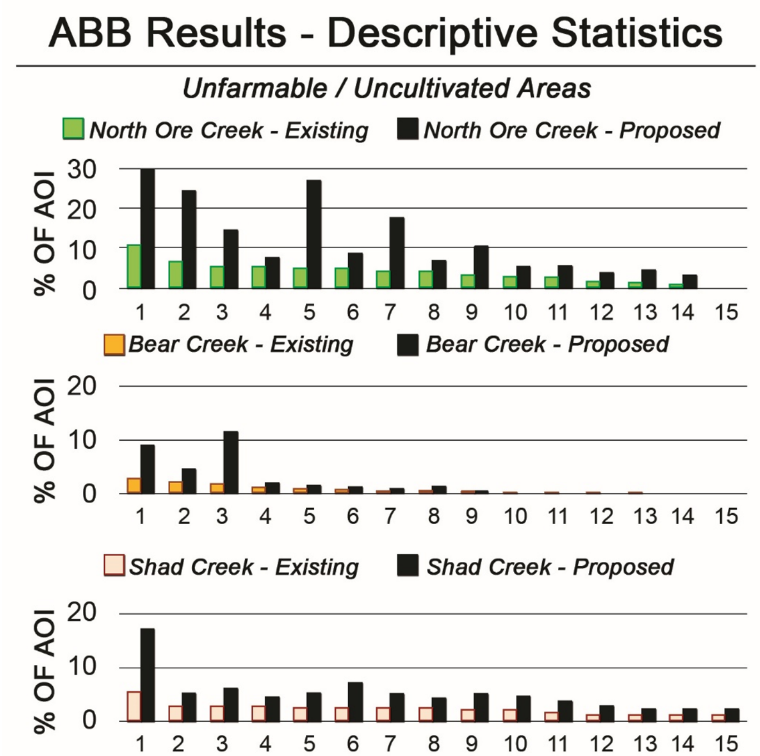
Figure 10. Descriptive statistics for sediment trapping efficiency of existing and proposed buffers. ABB is AgBufferBuilder; AOI is area of interest.



Area	Change Range	Mean Change
All AOIs	-48.14% to 66.81%	mean = 24.70%
North Ore Creek	-36.88% to 57.06%	mean = 30.22%
Bear Creek	-48.14% to 66.81%	mean = 5.26%
Shad Creek	9.88% to 54.82%	mean = 38.62%

- Area of interest size (ha): There are no statistically significant differences ($p < 0.05$) in AOI size among the subwatersheds. However, note that the average AOI (field) size of Shad Creek is larger than either North Ore or Bear Creeks.
- Existing buffer size (% of AOI): North Ore Creek stands out as having a significantly larger average existing buffer size (24.3% of AOI) than Bear Creek (9.9% of AOI) or Shad Creek (3.5% of AOI). There is no statistically significant difference in the mean existing buffer size between Bear and Shad Creeks.
- Proposed buffer size (% of AOI): Again, North Ore Creek stands out with a statistically significant difference in proposed buffer size (7.5% of AOI) when compared with Bear Creek (1.5% of AOI) and Shad Creek (2.9% of AOI). There is no statistically significant difference in the mean proposed buffer size between Bear and Shad Creeks.
- Unfarmable area (% of AOI): The same trend continues with a statistically significant larger unfarmable area for AOIs in North Ore Creek (4.1% of AOI) compared to Bear and Shad Creeks.
- Uncultivated area (% of AOI): The combined sum of the proposed buffer and the unfarmable area also results in North Ore Creek (11.6% of AOI) requiring a statistically larger

Figure 11. Descriptive statistics for unfarmable areas identified by tractor movement analysis and total uncultivated area (proposed buffer + unfarmable area). ABB is AgBufferBuilder; AOI is area of interest.



Area	% of AOI Unfarmable	% of AOI Uncultivated (Proposed Buffer + Unfarmable)
All AOIs	0% to 11.01% (mean = 2.35%)	0% to 30.11% (mean = 6.35%)
North Ore Creek	0.06% to 11.01% (mean = 4.10%)	0.14% to 30.11% (mean = 11.6%)
Bear Creek	0% to 2.78% (mean = 0.72%)	0% to 9.15% (mean = 2.23%)
Shad Creek	1.04% to 5.32% (mean = 2.24%)	2.28% to 17.10% (mean = 5.18%)

area to implement, on average, than Bear Creek (2.2% of AOI) or Shad Creek (5.2% of AOI).

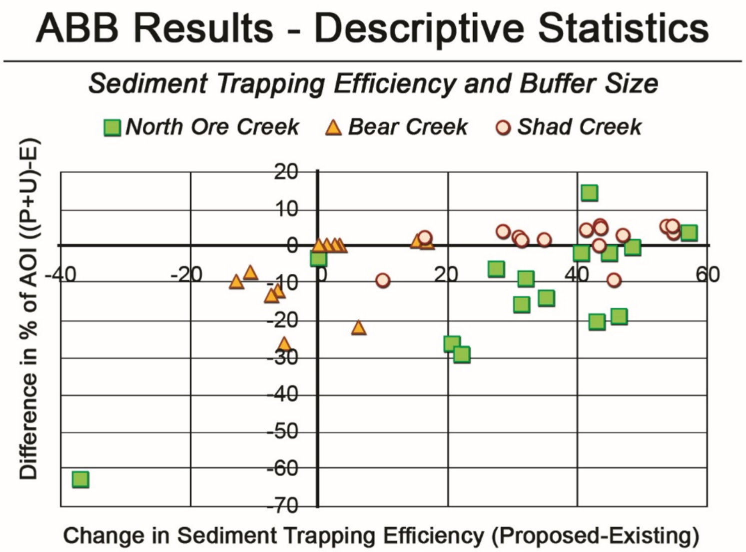
- Sediment trapping efficiency enhancement (% of total sediment): The ANOVA revealed that the highest overall potential for improvement in sediment trapping efficiency is statistically not different for North Ore Creek (30.2%) and Shad Creek (38.6%). Bear Creek exhibited the lowest overall improvement in sediment trapping efficiency with an average improvement potential of 5.3%, significantly lower than the other two subwatersheds.

These results demonstrate why careful site analysis is necessary when implementing conservation practice changes and suggest that spatial reconfiguration is only possible in some AOIs.

Discussion

Our results suggest that ABB has significant potential for informing buffer design at the field scale and providing visual aids to support decision-making. Its ability to model the impact of different buffer configurations on sediment trapping efficiency is a key strength. While the tool effectively identifies potential areas for

Figure 12. Plot of buffer area difference {[proposed (P) + unfarmable (U) % of AOI] - existing (E) % of AOI} versus sediment trapping efficiency difference for individual areas of interest (AOIs).



Area	Q1 Increase Sediment Capture, Increase Buffer Size	Q2 Decrease Sediment Capture, Increase Buffer Size	Q3 Decrease Sediment Capture, Decrease Buffer Size	Q4 Increase Sediment Capture, Decrease Buffer Size
All AOIs	21	0	8	15
North Ore Creek	3	0	2	10
Bear Creek	5	0	6	3
Shad Creek	13	0	0	2

Note: One AOI had no increase in sediment capture or size.

buffer placement, defining the AOI based on the legal parcel only partially accounts for broader watershed-scale factors, such as upstream influences and downstream impacts. Our analysis indicates that existing field-edge buffers often fail to capture a significant portion of sediment runoff. On average, 85.02% of existing buffers do not overlap with any proposed buffer areas, implying no predicted sediment trapping efficiency benefit. Although some properties with established vegetative cover demonstrated higher sediment trapping efficiency rates, the overall performance of existing buffers can be improved. We recognize that these existing buffers may have been installed for multiple reasons (wildlife or insect benefits, practical limitations addressing field obstructions, or wind erosion control) and are not intended to reduce soil erosion.

Additionally, maintenance of these existing buffers may not have been performed over time, resulting in their dimensions changing and reducing the efficacy of their placement. However, the Saginaw Bay watershed, including our study area (HUC12 Shiawassee River basin), is experiencing water quality impairments from nutrient loading associated with erosion-driven sediment transport on agricultural land uses. The poor modeled performance of these existing buffers, which ABB modeled at a mean of 12.86% of the total sediment trapping efficiency, suggests improvements are warranted.

Table 3. ANOVA results ("*" indicates significance is less than 0.05).

Variable	HUC12	Mean	ANOVA Sig.	Post Hoc – Tukey		
AOI size (ac)	(1) North Ore Creek	53.8	0.061	*HUC 12 comparisons*		*Sig.*
	(2) Bear Creek	70.4		1	2	0.495
	(3) Shad Creek	89.4		1	3	0.048*
				2	3	0.401
Existing buffer (% of AOI)	(1) North Ore Creek	24.3	0.001*	*HUC 12 comparisons*		*Sig.*
	(2) Bear Creek	9.9		1	2	0.006*
	(3) Shad Creek	3.5		1	3	0.001*
				2	3	0.318
Proposed buffer (% of AOI)	(1) North Ore Creek	7.5	0.003*	*HUC 12 comparisons*		*Sig.*
	(2) Bear Creek	1.5		1	2	0.003*
	(3) Shad Creek	2.9		1	3	0.029*
				2	3	0.681
Unfarmable area (% of AOI)	(1) North Ore Creek	4.1	0.001*	*HUC 12 comparisons*		*Sig.*
	(2) Bear Creek	0.07		1	2	0.001*
	(3) Shad Creek	2.2		1	3	0.014*
				2	3	0.055
Uncultivated area (% of AOI)	(1) North Ore Creek	11.6	0.001*	*HUC 12 comparisons*		*Sig.*
	(2) Bear Creek	2.2		1	2	0.001*
	(3) Shad Creek	5.2		1	3	0.017*
				2	3	0.391
Change in sediment trapping efficiency % (Proposed – Existing)	(1) North Ore Creek	30.2	0.001*	*HUC 12 comparisons*		*Sig.*
	(2) Bear Creek	5.3		1	2	0.010*
	(3) Shad Creek	38.6		1	3	0.559
				2	3	0.001*

Notes: AOI = area of interest; HUC = Hydrologic Unit Code.

Implementing ABB-designed buffers across broader landscapes holds significant potential for improving sediment trapping efficiency. This promising result supports a positive conclusion to research question 1—ABB-designed nonlinear buffers are more effective in capturing sediment compared to existing field-edge buffers across different agricultural landscapes. ABB-designed buffers showed potential for substantial improvements in sediment trapping efficiency, with a mean change in sediment trapping efficiency between existing and proposed buffers of 24.70% of the total modeled sediment. Although the proposed buffers did not achieve the 75% sediment trapping efficiency target, these results suggest the potential for optimizing nonlinear buffer design and placement. However, it is essential to note that the average increase in sediment trapping efficiency of 24.70% is less than half of the average gain reported by Dosskey et al. (2015), which is mainly due to the removal of unfarmable areas from production due to tractor movement limitations associated with nonlinear buffer geometries identified by this study. These results indicate that ABB-proposed nonlinear buffers can potentially increase sediment trapping efficiency at the field scale, but the rate may be far less than previously reported.

Research question 2 explores the potential for spatial reconfiguration of buffers that could lead to increased sediment trapping efficiency while not affecting the area in agricultural production. The results from running the ABB model on AOIs selected from within HUC12 subwatersheds with high, medium, and low sediment loading reveal that landscape characteristics influence the potential for nonlinear buffers to reduce sediment. This potential for spatial reconfiguration offers hope for the future of sediment trapping efficiency. The following paragraphs present a summary of subwatershed results.

The North Ore Creek (low sediment loading) watershed exhibited the highest proportion of existing buffers among the study areas, with a mean area of existing buffers among all three watersheds at 24.31% of AOI. Proposed buffers in this watershed demonstrated a substantial increase in sediment trapping efficiency, capturing an average of 30.2% of total sediment. Owing to the greater total existing buffer area in the North Ore Creek subwatershed, a mean of 44.71% of the proposed buffer area overlapped with existing buffers in this watershed. In this subwatershed, spatial reconfiguration of buffers may be possible to improve sediment trapping efficiency without decreasing the total area available for crop production.

The Bear Creek (medium sediment loading) watershed presented unique challenges for buffer optimization. While existing buffer coverage was higher than Shad Creek, existing and proposed buffers' overall sediment trapping efficiency performance was relatively low. Four out of 15 AOIs have zero sediment trapping efficiency by existing field-edge buffers. Existing buffers captured an average of 11.17% of total sediment, while proposed buffers captured only 16.43%. This difference represents a minimal improvement of 5.26% in sediment trapping efficiency. With these conditions, it is doubtful that spatial reconfiguration of buffers is an effective strategy.

The Shad Creek (high sediment loading) watershed presents a significant opportunity for improving sediment trapping efficiency through optimized buffer placement. Existing buffers are minimal, with 7 of 15 AOIs in Shad Creek having zero existing buffers. Existing buffers in Shad Creek captured only 4.34% of total sediment, while proposed buffers demonstrated significantly higher sediment trapping efficiency potential (42.96%). This difference represents a substantial improvement of 38.62% in sediment trapping efficiency. This result presents an opportunity for Shad Creek AOIs to capture additional sediment by implementing ABB-designed proposed buffers. The lack of existing buffers leaves little room to increase buffer coverage through spatial reconfiguration in this subwatershed. However, with minimal area taken out of production, only 1.64% of AOI on average when accounting for unfarmable areas, there is promise for nonlinear buffer implementation to make a significant difference in this subwatershed.

Spatial reconfiguration allowing for a win-win situation in which sediment trapping efficiency increases while reducing the total area out of production exists but has limits, with only 15 of the 45 AOIs showing this potential. While ABB offers the potential for optimizing buffer placement, the support of landowners and producers is crucial for successful implementation. Their support is not just necessary but integral to the project's success.

Methodological limitations

To fully realize the potential of nonlinear buffer design, future research should address the limitations of the ABB model. Specifically, software limitations should be addressed to incorporate higher-resolution elevation data and enhance how upslope contributing areas are incorporated and visualized. In the future, the ABB model could be adapted for open-source platforms, such as R or Q-GIS, that are not currently available, allowing for updates to address these challenges.

The ABB model's reliance on a 9 m (29.5 ft) spatial resolution represents a trade-off between computational efficiency and accuracy. While ABB shows promise at this resolution, its outdated platform limited our ability to incorporate larger, more complex datasets. The Bear Creek subwatershed results specifically highlight these issues. The flat topography and extensive drainage infrastructure in this region may have limited the effectiveness of the ABB model. Much of the differences in slope occur at a fine scale, on the order of 1 to 2 m (3.3 to 6.5 ft). Flat areas may have many small subbasins with 9 m by 9 m grid cells contributing to two or more of these basins. Given ABB rounding algorithm requirements, flat landscapes with microbasins likely make it difficult for the tool to include large parts of the necessary buffer area in its selections at coarse resolutions. As such, buffer delineations are constrained, and the utility of ABB in flat landscapes may require higher-resolution data—which may improve model performance. However, current limitations in the ABB software prevented its utilization.

Any decision regarding how to define AOIs will have real-world limitations. ABB's analysis is bounded by the user-input AOI, which may not adequately account for upslope runoff contributions or downslope buffer effects outside the AOI. This study used legal parcel boundaries to define study areas. Despite calls for greater collaboration around the design and placement of conservation practices when the land crosses ownership boundaries, this approach is not widely used or specifically supported by federal conservation policy and funding support (Nowak, Bowen, and Cabot 2006). Our legal parcel boundary approach corresponds with the producer's decision-making units. Individual landowners decide to adopt conservation buffers on their land, meaning we need modeling tools capable of producing parcel-specific results. Focusing on individual parcels may limit the analysis of broader landscape factors influencing water quality, such as upstream land use and hydrology. However, this is not a requirement of the ABB model in order to produce an accurate nonlinear buffer design. The ABB tool already identifies low exit points and upslope contributing areas, which are used to determine the sediment capture effectiveness of existing buffers, and the necessary size of proposed buffers based on modeled buffer-to-contributing-area ratios are calculated and summarized in the background. Improving ABB-model outputs by producing a graphic showing visual delineations of the various contributing areas for each flow exit point within a field would be a significant enhancement. This added feature, similar to the capabilities of other models that estimate the maximum sediment trapping efficiency, such as Momm et al. (2014), would allow the user to visualize each unique contributing zone better and improve the design of buffers and upslope practices.

SUMMARY AND CONCLUSIONS

The ABB model results from this study show that nonlinear targeted buffer design is a promising conservation strategy for enhancing water quality while minimizing agricultural production impacts. However, land clearing and related landscape simplification requires active decision-making to balance positive and negative impacts. When deciding to reconfigure buffers and clear new areas for farming, appropriate design considerations are necessary to minimize and mitigate the ecological impacts of this transition. Further, the unfarmable areas identified in this study have the potential to provide field-edge habitats that may provide ecosystem services and support biodiversity, improving agricultural sustainability (Sellers et al. 2018). A multifunctional landscape approach is critical when accounting for the benefits provided by both existing field-edge and new proposed buffers to create policies and guidelines that facilitate the realization of a landscape's maximum potential about a range of provisioning, regulating, cultural, and supporting ecosystem services (Qiu and Dosskey 2012). The successful deployment of ABB as a conservation tool depends on a collaborative approach that integrates technical modeling with local knowledge and stakeholder engagement. A place-based conservation framework is an approach that considers social, cultural, and ecological factors to enhance conservation adoption and maintenance (Stewart, Williams, and Kruger 2013). A successful place-based approach to water quality conservation will combine geospatial information gained from landscape-scale and field-scale modeling with historical, cultural, and social understanding to identify the best paths for moving conservation efforts forward.

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REFERENCES

Ahearn, D. S., R. W. Sheibley, R. A. Dahlgren, M. Anderson, J. Johnson, and K. W. Tate. 2005. "Land Use and Land Cover Influence on Water Quality in the Last Free-Flowing River Draining the Western Sierra Nevada, California." *Journal of Hydrology* 313 (3-4): 234–247. https://doi.org/10.1016/j.jhydrol.2005.02.038.

Bartlett, J. A., and A. Dedekorkut-Howes. 2023. "Adaptation Strategies for Climate Change Impacts on Water Quality: A Systematic Review of the Literature." *Journal of Water and Climate Change* 14 (3): 651–675. https://doi.org/10.2166/wcc.2022.279.

Beletsky, D., R. Beletsky, A. Burtner, J. H. Bredin, J. Cavaletto, Y. Cha, C. de Marchi, et al. 2013. *Saginaw Bay Multiple Stressors Summary Report*. National Oceanic and Atmospheric Administration. https://repository.library.noaa.gov/view/noaa/11142.

Bongiovanni, R., and J. Lowenberg-Deboer. 2004. "Precision Agriculture and Sustainability." *Precision Agriculture* 5 (4): 359–387. https://doi.org/10.1023/B:PRAG.0000040806.39604.aa.

Capel, P. D., K. A. McCarthy, R. H. Coupe, K. M. Grey, S. E. Amenumey, N. T. Baker, and R. L. Johnson. 2018. "Agriculture – A River Runs through It – The Connections between Agriculture and Water Quality." US Geological Survey Circular 1433. https://doi.org/10.3133/cir1433.

Coulter, C. B., R. K. Kolka, and J. A. Thompson. 2004. "Water Quality in Agricultural, Urban, and Mixed Land Use Watersheds 1." *JAWRA Journal of the American Water Resources Association* 40 (6): 1593–1601. https://doi.org/10.1111/j.1752-1688.2004.tb01608.x.

Dabney, S. M., M. T. Moore, and M. A. Locke. 2006. "Integrated Management of in-Field, Edge-of-Field, and after-Field Buffers." *JAWRA Journal of the American Water Resources Association* 42 (1): 15–24. https://doi.org/10.1111/j.1752-1688.2006.tb03819.x.

Dewitz, J. 2023. "National Land Cover Database (NLCD) 2021 Products." US Geological Data Release. https://doi.org/10.5066/P9JZ7AO3.

Dillaha, T. A., R. B. Reneau, S. Mostaghimi, and D. Lee. 1989. "Vegetative Filter Strips for Agricultural Nonpoint Source Pollution Control." *Transactions of the ASAE* 32 (2): 513–519.

Dosskey, M. G., M. J. Helmers, and D. E. Eisenhauer. 2008. "A Design Aid for Determining Width of Filter Strips." *Journal of Soil and Water Conservation* 63 (4): 232–241. https://doi.org/10.2489/jswc.63.4.232.

Dosskey, M. G., M. J. Helmers, and D. E. Eisenhauer. 2011. "A Design Aid for Sizing Filter Strips Using Buffer Area Ratio." *Journal of Soil and Water Conservation* 66 (1): 29–39. https://doi.org/10.2489/jswc.66.1.29.

Dosskey, M. G., M. J. Helmers, D. E. Eisenhauer, T. G. Franti, and K. D. Hoagland. 2002. "Assessment of Concentrated Flow through Riparian Buffers." *Journal of Soil and Water Conservation* 57 (6): 336–343.

Dosskey, M. G., S. Neelakantan, T. G. Mueller, T. Kellerman, M. J. Helmers, and E. Rienzi. 2015. "ABB: A Geographic Information System (GIS) Tool for Precision Design and Performance Assessment of Filter Strips." *Journal of Soil and Water Conservation* 70 (4): 209–217. https://doi.org/10.2489/jswc.70.4.209.

ESRI. 2019. *ArcGIS Desktop: Release 10.8*. Redlands, CA: Environmental Systems Research Institute.

ESRI. 2023. *ArcGIS Pro: Release 3.2.2*. Redlands, CA: Environmental Systems Research Institute.

Fales, M., R. Dell, M. E. Herbert, S. P. Sowa, J. Asher, G. O'Neil, P. J. Doran, and B. Wickerham. 2016. "Making the Leap from Science to Implementation: Strategic Agricultural Conservation in Michigan's Saginaw Bay Watershed." *Journal of Great Lakes Research* 42 (6): 1372–1385. https://doi.org/10.1016/j.jglr.2016.09.010.

Gowda, P. H., J. Steiner, C. Olson, M. Boggess, T. Farrigan, and M. A. Grusak. 2018. "Chapter 10: Agriculture and Rural Communities." In *Impacts, Risks, and Adaptation in the United States: The Fourth National Climate Assessment*, Volume II. Washington, DC: U.S. Global Change Research Program. https://doi.org/10.7930/NCA4.2018.CH10.

He, C., L. Zhang, C. DeMarchi, and T. E. Croley. 2014. "Estimating Point and Non-Point Source Nutrient Loads in the Saginaw Bay Watersheds." *Journal of Great Lakes Research* 40 (S1): 11–17. https://doi.org/10.1016/j.jglr.2014.01.013.

Helmers, M. J., D. E. Eisenhauer, M. G. Dosskey, T. G. Franti, J. M. Brothers, and M. C. Mccullough. 2005a. "Flow Pathways and Sediment Trapping in a Field-Scale Vegetative Filter." *Transactions of the ASAE* 48 (3): 955–968.

Helmers, M. J., D. E. Eisenhauer, T. G. Franti, and M. G. Dosskey. 2005b. "Modeling Sediment Trapping in a Vegetative Filter Accounting for Converging Overland Flow." *Transactions of the ASAE* 48 (2): 541–555.

IBM Corp. 2021. *IBM SPSS Statistics for Windows, Version 28.0*. Armonk, NY: IBM Corp.

King, S. E., D. L. Osmond, J. Smith, M. R. Burchell, M. Dukes, R. O. Evans, S. Knies, and S. Kunickis. 2016.

"Effects of Riparian Buffer Vegetation and Width: A 12-Year Longitudinal Study." *Journal of Environmental Quality* 45 (4): 1243–1251. https://doi.org/10.2134/JEQ2015.06.0321.

Jabbar, F. K., and K. Grote. 2019. "Statistical Assessment of Nonpoint Source Pollution in Agricultural Watersheds in the Lower Grand River Watershed, MO, USA." *Environmental Science and Pollution Research International* 26 (2): 1487–1506. https://doi.org/10.1007/s11356-018-3682-7.

Lee, P., C. Smyth, and S. Boutin. 2004. "Quantitative Review of Riparian Buffer Width Guidelines from Canada and the United States." *Journal of Environmental Management* 70 (2): 165–180. https://doi.org/10.1016/J.JENVMAN.2003.11.009.

Lerch, R. N., C. H. Lin, K. W. Goyne, R. J. Kremer, and S. H. Anderson. 2017. "Vegetative Buffer Strips for Reducing Herbicide Transport in Runoff: Effects of Buffer Width, Vegetation, and Season." *JAWRA Journal of the American Water Resources Association* 53 (3): 667–683. https://doi.org/10.1111/1752-1688.12526.

Logan, T. J. 1993. "Agricultural Best Management Practices for Water Pollution Control: Current Issues." *Agriculture, Ecosystems & Environment* 46 (1-4): 223–231. https://doi.org/10.1016/0167-8809(93)90026-L.

Lovell, S. T., and W. C. Sullivan. 2006. "Environmental Benefits of Conservation Buffers in the United States: Evidence, Promise, and Open Questions." *Agriculture, Ecosystems & Environment* 112 (4): 249–260. https://doi.org/10.1016/j.agee.2005.08.002.

Lowrance, R., S. Dabney, and R. Schultz. 2002. "Improving Water and Soil Quality with Conservation Buffers." *Journal of Soil and Water Conservation* 57 (2): 36A–43A.

Lv, J., and Y. Wu. 2021. "Nitrogen Removal by Different Riparian Vegetation Buffer Strips with Different Stand Densities and Widths." *Water Supply* 21 (7): 3541–3556. https://doi.org/10.2166/ws.2021.119.

Mayer, P., S. Reynolds, and T. Canfield. 2005. "Riparian Buffer Width, Vegetative Cover, and Nitrogen Removal Effectiveness: A Review of Current Science and Regulations."

Mayer, P. M., S. K. Reynolds, M. D. Mccutchen, and T. J. Canfield. 2007. "Meta-Analysis of Nitrogen Removal in Riparian Buffers." *Journal of Environmental Quality* 36 (4): 1172–1180. https://doi.org/10.2134/jeq2006.0462.

Mehdi, B., B. Lehner, C. Gombault, A. Michaud, I. Beaudin, M.-F. Sottile, and A. Blondlot. 2015. "Simulated Impacts of Climate Change and Agricultural Land Use Change on Surface Water Quality with and without Adaptation Management Strategies." *Agriculture, Ecosystems & Environment* 213: 47–60. https://doi.org/10.1016/j.agee.2015.07.019.

MI EGLE (Michigan Department of Environment, Great Lakes, and Energy). n.d. "Nonpoint Source Program." https://www.michigan.gov/egle/about/organization/water-resources/nonpoint-source.

Michigan (MI) Sea Grant. n.d. "Supporting Habitat and Resilience in Saginaw Bay." https://www.michiganseagrant.org/saginaw-bay-reef/.

MN BWSR (Minnesota Board of Water & Soil Resources). n.d. "Alternative Practices Introduction." https://bwsr.state.mn.us/alternative-practices-introduction.

MN BWSR (Minnesota Board of Water & Soil Resources). 2021. "Buffer Program Update." https://bwsr.state.mn.us/buffer-program-update.

Momm, H. G., R. L. Bingner, Y. Yuan, M. A. Locke, and R. R. Wells. 2014. "Spatial Characterization of Riparian Buffer Effects on Sediment Loads from Watershed Systems." *Journal of Environmental Quality* 43 (5): 1736–1753. https://doi.org/10.2134/jeq2013.10.0413.

MSU IWR (Michigan State University Institute of Water Research), The Nature Conservancy, Purdue University, U. S. A. C. of E (United States Army Corps of Engineers). 2021. Great Lakes Watershed Management system. http://www.iwr.msu.edu/glwms/.

Myers, C. F., J. Meek, S. Tuller, and A. Weinberg. 1985. "Nonpoint Sources of Water Pollution." *Journal of Soil and Water Conservation* 40 (1): 14–18.

Nowak, P., S. Bowen, and P. E. Cabot. 2006. "Disproportionality as a Framework for Linking Social and Biophysical Systems." *Society & Natural Resources* 19 (2): 153–173. https://doi.org/10.1080/08941920500394816.

Pankau, R. C., J. E. Schoonover, K. W. J. Williard, and P. J. Edwards. 2012. "Concentrated Flow Paths in Riparian Buffer Zones of Southern Illinois." *Agroforestry Systems* 84 (2): 191–205. https://doi.org/10.1007/s10457-011-9457-5.

Parcel Boundaries of Michigan. 2021. "Parcel Boundaries Maintained by Saginaw, Gratiot, and Livingston County Agencies in Michigan." Department of Environment, Great Lakes, and Energy (EGLE) Maps and Data, File Geodatabase, Polygon Feature Class.

Prosser, R. S., P. F. Hoekstra, S. Gene, C. Truman, M. White, and M. L. Hanson. 2020. "A Review of the Effectiveness of Vegetated Buffers to Mitigate Pesticide and Nutrient Transport into Surface Waters from Agricultural Areas." *Journal of Environmental Management* 261: 110210. https://doi.org/10.1016/J.JENVMAN.2020.110210.

Qiu, Z., and M. G. Dosskey. 2012. "Multiple Function Benefit – Cost Comparison of Conservation Buffer Placement Strategies." *Landscape and Urban Planning* 107 (2): 89–99. https://doi.org/10.1016/j.landurbplan.2012.05.001.

Ruffatti, M. D., R. T. Roth, C. G. Lacey, and S. D. Armstrong. 2019. "Impacts of Nitrogen Application Timing and Cover Crop Inclusion on Subsurface Drainage Water Quality." *Agricultural Water Management* 211: 81–88. https://doi.org/10.1016/j.agwat.2018.09.016.

State of Minnesota Revisor of Statutes. 2021. *Riparian Protection and Water Quality Practices*. Pub. L. No. 103F.48, Minnesota Statutes 2021.

Schnepf, M., and C. Cox. 2006. *Environmental Benefits of Conservation on Cropland: The Status of Our Knowledge*. Ankeny, IA: Soil and Water Conservation Society.

Sellers, L. A., R. F. Long, M. T. Jay-Russell, X. Li, E. R. Atwill, R. M. Engeman, and R. A. Baldwin. 2018. "Impact of Field-Edge Habitat on Mammalian Wildlife Abundance, Distribution, and Vectored Foodborne Pathogens in Adjacent Crops." *Crop Protection* 108: 1–11. https://doi.org/10.1016/j.cropro.2018.02.005.

Shrestha, P., K. W. J. Williard, J. E. Schoonover, and L. Park. 2018. "Prevalence of Concentrated Flow Paths in Agricultural Fields in Southern Illinois." *Water, Air, & Soil Pollution* 229 (6): 41. https://doi.org/10.1007/s11270-018-3841-y.

Sowa, S. P., M. Herbert, K. R. Hall, L. Cole, S. Mysorekar, M. Fales, T. Bowe, G. Annis, A. P. Nejadhashemi, and L. Wang. 2013. *Conservation Effects Assessment Project Great Lakes Phase 2 Final Report*. https://url.us.m.mimecastprotect.com/s/HGz5CKrY6nH4kzZM9tAsvT578vS?domain=nrcs.usda.gov.

Stewart, W. P., D. R. Williams, and L. E. Kruger. 2013. *Place-Based Conservation: Perspective from the Social Sciences*. Springer eBooks.

The Nature Conservancy. n.d. "Saginaw Bay Watershed Conservation Partnership." www.iwr.msu.edu/glwms.

Tong, S. T. Y., and W. Chen. 2002. "Modeling the Relationship between Land Use and Surface Water Quality." *Journal of Environmental Management* 66 (4): 377–393. https://doi.org/10.1006/jema.2002.0593.

USDA FSA (United States Department of Agriculture Farm Service Agency). 2016. MichiganView. National Agricultural Imagery Program. https://michiganview.org/naip.html.

USDA NRCS (United States Department of Agriculture Natural Resources Conservation Service). 2024. Geospatial Data Gateway. http://datagateway.nrcs.usda.gov.

USDA NRCS (United States Department of Agriculture Natural Resources Conservation Service). 2019. Web Soil Survey. http://websoilsurvey.sc.egov.usda.gov/.

US Department of the Interior. 2021. *Bureau of Land Management National Public Land Survey System Polygons*. Washington, DC: Bureau of Land Management.

US EPA (United States Environmental Protection Agency). 2015. "Nonpoint Source: Agriculture [Overviews and Factsheets]." https://www.epa.gov/nps/nonpoint-source-agriculture.

US EPA (United States Environmental Protection Agency). 2021. "Saginaw River and Bay AOC. Great Lakes AOCs." https://www.epa.gov/great-lakes-aocs/saginaw-river-and-bay-aoc#bg.

Wallace, C. W., G. McCarty, S. Lee, R. P. Brooks, T. L. Veith, P. J. A. Kleinman, and A. M. Sadeghi. 2018. "Evaluating Concentrated Flowpaths in Riparian Forest Buffer Contributing Areas Using LiDAR Imagery and Topographic Metrics." *Remote Sensing* 10 (4): 614. https://doi.org/10.3390/rs1004061.

Wu, S., M. A. Bashir, Q.-U.-A. Raza, A. Rehim, Y. Geng, and L. Cao. 2023. "Application of Riparian Buffer Zone in Agricultural Non-Point Source Pollution Control – A Review." *Frontiers in Sustainable Food Systems* 7. https://doi.org/10.3389/fsufs.2023.985870.

Zhang, X., X. Liu, M. Zhang, R. A. Dahlgren, and M. Eitzel. 2010. "A Review of Vegetated Buffers and a Meta-Analysis of Their Mitigation Efficacy in Reducing Nonpoint Source Pollution." *Journal of Environmental Quality* 39 (1): 76–84. https://doi.org/10.2134/jeq2008.0496.

Zimnicki, T., T. Boring, J. E. Doll, C. Lippstreu, and A. Reimer. 2021. *Understanding Barriers and Opportunities to Expanding Conservation Practice Adoption among Farmers in Michigan*. Report to the Erb Family Foundation.