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The Iowa Nutrient Research and Education Council
900 Des Moines Street
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Quantification of Phosphorus Loss due to Structural Agricultural BMP Implementation

Final Report

Prepared by

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ACRONYMS AND ABBREVIATIONS

A	Land area
BMP	Best management practice
DEM	Digital elevation model
E_{BMP}	Effectiveness of a BMP for reducing phosphorus loss, expressed as a percentage
GDB	Geodatabase; generally references files containing BMP inventory data at the HUC12 scale
GIS	Geographic Information System
HUC12	A 12-Digit U.S. Geological Survey "Hydrologic Unit Code" Identifying a Sub-Watershed-Scale Catchment
IDALS	Iowa Department of Agriculture and Land Stewardship
IDNR	Iowa Department of Natural Resources
INREC	Iowa Nutrient Research and Education Council
INRS	Iowa Nutrient Reduction Strategy
ISU	Iowa State University
$J_{P\ loss}$	Mass flux of phosphorus from land to waterways, with units of kg ac^{-1} yr^{-1}
LiDAR	Light Detection and Ranging
$M_{P\ loss}$	Yearly mass of P lost from a land area, with units of kg yr^{-1}
MLRA	Major Land Resource Area
P	Phosphorus
WASCOB	Water and sediment control basin

EXECUTIVE SUMMARY

Agricultural producers in Iowa have installed or implemented structures on their land to decrease the sediment exported from land to streams and rivers. These structures are considered “best management practices” (BMPs), and they also reduce phosphorus loss from fields to waterways. This project estimated reductions of phosphorus loss due to the implementation of three types of BMPs on Iowa agricultural land: pond dams, terraces, and water and sediment control basins (WASCOBs).

Estimates of phosphorus loss reductions were generated in three steps. First, a literature review informed ranges of phosphorus loss reductions for individual implementations of pond dams, terraces, and WASCOBs. These ranges are described in a previous memorandum and reiterated briefly in this report. Reductions in phosphorus loss by BMPs are expressed on a relative basis (i.e., as a percentage). Second, a geographic information systems analysis was completed to determine the land area treated by BMPs in 20% of Iowa watersheds. A survey of BMP occurrence for these watersheds was completed by the Iowa BMP Mapping Project for the 1980s, 2007-2010, and 2016-2018. Third, the estimates of the first two steps were combined to determine the phosphorus loss reductions due to BMP construction in the surveyed watersheds. Because these watersheds are randomly distributed across Iowa, the estimate of phosphorus loss reductions there can represent that of the state.

The pond dams, terraces, and WASCOBs implemented in the 1980s retained 4% of phosphorus lost from agricultural land (range: 2.8% to 5.2%). For 2016-2018, this value is estimated at 7% (range: 4.8% to 9.5%). This implies that ongoing construction of these three types of BMPs between the 1980s and 2016-2018 led to an increase in the control of nonpoint source phosphorus export from agricultural land of 3 percentage points.

This comparison between eras is important because the 1980s is used as a baseline period for statewide nutrient reductions (Mississippi River/Gulf of Mexico Hypoxia Task Force). Nonpoint sources in Iowa are implementing a variety of BMPs and other measures to achieve a reduction goal of 29% from 1980s levels. This project estimates the contribution of the construction of agricultural pond dams, terraces, and WASCOBs towards that goal.

1. INTRODUCTION

This project aims to determine the effectiveness of three structural best management practices (BMPs) for reducing losses of phosphorus (P) from Iowa agricultural land via stormwater runoff. The three BMPs selected for this study are pond dams, terraces, and water and sediment control basins (WASCOBs). A previous memorandum estimated ranges of effectiveness for P loss reductions at 45% to 85% for pond dams, 50% to 80% for terraces, and 25% to 85% for WASCOBs (Geosyntec Consultants, 2020). These three types of BMPs were selected because they were mapped in the recently completed Iowa BMP Mapping Project (McNeely et al., 2017) and included in the Iowa Nutrient Reduction Strategy (INRS; IDALS, IDNR, and ISU, 2017). Three other BMPs, contour buffer strips, grassed waterways, and strip cropping, were part of the Iowa BMP Mapping Project but were not included in this analysis because they have not been included in the INRS and because estimates of their effectiveness for P loss reduction are scarce.

This report documents the calculation of P loss reductions across Iowa resulting from occurrences of these three BMPs. The method used Geographic Information System (GIS) analyses to determine the upstream land area of each type of BMP based on locations identified by the Iowa BMP Mapping Project (McNeely et al., 2017). The resulting land areas were combined with the BMP effectiveness estimates stated above to estimate the statewide reduction in losses of P via stormwater runoff due to the implementation of structural BMPs. These reductions are reported at the watershed scale and at a regional scale in two eras: the 1980s and 2016-2018. Statewide P loss reductions are compared between eras to assess the impact of BMPs on reducing P loads over time.

2. DATA

Two main spatial datasets were used in the determination of the upstream land area for each structural BMP. The source and attributes of each data set along with processing steps of acquisition, manipulation, and use are described below.

2.1 BMP Geodatabases

This analysis leverages work completed by the Iowa BMP Mapping Project (McNeely et al., 2017), which used aerial photographs and Light Detection and Ranging (LiDAR) derived products such as Digital Elevation Models (DEMs) and slope estimates to map the locations of six BMPs from 2007-2010 at the 12-digit Hydrologic Unit Code (HUC12) watershed scale across the state. In addition to the 2007-2010 statewide coverage, the existence of BMPs during the 1980s and 2016-2018 was mapped for 325 randomly-distributed "repeat-survey" HUC12 watersheds (Figure 1).

Geodatabases (GDBs) containing the BMP inventory are available for each mapped HUC12 watershed through the Iowa State University College of Design's GIS Facility online web mapping application[1]. The 325 repeat-survey HUC12 watersheds containing inventories from the 1980s,

[1] https://benson.gis.iastate.edu/ISU/BMP/BMP.html

2007-2010, and 2016-2018, were identified, downloaded, unzipped, and saved in individual directories.

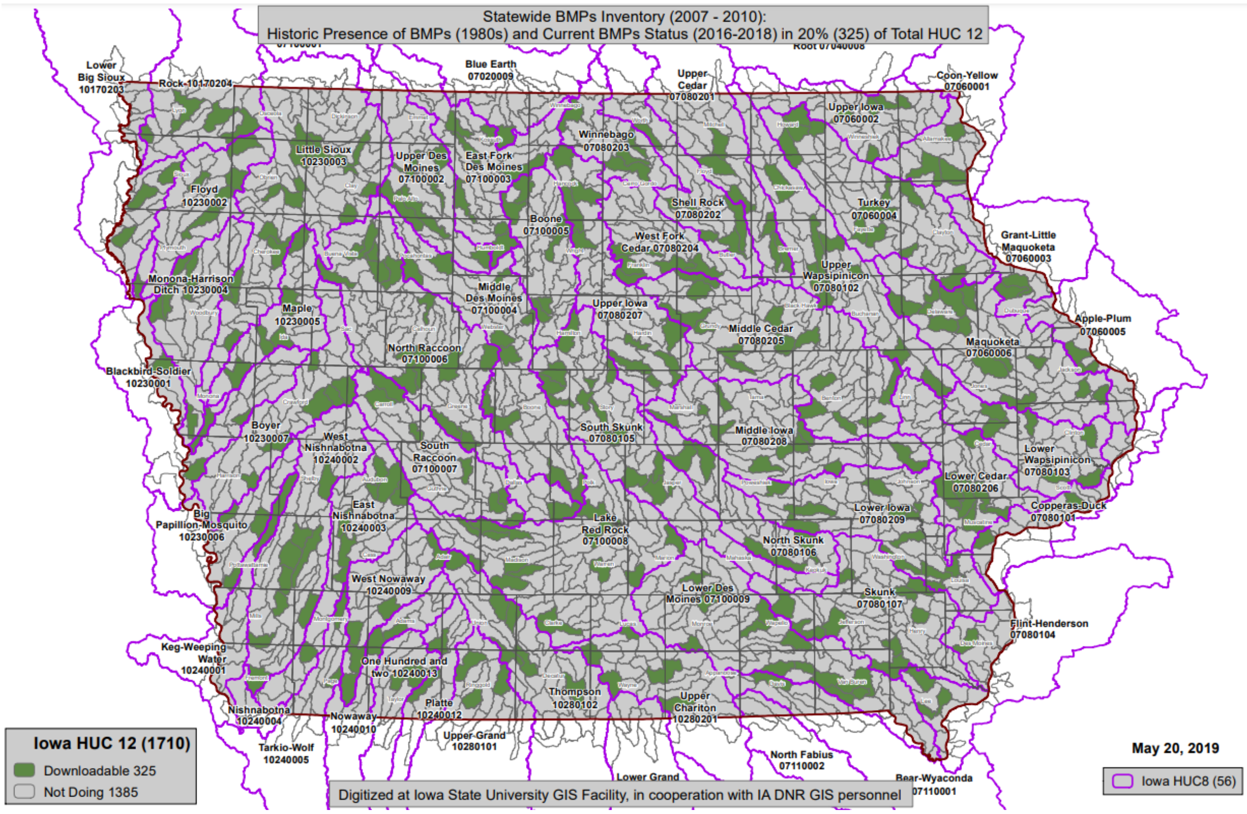

Figure 1. Map displaying the locations of 325 “repeat-survey” HUC12 watersheds containing historic and current BMPs (green; Iowa State University Geographic Information Systems, 2021)

2.1.1 Description of Data

GDBs contain datasets pertaining to each structural BMP type inventoried in the Iowa BMP Mapping Project. Pond dams, terraces, and WASCOBs are all represented using polylines. Populated attributes for these datasets include:

- Object ID
- Shape type (e.g., polyline)
- Practice type (i.e., BMP type)
- Date created
- Creator name
- Presence in the 1980s
- Presence in 2010
- Presence in 2016
- HUC12
- Shape length.

When presence in the 1980s is indicated in the attribute table of repeat-survey HUC12 watersheds, this applies only to BMPs identified in 2007-2010. The Iowa BMP Mapping Project did not evaluate the presence of BMPs in the 1980s in locations that did not have a BMP in 2007-2010. However, for 2016-2018, the presence of BMPs was noted not only for locations with BMPs in 2007-2010 but also for new locations. This different treatment of the 1980s and 2016-2018 occurred because the resolution of aerial imagery in the 1980s was insufficient to allow the same type of analysis that was done for 2016-2018.

2.1.2 Key Assumptions

It was assumed for this analysis that the BMP data contained in the GDBs as downloaded from Iowa State University's GIS online web mapping application were reasonably complete. No attempt was made to estimate the number or extent of any BMPs that were not present in the GDBs. Consequently, the total estimated treatment areas only reflect the areas treated by this existing BMP inventory.

2.2 Digital Elevation Models

DEMs are raster files that contain arrays of elevation values referenced to a geographic coordinate system. They produce images that represent terrain. DEMs at a horizontal three-meter resolution were accessed through Iowa Geodata.[2] The data were aggregated from 1-meter resolution elevation data from the state of Iowa's LiDAR program. DEMs are available for each county in Iowa. The files were downloaded, unzipped, and saved in individual directories.

2.2.1 Key Assumptions

Some processing of DEMs was assumed to be required in order to produce meaningful results from this analysis. It was assumed that filling sinks in the DEM raster would sufficiently manage hydrologic discontinuities such as hydrologic "dead ends", depressions, culvert crossings at roadways, etc.

2.2.2 Other Datasets Considered

An alternative set of county-level DEMs available from the Iowa Department of Natural Resources[3] was considered for use in this study. However, the 30-m resolution was too coarse to reliably delineate the upstream areas of BMPs in flatter terrain or closer to ridgelines.

2.3 Other Data Sets

GIS layers for Major Land Resource Areas (MLRAs) of Iowa and major landforms of Iowa were provided by R. McNeely and J. Obrecht of the Iowa State University GIS Support and Research

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[2] https://geodata.iowa.gov/dataset/three-meter-digital-elevation-model-iowa-derived-lidar
[3] https://www.iowadnr.gov/environmental-protection/air-quality/modeling/dispersion-modeling/elevation-data

Facility. The repeat-survey HUC12 watersheds were chosen by the ISU GIS Facility during the Iowa BMP Mapping Project at random within a combination of HUC8 watersheds and MLRAs to achieve a desired sampling rate. The variation of the land area of each MLRA that they represent varies minimally, from 18.2% to 21.4% (Figure 2, Table 1).

Shapefiles of land use from the High-Resolution Land Cover dataset from 2009 were downloaded from the State of Iowa Open Spatial Data service[4]. This data set was used for analyses pertaining to the three eras of the Iowa BMP Mapping Project (i.e., the 1980s, 2007-2010, and 2016-2018) because land cover data were not available for the 1980s and so each era could not be analyzed with its own land cover data set. For the purposes of this analysis, we were primarily interested in differentiating between land where P fertilizer is likely applied routinely and land where application is unlikely. Consequently, we created simple groupings that focused on A) land used for cultivation of corn and soybeans; B) grassland, pasture, and bare land; C) forests and tree cover; D) impervious land; and E) water and wetlands (Figure 3). Land used for corn and soybean cultivation is likely to receive P application regularly. Grassland, pasture, bare land, and tree cover may have once been farmed but may have been rotated to hay or added to the Conservation Reserve Program at the time when land cover data were collected. Thus, occurrences of BMPs in these land uses is not unreasonable. Impervious land (e.g., urban areas) and water are unlikely to have been used for farming, and BMPs are not expected in these areas. Consistent with land use patterns across Iowa, most repeat-survey HUC12s are found in land devoted to corn and soy cultivation (Figure 3).

[4]https://open-iowa.opendata.arcgis.com/datasets/iowadnr::2009-high-resolution-land-cover-web-service and https://iastate.app.box.com/s/dboob8jvve6qvk639smhbpsw0b7g4qbf/folder/52286308269

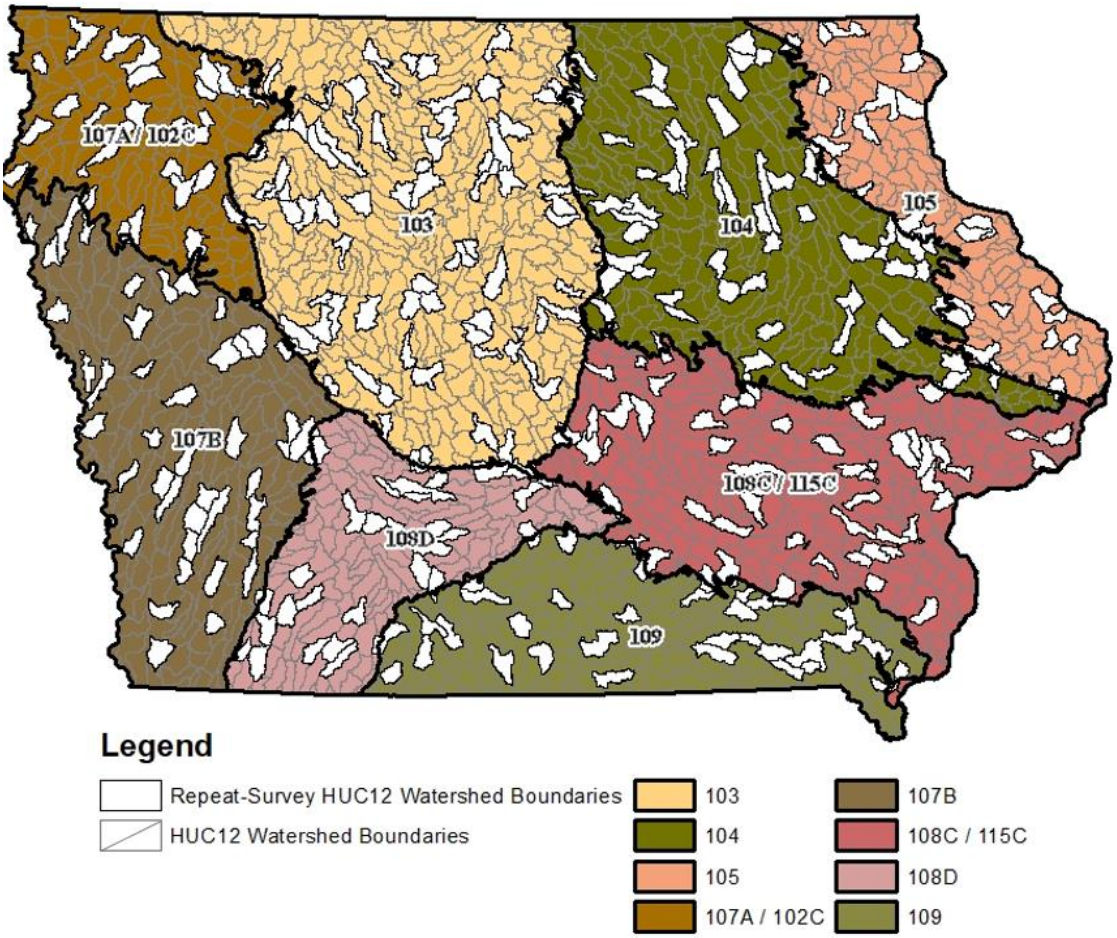

Figure 2. Randomly selected repeat-survey HUC12 watersheds and Major Land Resource Areas

Table 1. Randomly selected repeat-survey HUC12 watersheds in MLRAs

MLRA	Description	Area covered by repeat-survey HUC12s (%)
103	Central Iowa and Minnesota Till Prairies	20.9%
104	Eastern Iowa and Minnesota Till Prairies	20.3%
105	Northern Mississippi Valley Loess Hills	18.2%
107A+102C	Iowa and Minnesota Loess Hills *and* Loess Uplands	20.1%
107B	Iowa and Missouri Deep Loess Hills	19.1%
115C+108C	Central Mississippi Valley Wooded Slopes, Northern Part *and* Illinois and Iowa Deep Loess Drift, West Central Part	19.0%
108D	Illinois and Iowa Deep Loess Drift, Western Part	21.4%
109	Iowa and Missouri Heavy Till Plain	19.1%

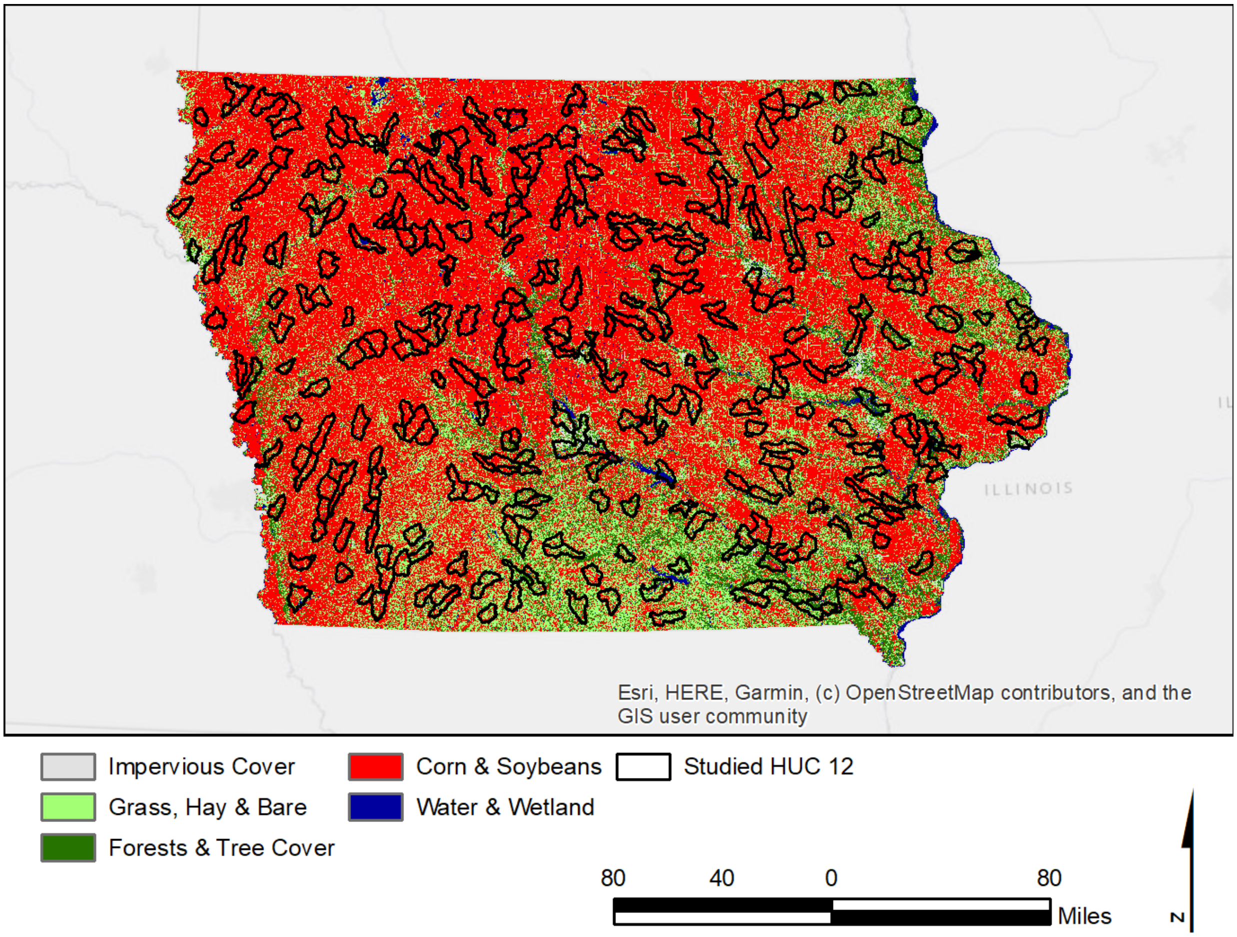

Figure 3. Repeat-survey HUC12s and 2009 land uses in Iowa

3. DATA PRE-PROCESSING

Data pre-processing was necessary for the integration of DEM and GDB datasets and the preparation of BMPs for analysis. Pre-processing actions were performed using Python and a suite of open source geospatial libraries including rasterio[5] (general raster file input/output, reformatting, and reprojection) and WhiteboxTools[6] (hydrologic terrain analysis).

3.1 Digital Elevation Models

If necessary, each DEM was re-projected to NAD 1983 UTM Zone 15 N (EPSG 26915). This is the projection used by the GDBs and provides sufficiently accurate coverage of the entire state. A

5 https://rasterio.readthedocs.io/en/latest/index.html#
6 https://jblindsay.github.io/ghrg/WhiteboxTools/index.html

polygon shapefile of the geographic extents of the DEMs was created to facilitate the spatial association (i.e., spatial joining) of the DEMs with the BMP geodatabases.

3.2 BMP Geodatabases

The BMP GDBs contain datasets pertaining to each structural BMP type inventoried in the Iowa BMP Mapping Project: contour buffer strips, grassed waterways, pond dams, strip cropping, terraces, and WASCOBs. This project was limited to pond dams, terraces, and WASCOBs because these were included in the Iowa Nonpoint Source Science Assessment and because information pertaining to P loss reductions by contour buffer strips, grassed waterways, and strip cropping is scarce.

To facilitate an analysis of upstream land area, it was necessary to transform each BMP polyline into a series of point geometries. In a typical watershed delineation workflow, watersheds are delineated upstream of so-called "pour points". Since DEMs are arranged in rectilinear grids of pixels, the modeled overland flow to and from a given pixel in a DEM can only proceed in one of the eight directions towards the neighbors with which it shares edges or corners (this is known as the D8 flow direction). This limitation of D8 flow directions means that often pixels in the middle of a hillside or even a few pixels away from a stream will receive very small watershed delineations that include the pixels directly along the fall line.

To work around the limitations of D8 flow directions in delineating watersheds, hydrologists and GIS analysts will snap the pour points to the closest nearby stream within a radius of the original location (i.e., the snapping distance).

The linear nature of WASCOBs and terraces and their orientation that is perpendicular to the fall line away from streams precludes their treatment as singular points in an upstream land area assessment; they cannot be treated as if they "discharge" from a single point. Rather, a point was interpolated every three meters along the geometry of each terrace and WASCOB polyline. Three meters was chosen to match the resolution of the DEMs. Upstream area was determined for each interpolated point as described in Section 5 below. Snapping to waterways was regarded as inappropriate for terraces and WASCOBs.

Pond dams are placed in streams and ditches and therefore may be treated as traditional, singular "pour points" when delineating their upstream areas. Pond dam geometries were initially converted to single points at each polyline's midpoint and then snapped to the nearest stream within 20 meters; this is assumed to be representative of the channel's midline. However, this led to significant mischaracterizations of treated areas when pond dams snapped incorrectly to sizeable waterways. Thus, no snapping of pond dams was used in this analysis.

Points created from all structural BMPs in a HUC12 watershed were unified in a single feature layer that was named for its respective watershed and saved in a new directory. The result of this activity was a directory consisting of 325 feature layers (one for each HUC12 watershed) that each contain points representing the structural BMPs contained in the HUC12 watershed.

4. DATA INTEGRATION

It was necessary for analysis speed and function to spatially match each HUC12 to the DEM(s) necessary to provide full coverage of the HUC12. The bounding boxes of each repeat-survey HUC12 boundary were computed and then given a 1,000-meter buffer. Applying the buffer around the HUC12 boundary ensures there would be sufficient land upstream of BMPs near the edges of the HUC12 layers to delineate their full watersheds in case there were minor discrepancies between HUC12 boundaries and the DEM in use. The shapefile of DEM boundaries was spatially joined to those of the HUC12 extents to identify the DEMs that would be needed to wholly contain the buffered extent of the repeat-survey HUC12s. The extent of the DEM that covered the buffered extent of the BMP layer was extracted and saved in the corresponding HUC12 results directory.

If the buffered extent of a HUC12 was not wholly contained in one DEM, then all DEMs overlapping the HUC12 boundary were merged into single temporary file. The extent of the merged DEM that covered the buffered extent of the BMP layer was extracted and saved in the corresponding HUC12 directory. The result of this activity was that each HUC12 GDB directory contained a clipped DEM that covered the extent of the HUC12 and the BMP layer.

5. DETERMINATION OF AREAS UPSTREAM OF EACH BMP

5.1 <u>Determination of Land Area</u>

The following process was used to determine the land area upstream of each BMP. This analysis was performed using the Python WhiteboxTools library.

1) The extracted DEM for each respective HUC12 watershed was read and all topographical sinks were filled to remove depressions, hydrologic dead ends, and hydrologic discontinuities. Raw and processed DEMs were reviewed broadly to verify hydrologic continuity.
2) Flow direction was computed for the processed DEMs using the D8 algorithm (O'Callaghan & Mark, 1984). The direction of flow is determined by the direction of steepest descent from each DEM pixel to one of its eight neighbors.
3) The land area upstream of each BMP was determined by tracing upstream from the pour points placed along the linear feature until the treated area of another BMP upstream or a ridge was encountered (see Section 6.2 below). The output from this analysis was a raster file in which each pixel is linked to a point along a BMP. The number of pixels can be counted for each BMP to determine the upstream area of the BMP. Pixels are 3 meters on a side, and thus 449.65 pixels equal 1 acre.

Land areas determined by this automated method were validated by visual examination in 8 specific HUC12 watersheds used for pilot testing this method (Table 2). Pilot watersheds were chosen to represent a variety of slopes and MLRA types across Iowa. This examination showed that delineations of land upstream of BMPs was more reliable in steeper areas because our methodology could identify flow direction more reliably. Conversely, in flatter areas (including near hilltops), our methodology frequently calculated smaller treated areas for WASCOBs and terraces because our algorithm ceased counting pixels upstream when pixels were at the same elevation. We considered adjusting the delineation of upstream area by allowing flow direction to be determined by differences in elevation beyond the eight neighbors of a given pixel. However, we regarded an underestimate of treated area as acceptable because of potential reduced overland flow in these areas and because of the potential for greater errors if additional pixels were used to determine flow direction. This underrepresentation of treated area appears to be minor, and thus it adds an element of conservativism to the results presented below.

Table 2. Pilot HUC12 Watersheds

HUC12 Watershed	Major Land Use Resource Area	County
070802050501	Eastern Iowa and Minnesota Till Prairies	Grundy
070600020503	Northern Mississippi Valley Loess Hills	Allamakee/Winneshiek
070200090102	Central Iowa and Minnesota Till Prairies	Kossuth
070802090905	Illinois and Iowa Deep Loess and Drift, West-Central Part	Washington/Louisa
071000060307	Iowa and Minnesota Loess Hills	Buena Vista
102300070602	Iowa and Missouri Deep Loess Hills	Harrison
071000080503	Illinois and Iowa Deep Loess and Drift, Western Part	Madison
102802010102	Iowa and Missouri Heavy Till Plain	Wayne

5.2 <u>Approach for Multiple BMPs</u>

For the purposes of this GIS methodology, it was necessary to consider whether land area should be attributed to BMPs when it contained additional BMPs upstream. Researchers have examined the question of how BMPs upstream of other BMPs (i.e., the "nesting" of BMPs) might affect P loss reductions achieved by groups of BMPs. The percent reductions of multiple BMPs in a watercourse should not be added (Tomlinson et al., 2015; Christianson et al., 2018); a multiplicative approach may be more appropriate (Christianson et al., 2018).

In this analysis, differing types of BMPs and BMPs within the same group were not considered "nested" for the purposes of determining the area treated by each BMP. That is, any given BMP only treats runoff that has *not* encountered another inventoried BMP. This assumption results in counting each parcel of treated land as if its runoff is only subject to treatment from exactly one

BMP, even if the parcel of land is upstream of multiple BMPs. This assumption applies to each type of BMP considered in this analysis.

We reasoned that agricultural producers would not install more BMPs closer to each other than necessary. Therefore, a specific pond dam would trap sediment in the stream channel that entered upstream of that dam and downstream of the pond dam upstream of it. For example, Pond Dam A and Pond Dam B are in the same stream channel with A upstream of B (Figure 4). These assumptions result in Pond Dam B treating only the stream channel between it and Pond Dam A upstream (i.e., the light blue area in Figure 4). In this analysis, Pond Dam B would not treat the area upstream of Pond Dam A (i.e., the dark blue area in Figure 4), even though that water eventually flows to Pond Dam B. That portion of the stream channel upstream of Pond Dam A would be treated only by Pond Dam A, not also by successive pond dams downstream. Although this example has used pond dams, the same concept applies to terraces, WASCOBs, and combinations of BMP types in this analysis.

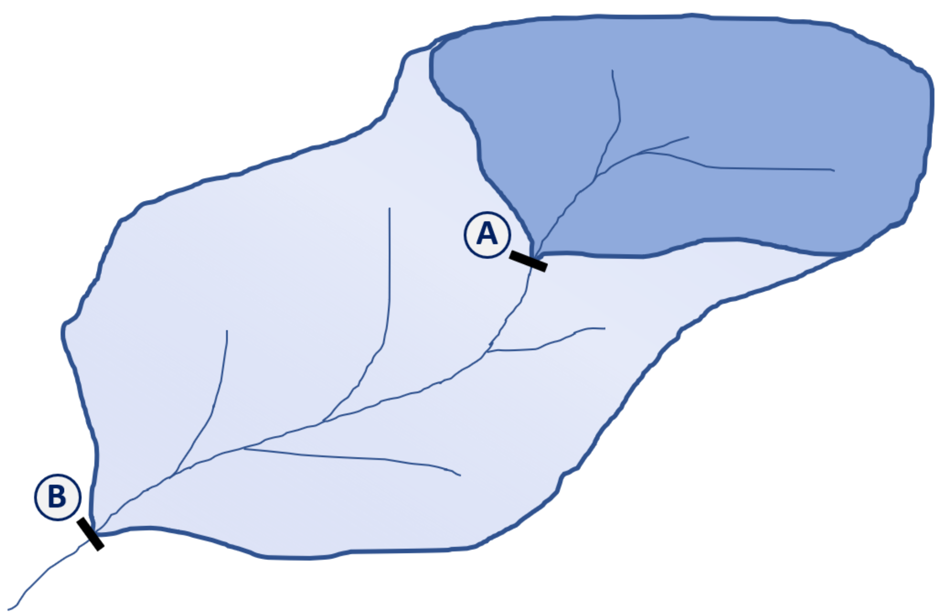

Figure 4. Example watershed showing two pond dams (black lines labeled "A" and "B") and their treated areas (shades of blue). Stream flow is from upper right to lower left.

This assumption is an approximation, as BMPs are unlikely to perfectly remove sediment and P from the stream. Therefore, they will release some downstream to be potentially intercepted by another BMP. However, this assumption is less complex than those required to explicitly incorporate nesting in this analysis. Additionally, the estimates resulting from this approximation may underestimate P loss reductions. This would occur due to treatment redundancy provided by nesting when downstream BMPs are sized to handle runoff from first reaching upstream BMPs as well as the runoff generated below upstream BMPs. Non-utilization of nesting in this analysis is an element of conservativism.

5.3 Adjustments Made for Specific Pond Dams

Upon examination of treated land areas in the repeat-survey HUC12s, Geosyntec made adjustments to remove area treated by specific pond dams. This occurred for two reasons. First, the Iowa BMP Mapping Project occasionally classified dams designed to create reservoirs in major stream or river channels as pond dams. Specifically, Lost Grove Lake, which is located in Scott County and HUC12 070801030606, has a maximum depth of 50 feet and a water surface area of 400 acres (IDNR, 2021a). A review of historical imagery on Google Earth indicates that this reservoir was completed in 2012, and thus its removal from this analysis adds a degree of conservativism to the results presented below. Binder Lake, located in Adams County and HUC12 102400100107, has a maximum depth of 18.8 feet and an area of 72 acres (IDNR, 2021b). This reservoir was created in 1942 (U.S. EPA, 2012), so its removal should have no effect on changes in P loss reduction between eras. Conversely, the dam creating Rock Creek Lake, which lies in Jasper County and HUC12 070801060104 and has a maximum depth of 17.8 feet and an area of 466 acres (IDNR, 2021c), is one of many sizeable dams that is not classified as a pond dam by the Iowa BMP Mapping Project. To ensure that large dams were treated consistently across the repeat-survey HUC12s, Geosyntec manually removed the assignment of the treated area associated with Lost Grove Lake and Binder Lake.

Secondly, the assignment of treated area to specific pond dams was removed when those pond dams led to treated areas that were many times larger than the treated areas of other pond dams in a given HUC12. This was based largely on visual inspection and professional judgement. These treated areas were assessed by visual examination of treated-area maps of repeat-survey HUC12 watersheds in 2016-2018 (Appendix A). Generally, we defaulted against making modifications since it is plausible that pond dams can influence large areas in flat terrain. However, two HUC12 watersheds contained obviously incorrect depictions of treated areas. The most obvious of these occurred in HUC12 071000091206, where a pond dam appears to have been erroneously located in the Des Moines River and thus treated area in multiple HUC12s for some distance upstream (Figure 5). In another example, up to two pond dams in HUC12 102300010302 may have been erroneously located in large stream channels or may have interacted with a flat area whose topographic variation was within the error of the DEM used in this analysis (Figure 5). Each of the subject dams in these two HUC12 watersheds was removed.

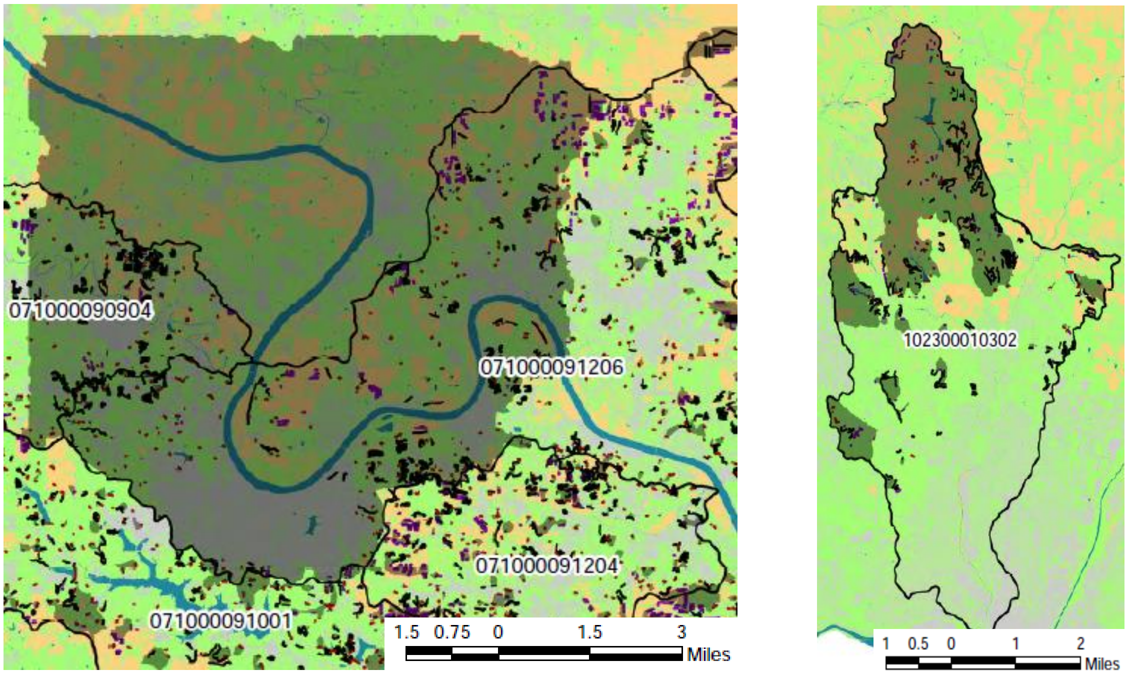

Figure 5. Unreasonably large areas shown prior to correction. These HUC12 watersheds appear after correction on pages 224 and 233 of Appendix A, respectively. Gray shading denotes treated areas, black lines represent HUC12 boundaries, and small polygons represent individual BMP occurrences.

6. CALCULATION OF P LOSS REDUCTIONS DUE TO BMPs

6.1 Calculation Methodology

Absent any BMPs, the yearly loss of P from a land area is the product of a yearly mass flux of P from the land to nearby waterways (J) and the area of the land evaluated (A):

$$M_{P\ \mathrm{loss}} = J_{P\ \mathrm{loss}} \cdot A \qquad (1)$$

where $M_{P\ loss}$ is the yearly mass of P lost from the land area, with units of kg yr^{-1}
$J_{P\ loss}$ is the flux of P from land to waterways, with units of kg ac^{-1} yr^{-1}
A is land area, with units of acres.

Treatment of some land in a HUC12 watershed due to the presence of BMPs reduces $M_{P\ loss}$. This reduction varies across different BMP types, and it varies within individual types of BMPs due to ranges in literature estimates of BMP effectiveness. Previous work generated ranges of estimates for pond dams, terraces, and WASCOBs (Table 3). The estimate of P loss reduction described here was repeated for each of the 12 cases in Table 3; the estimates for the three different BMP types in one scenario were summed to generate a total P loss reduction due to these three BMPs.

Table 3. Estimates of P loss reductions by BMP type[a]

Scenario	Pond Dams	Terraces	WASCOBs
Minimum	45%	50%	25%
Midpoint	65%	65%	55%
Maximum	85%	80%	75%
INRS Value	85%	77%	85%

[a] Table reproduced from memorandum by Geosyntec Consultants (2020). Minimum, midpoint, and maximum values were estimated as part of this project. The INRS value is quoted from IDALS, IDNR, and ISU (2017).

Using the estimate of area treated by a given type of BMP in a HUC12 watershed (described above), we partitioned each repeat-survey HUC12 into "treated" and "untreated" land, where treated land lies upstream of BMPs and untreated land does not. The mass of P lost from a given HUC12 is thus:

$$M_{P\text{ loss, HUC12}} = M_{P\text{ loss, treated}} + M_{P\text{ loss, untreated}} \tag{2}$$

where $M_{P\text{ loss, HUC12}}$ is the yearly mass of P lost from the HUC12 watershed, with units of kg yr^{-1}
$M_{P\text{ loss, treated}}$ is the yearly mass of P lost from the treated area in the HUC12 watershed, with units of kg yr^{-1}
$M_{P\text{ loss, untreated}}$ is the yearly mass of P lost from the untreated area in the HUC12 watershed, with units of kg yr^{-1}.

Mass of P lost from untreated land was calculated as in Equation 1. We did not seek to estimate $J_{P\ loss}$ for each HUC12 watershed. Instead, we found $M_{P\ loss,\ treated}$ by multiplying $A_{treated}$ by the effectiveness of a BMP type subtracted from 1 and expressed as a decimal:

$$M_{P\text{ loss, treated}} = J_{P\text{ loss}} \cdot \left(A_{\text{treated}} \cdot (1 - E_{\text{BMP}}/100)\right) \tag{3}$$

where $A_{treated}$ is the treated area of the HUC12 watershed, with units of acres
E_{BMP} is the effectiveness of a BMP for reducing P loss in a given scenario, expressed as a percentage and taken from Table 3
The value 100 converts a percentage into a decimal.

Algebraically, this approach is identical to applying the estimates of BMP effectiveness from Table 3 to the flux of P from a land area to a waterway. Conceptually, this approach is equivalent to assuming that $J_{P\text{ loss}}$ is 0 in a percentage of the area upstream of a BMP equal to E_{BMP} while $J_{P\text{ loss}}$ is unchanged in remaining area.

The reduction in P loss due to all occurrences of one BMP type in a HUC12 watershed was calculated by dividing $M_{P\text{ loss, HUC12}}$ by the mass of P loss in the equivalent area without occurrences of that BMP type:

$$\Delta M_{P\text{ loss, BMP}} = 1 - \frac{M_{P\text{ loss, HUC12}}}{J_{P\text{ loss}} \cdot A_{\text{HUC12}}} \tag{4}$$

Equation 4 simplifies by cancelling $J_{P\ loss}$ from each term in the fraction:

$$\Delta M_{P\text{ loss, BMP}} = 1 - \frac{A_{\text{untreated}} + A_{\text{treated}} \cdot (1 - E_{\text{BMP}}/100)}{A_{\text{HUC12}}} \tag{5}$$

This is equivalent to:

$$\Delta M_{P\text{ loss, BMP}} = \frac{A_{\text{treated}} \cdot E_{\text{BMP}}/100}{A_{\text{HUC12}}} \tag{6}$$

To find the reduction in P loss for a given scenario, $\Delta M_{P\text{ loss}}$ values calculated for each BMP type were summed. This analysis was repeated for each of the eras evaluated for the repeat-survey HUC12 watersheds (i.e., the 1980s, 2007-2010, and 2016-2018), and these were compared to assess improvements in P loss reduction over time due to ongoing BMP implementation.

The calculation described above would not give relevant results because including all land in a HUC12 watershed would assess impervious, developed land as though it might contain BMPs or release P to waterways as a nonpoint source. Consequently, the calculation of $\Delta M_{P\text{ loss}}$ values was performed after restricting the calculation to agricultural land within a HUC12 watershed. Two separate definitions of agricultural land were used in two calculations that allow for an interesting comparison of results. First, “Ag-Plus” land included land in the 2009 High Resolution Land Cover dataset that was classified by corn, soybeans, short deciduous forest, medium deciduous forest, grass, or hay, as well as barren or fallow land. Second, “Corn-Soy” land included only land used for corn and soybean cultivation. The narrower Corn-Soy definition of agricultural land is appropriate because these are the land classifications where we expect the vast majority of P is applied. The broader Ag-Plus description of land use is also appropriate not only because it includes land that may have high soil P due to prior cultivation (deciduous forest was included because it frequently appears to exist in riparian buffer strips) but also because numerous BMPs exist in Ag-Plus land that is not Corn-Soy land.

We evaluated the reasonableness of calculating reduction of P losses from agricultural land to waterways on a relative basis (i.e., as percentages). A review by Dinnes (2004) of the effectiveness of terraces in Iowa indicates that reasonable percent reductions were calculated at P losses as low as 0.1 pounds of P per acre. Below this value, use of percent reductions may be challenging due to large percentages that could result from comparison of small load values. We estimated P losses in MLRAs by dividing the estimates from the INRS as tabulated by Helmers et al. (2017) by MLRA areas taken from the MLRA GIS shapefile. Losses of P from MLRAs ranged from 0.53 to

1.36 pounds per acre. This indicates that P losses in Iowa are likely large enough that characterizing them with percent reductions is reasonable.

This method is subject to limitations. First, it does not account for proximity of BMPs to waterways. This could be relevant because hillside BMPs (i.e., terraces and WASCOBs) will likely receive different P loads and may perform differently if, for example, they are near a hilltop or near a stream channel. However, at the HUC12 scale, we assumed that variations in hydrology or proximity to waterways would average to net effects that are small relative to the range of performance documented for each BMP type (Table 3). Second, agricultural producers can be acutely aware of land areas that are higher in soil P, but this analysis is not conducted at a spatial resolution that can resolve differences within a given farm. Third, the same percent reduction by BMP type was used regardless of the land use tributary to it. Areas with low loss rates may not see the same level of load reduction as areas with high phosphorus loss rates because levels of load reductions are constrained by natural background concentration levels.

6.2 Corrections Related to Land Classification

Visual examination of treated-area maps of individual HUC12 watersheds in Appendix A suggests BMPs are more common in Corn-Soy land, but BMPs were prevalent in Ag-Plus land as well. Figure 6 shows an example of a HUC12 watershed in which both Corn-Soy land and Ag-Plus land are treated by BMPs.

The classification of Ag-Plus land was generally appropriate for two reasons. First, several HUC12 watersheds contained numerous BMPs in Ag-Plus land that was not Corn-Soy land in the 2009 land use layer used in this analysis. Examples are HUC12 watersheds appearing on pages 71, 111, 135, 197, 202, and 314 of Appendix A. This indicates that the definition of Ag-Plus land is sufficiently broad to capture the land in the repeat-survey watersheds that contain BMPs. Second, because we excluded tall deciduous forest, water, and wetlands from the definition of Ag-Plus land, undeveloped riparian land not used for agriculture was not counted as land that could have been treated by BMPs in the calculation described above. An example of this phenomenon occurs along the Wapsipinicon River east of Waterloo and northwest of Independence in the vicinity of the Mickey Fox Wildlife Area and the Otterville Bridge State Access Area (Appendix A page 42). Because no BMP occurrences appear in riparian areas that are not classified as Ag-Plus land, this indicates that the definition of Ag-Plus land is not overly broad.

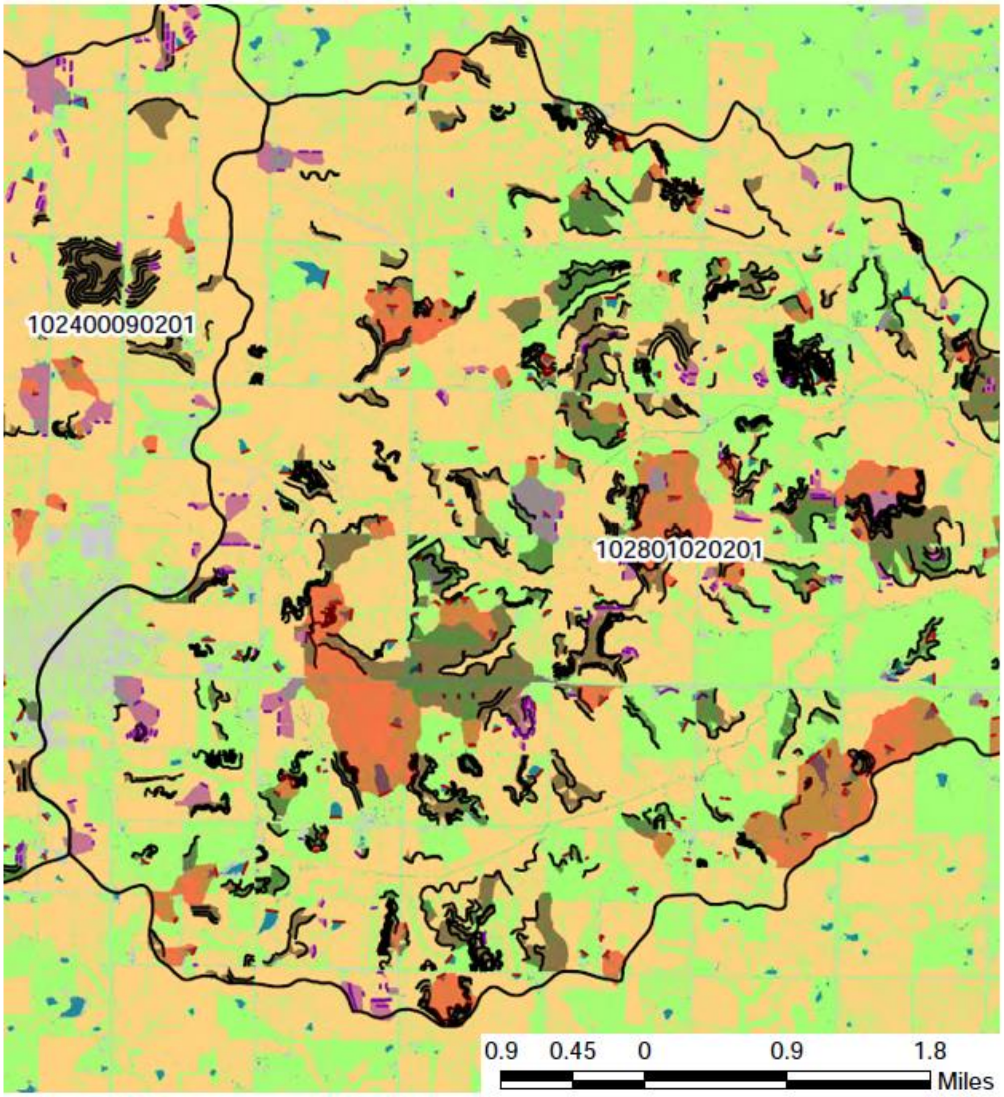

Figure 6. Example HUC12 watershed showing BMPs treating Corn-Soy (yellow) and Ag-Plus (green) land. Terraces appear as black lines, and area treated by terraces is shaded gray. Pond dams appear as red lines and their treated areas are shaded pink. Numbers identify HUC12 watersheds. This map appears on page 310 of Appendix A.

Although the definition of Ag-Plus land appears to be appropriate for rural areas where grass, small trees or medium trees might grow in land that was once used for agriculture and that contains BMPs, this definition is problematic in urban areas. Because the Iowa BMP Mapping Project randomly distributed repeat-survey watersheds across Iowa, some are located in areas where trees and grass are not the result of corn and soy field laying fallow or land being devoted to the Conservation Reserve Program. Instead, trees and grass in urban areas are part of parks, residential yards, and athletic fields. Because these would never have agricultural BMPs, classifying this land as Ag-Plus represented an unreasonable increase in untreated Ag-Plus land in some MLRAs. Consequently, the following repeat-survey HUC12 watersheds were removed from this analysis:

- HUC12 070801010302, in the City of Davenport,
- HUC12 070802020704, which contains the City of Clarksville,
- HUC12 071000040911, the western suburban area of the Des Moines metropolitan area,
- HUC12 071000041003, the eastern suburban area of the Des Moines metropolitan area,
- HUC12 071000061703, the southwestern suburban area of the Des Moines metropolitan area, and
- HUC12 071000070203, where most Ag-Plus land is within the City of Carroll.

HUC12 watersheds containing Des Moines suburbs or Davenport were nearly entirely urban land classified as "Other" (i.e., non-agricultural) or urban developed pervious land erroneously classified as "Ag-Plus" in our analysis, and thus removing these HUC12s is appropriate. Although Clarksville and Carroll are not large cities, their developed pervious area comprised most of the Ag-Plus land in these HUC12 watersheds. The large number of repeat-survey HUC12s in this study allowed us to remove these HUC12s without concern for negative effects on the overall results. Conversely, the Ag-Plus area around Mason City (Appendix A page 94) is an example of near-urban agricultural land that is identified correctly; incorrectly identified Ag-Plus land in this area appears to be minor. Consequently, this HUC12 watershed was left in the analysis.

The Iowa BMP Mapping Project created 325 repeat-survey HUC12 watersheds. The removal of 6 HUC12 watersheds that contained meaningful urban areas left 319 repeat-survey HUC12 watersheds in the study. These are the basis of the results presented below.

7. BMP OCCURRENCE

Of the BMPs assessed by the Iowa BMP Mapping Project, grassed waterways and terraces were the most numerous, together comprising over 75% of the BMPs in the 319 repeat-survey HUC12s that were part of this study in 2016-2018 (Table 5). Pond dams and WASCOBs comprised 7% and 17%, respectively. Occurrence of each BMP type increased substantially from the 1980s to 2016-2018, with the count of WASCOBs, contour buffer strips, and grassed waterways more than tripling and the total number of BMPs more than doubling.

Table 4. Statewide Counts of BMPs in the 319 HUC12 Watersheds Included in this Study

BMP Type	1980s	2016-2018
Pond Dams	14,884	20,429
Terraces	63,815	102,867
WASCOBs	16,213	53,835
Contour Buffer Strips	618	2,264
Grassed Waterways	40,888	134,007
Strip Cropping	258	527
Total	136,676	313,929

8. AREA TREATED BY BMPS

In 2016-2018, implementation of terraces, pond dams, and WASCOBs varied widely across MLRAs based on topography. Generally, the hilly MLRAs of western Iowa and northeastern Iowa have by far the greatest density of BMPs. In the Illinois and Iowa Deep Loess and Drift and the Iowa and Missouri Deep Loess Hills, 24% of Corn-Soy area in each of these MLRAs and 22% and 24% of Ag-Plus area, respectively, are treated by these three BMP types. Conversely, the flatter MLRAs of central Iowa have fewer terraces, pond dams, and WASCOBs. In the Central and Eastern Iowa and Minnesota Till Prairies, 4% of both Corn-Soy and Ag-Plus land is treated by these three BMPs. Table 5 shows this trend for Corn-Soy land; treated land areas are larger but trends are similar for Ag-Plus land, which is shown in Appendix B. Results in Table 5 and Appendix B are aggregations of results expressed by individual repeat-survey HUC12 watersheds, which are shown in Appendix C.

Between the 1980s and 2016-2018 in the repeat-survey HUC12 watersheds evaluated as part of this study, the total number of terraces and the Corn-Soy area treated by terraces increased by 61% and 81%, respectively (Table 5). For pond dams, these increases were 37% and 47%, respectively, and, the number and treated area of WASCOBs increased by 232% and 156%, respectively. Examination of maps of treated areas for each era in each HUC12 (Appendix D) shows the increase in the numbers of BMPs between these eras. For example, HUC12s appearing on pages 68, 76, 77, 149, 215, 256, 262, and 271 of Appendix D show major increases in BMP occurrences between the 1980s and 2016-2018.

Across all repeat-survey HUC12 watersheds in this study, pond dams, terraces, and WASCOBs together treated 6% and 11% agricultural land in the 1980s and 2016-2018, respectively. The percentage of Ag-Plus land treated was slightly higher than the percentage of Corn-Soy land treated.

9. PHOSPHORUS REMOVAL BY BMPS

As a consequence of Equation 6, the P loss due to the presence of BMPs in the repeat-survey HUC12 watersheds tracked closely with the trends in treated land area described above. Table 6 shows results by MLRA for Corn-Soy land in 2016-2018. For brevity, only minimum, midpoint (i.e., halfway between minimum and maximum), and maximum P loss reductions, which correspond to the minimum, midpoint, and maximum estimates of BMP effectiveness in Table 3, are shown. Trends by MLRA are generally similar for Ag-Plus land (Appendix B) although differences of 1 to 2 percentage points occur between the different land types for some MLRAs. Pond dams show higher P loss reductions in Ag-Plus land because the treated areas of these BMPs frequently extend from Corn-Soy land into Ag-Plus land and this offsets the greater total land area of Ag-Plus land. The opposite is true for terraces and WASCOBs, which show lower P loss reductions in Ag-Plus land than in Corn-Soy land. P loss reductions of all HUC12 watersheds appear in Appendix C. Concomitant with the increase in treated area of both Corn-Soy land and Ag-Plus land in the repeat-survey HUC12 watersheds in this study, P loss reductions increased for pond dams, terraces, and WASCOBs between the 1980s and 2016-2018 (Table 7).

The statewide reduction in P loss due to the combined effect of pond dams, terraces, and WASCOBs in Iowa appears in Table 8. Consistent with the estimates of BMP effectiveness in Table 3, the maxima in each era and each land use type are slightly less than double the minima. Notably, the statewide P loss reductions in 2016-2018 that result from the INRS estimates of BMP effectiveness (e.g., 9.3% and 9.5% for Corn-Soy and Ag-Plus land, respectively) exceed those based on the maximum BMP effectiveness estimated from our recent literature review (e.g., 9.1% and 9.3%, respectively). This is a consequence of the INRS effectiveness estimate for WASCOBs (85%) exceeding that of the maximum literature-based estimate for WASCOBs (75%; Table 3) and the substantial areas treated by WASCOBs in this era (Table 5).

The statewide P loss reduction increased in Ag-Plus land by 2.1 to 4.2 percentage points between the 1980s and 2016-2018. These values were slightly higher for Corn-Soy land.

10. SUMMARY OF FINDINGS

The locations of pond dams, terraces, and WASCOBs identified by the Iowa BMP Mapping Project (McNeely et al., 2017) were combined with digital elevation models in a GIS analysis to identify land areas treated by these three types of BMPs. This analysis was performed in 319 HUC12 watersheds in which the Iowa BMP Mapping Project identified BMPs in the 1980s, 2007-2010, and 2016-2018. These estimates indicate that areas treated by BMPs vary widely across the Major Land Resource Areas of Iowa; BMPs are far more numerous and treated areas are far greater in the hilly areas of western and eastern Iowa. The numbers of terraces and pond dams each increased notably from the 1980s to 2016-2018, and the number of WASCOBs more than tripled during this period. Accordingly, the treated areas of all three BMP types increased during this period.

These estimates of treated area were combined with four separate estimates of percent reductions of P loss attributable to pond dams, terraces, and WASCOBs (Geosyntec Consultants, 2020). This resulted in P loss reductions that tracked the regional and temporal trends observed for treated area. The estimates of BMP effectiveness imply an increase in the P loss reduction attributable to the three BMP types in this study of 2.1 to 4.2 percentage points from the 1980s to 2016-2018 in "Ag-Plus" agricultural land across Iowa.

Multiple elements of conservativism in the methodology of this study imply that actual statewide P loss reductions may be higher than the estimates presented here. Most notably, BMPs frequently occur downstream of other BMPs (see Appendices A and D) and thus runoff water may be treated multiple times. This phenomenon was not utilized in this analysis, and this suggests that the upper range of our results may be useful for agricultural policymaking. However, the possible underestimate of BMP occurrences in the 1980s is an unquantified data gap. If it is not negligible, then the P loss reductions from that era reported here may be underestimates. In this case, the changes reported here between that era and 2016-2018 would be overestimates. Consequently, the midpoint values of the results presented here may be most appropriate for policymaking. These results suggest that the construction of pond dams, terraces, and WASCOBs across Iowa has led to an increase in a P loss reduction of 3.2 percentage points between the 1980s and 2016-2018 in "Ag-Plus" agricultural land. In land devoted to the cultivation of corn and soybeans, these increases are slightly higher: 3.3 percentage points between the 1980s and 2016-2018.

These increases in P loss reductions are the result of substantial increases in the occurrence of pond dams, terraces, and WASCOBs from the 1980s to 2016-2018. The increases in these three BMP types were surpassed by that of grassed waterways, which are the most numerous BMP in Iowa. Contour buffer strips and strip cropping are far less prevalent than the other four BMP types assessed in the Iowa BMP Mapping Project, but their relative gains were also substantial between the 1980s and 2016-2018. Grassed waterways, contour buffer strips, and strip cropping were not assessed as part of this study because their P loss reduction values are not well understood. Should P loss reduction estimates be established for these BMPs, the analysis presented here could be repeated for them as a supplement to this study.

Table 5. BMP Occurrence and Treated Area by MLRA[a] in 2016-2018, Corn-Soy Land

MLRA	Total Area (ac)	Pond Dams		Terraces		WASCOBS		Sum	
		BMPs	Treated Area (ac)	BMPs	Treated Area (ac)	BMPs	Treated Area (ac)	BMPs	Treated Area (ac)
Cent. IA and MN Till Prairies	1,226,400	412	23,169	1,901	9,824	2,674	27,035	4,987	60,028
Cent. Miss. Valley Wooded Slopes, Northern Part *and* Ill. and Iowa Deep Loess and Drift, West-Central Part	584,128	3,024	11,771	8,206	17,732	13,641	38,387	24,871	67,889
E. Iowa and Minn. Till Prairies	854,644	590	7,840	2,378	8,093	3,053	15,283	6,021	31,217
Ill. and Iowa Deep Loess and Drift, Western Part	279,068	5,487	14,783	18,074	32,534	11,650	22,561	35,211	69,878
Iowa and Minn. Loess Hills *and* Loess Uplands	465,716	173	4,369	8,542	32,696	1,201	6,033	9,916	43,099
Iowa and Mo. Deep Loess Hills	663,043	1,577	19,865	48,989	121,824	6,122	19,124	56,688	160,812
Iowa and Mo. Heavy Till Plain	223,854	7,675	14,441	8,358	13,403	12,893	25,629	28,926	53,472
Northern Mississippi Valley Loess Hills	196,081	1,491	8,075	6,419	13,453	2,601	5,453	10,511	26,981
Total, 1980s	4,492,934	14,884	70,831	63,815	137,948	16,213	62,407	94,912	271,186
Total, 2016-2018	4,492,934	20,429	104,312	102,867	249,559	53,835	159,504	177,131	513,376

[a] Land areas and counts of BMPs are summed within each MLRA only for the 319 repeat-survey HUC12 watersheds included in this study. These areas do not represent the total areas within each MLRA.

Table 6. P loss reductions in 2016-2018, Corn-Soy Land

MLRA	Treated Area[a] (ac)	Pond Dams Min. (%)	Pond Dams Mid. (%)	Pond Dams Max. (%)	Terraces Min. (%)	Terraces Mid. (%)	Terraces Max. (%)	WASCOBS Min. (%)	WASCOBS Mid. (%)	WASCOBS Max. (%)	Cumulative Min. (%)	Cumulative Mid. (%)	Cumulative Max. (%)
Cent. IA and MN Till Prairies	60,028	0.9	1.2	1.6	0.4	0.5	0.6	0.6	1.2	1.7	1.8	3.0	3.9
Cent. Miss. Valley Wooded Slopes, Northern Part *and* Ill. and Iowa Deep Loess and Drift, West-Central Part	67,889	0.9	1.3	1.7	1.5	2.0	2.4	1.6	3.6	4.9	4.1	6.9	9.1
E. Iowa and Minn. Till Prairies	31,217	0.4	0.6	0.8	0.5	0.6	0.8	0.4	1.0	1.3	1.3	2.2	2.9
Ill. and Iowa Deep Loess and Drift, Western Part	69,878	2.4	3.4	4.5	5.8	7.6	9.3	2.0	4.4	6.1	10.2	15.5	19.9
Iowa and Minn. Loess Hills *and* Loess Uplands	43,099	0.4	0.6	0.8	3.5	4.6	5.6	0.3	0.7	1.0	4.3	5.9	7.4
Iowa and Mo. Deep Loess Hills	160,812	1.3	1.9	2.5	9.2	11.9	14.7	0.7	1.6	2.2	11.3	15.5	19.4
Iowa and Mo. Heavy Till Plain	53,472	2.9	4.2	5.5	3.0	3.9	4.8	2.9	6.3	8.6	8.8	14.4	18.9
Northern Mississippi Valley Loess Hills	26,981	1.9	2.7	3.5	3.4	4.5	5.5	0.7	1.5	2.1	6.0	8.7	11.1

[a] Land areas are summed within each MLRA only for the 319 repeat-survey HUC12 watersheds included in this study. These areas do not represent the total areas within each MLRA.

Table 7. P loss reductions within and between eras by BMP type

	Treated Area[a] (ac)	Pond Dams Min. (%)	Pond Dams Mid. (%)	Pond Dams Max. (%)	Terraces Min. (%)	Terraces Mid. (%)	Terraces Max. (%)	WASCOBS Min. (%)	WASCOBS Mid. (%)	WASCOBS Max. (%)
Corn-Soy Land										
Sum of area; Average of P loss reduction, 1980s	271,186	0.7	1.0	1.3	1.5	2.0	2.5	0.3	0.8	1.0
Sum of area; Average of P loss reduction, 2016-18	513,376	1.0	1.5	2.0	2.8	3.6	4.4	0.9	2.0	2.7
Difference between 1980s and 2016-2018	242,190	0.3	0.5	0.6	1.2	1.6	2.0	0.5	1.2	1.6
Ag-Plus Land										
Sum of area; Average of P loss reduction, 1980s	418,699	1.0	1.4	1.8	1.5	2.0	2.4	0.3	0.7	1.0
Sum of area; Average of P loss reduction, 2016-18	754,943	1.5	2.1	2.8	2.6	3.3	4.1	0.8	1.8	2.4
Difference between 1980s and 2016-2018	336,244	0.5	0.7	1.0	1.1	1.4	1.7	0.5	1.0	1.4

[a] Land areas are summed only for the 319 repeat-survey HUC12 watersheds included in this study. These areas do not represent the total treated areas of Corn-Soy land or Ag-Plus land in Iowa.

Table 8. Statewide P loss reductions within and between eras, calculated separately for each of the sets of BMP effectiveness estimates in Table 3

	Treated Area[a] (ac)	Min. (%)	Midpoint (%)	Max. (%)	INRS (%)
Corn-Soy Land					
Sum of area; P loss reduction, 1980s	271,186	2.6	3.8	4.8	4.9
Sum of area; P loss reduction, 2016-2018	513,376	4.7	7.1	9.1	9.3
Difference between 1980s and 2016-2018	242,190	2.1	3.3	4.2	4.4
Ag-Plus Land					
Sum of area; P loss reduction, 1980s	418,699	2.8	4.1	5.2	5.2
Sum of area; P loss reduction, 2016-2018	754,943	4.8	7.2	9.3	9.5
Difference between 1980s and 2016-2018	336,244	2.1	3.2	4.1	4.2

[a] Land areas are summed only for the 319 repeat-survey HUC12 watersheds included in this study. These areas do not represent the total treated areas of Corn-Soy land or Ag-Plus land in Iowa

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