CHARACTERIZATION AND PLACEMENT OF WETLANDS FOR INTEGRATED CONSERVATION PRACTICE PLANNING

H. G. Momm, R. L. Bingner, Y. Yuan, J. Kostel,
J. J. Monchak, M. A. Locke, A. Gilley

ABSTRACT. *Constructed wetlands have been recognized as an efficient and cost-effective conservation practice to protect water quality through reducing the transport of sediments and nutrients from upstream croplands to downstream water bodies. The challenge resides in targeting the strategic location of wetlands within agricultural watersheds to maximize the reduction in nutrient loads while minimizing their impact on crop production. Furthermore, agricultural watersheds involve complex interrelated processes requiring a systems approach to evaluate the inherent relationships between wetlands and multiple sediment/nutrient sources (sheet, rill, ephemeral gully, channels) and other conservation practices (filter strips). This study describes new capabilities of the USDA's Annualized Agricultural Non-Point Source pollutant loading model, AnnAGNPS. A developed AnnAGNPS GIS-based wetland component, AgWet, is introduced to identify potential sites and characterize individual artificial or natural wetlands at a watershed scale. AgWet provides a simplified, semi-automated, and spatially distributed approach to quantitatively evaluate wetlands as potential conservation management alternatives. AgWet is integrated with other AnnAGNPS components providing seamless capabilities of estimating the potential sediment/nutrient reduction of individual wetlands. This technology provides conservationists the capability for improved management of watershed systems and support for nutrient credit trading programs.*

Keywords. *GIS, Precision conservation, Topographic analysis, Watershed modeling, Wetland.*

The successful implementation of conservation practices designed to promote water quality and to minimize their impact on agricultural production depends on how well watershed systems are understood and modeled. Comprehension of how an individual physical process acts on sediment and nutrient detachment, transport, and deposition from fields to water bodies and the trapping efficiency of individual conservation practices are of paramount importance. However, this knowledge alone is not sufficient to describe the inherent complexity of watershed systems. It is necessary to account for the spatiotemporal linkage between different types of sediment and agrochemical sources, farming practices, and conservation alternatives (Tomer et al., 2013b). Likewise, selection of the optimal watershed management plan, based on identifying types of practices and their implementation sites within the watershed, often involves evaluation of multiple watershed-specific alternatives (Tomer et al., 2015). Improved technology is needed to design management plans that support the watershed water quality goals. These tools should (1) link scientific knowledge of individual physical processes to the spatiotemporal dynamics of mixed practices and to different non-point pollutant sources, (2) be user friendly, (3) be cost effective, and (4) produce simulation results that are in reasonable agreement with field measurements.

The sought technology should be designed to account for key characteristics that influence the performance of conservation practices on sediment and nutrient reduction. One noteworthy conservation practice is the implementation of shallow ponds, referred to herein as "wetlands." In this context, wetlands include repurposed existing natural ponds, artificial inundated pools, or a combination of both. This practice has received considerable attention as an effective alternative for reducing sediment and nitrate loads from upland agricultural fields to downstream water bodies (Crumpton et al., 2006). However, the efficiency of wetlands in peak flow reduction and in trapping sediments and nitrate depends on their physical characteristics and location within the watershed (Tanner and Kadlec, 2013; Trepel and Palmeri, 2002). Similar to riparian vegetative buffers, wetlands promote reduction of surface flow velocity and

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The authors are **Henrique G. Momm,** Assistant Professor, Department of Geosciences, Middle Tennessee State University, Murfreesboro, Tennessee; **Ronald L. Bingner, ASABE Member,** Agricultural Engineer, USDA-ARS National Sedimentation Laboratory, Oxford, Mississippi; **Yongping Yuan, ASABE Member,** Research Hydrologist, U.S. Environmental Protection Agency, Las Vegas, Nevada; **Jill Kostel,** Senior Environmental Engineer, and **Jim J. Monchak,** Senior GIS Analyst, The Wetlands Initiative, Chicago, Illinois; **Martin A. Locke,** Research Leader, USDA-ARS National Sedimentation Laboratory, Oxford, Mississippi; **Amy Gilley,** Graduate Student, Department of Geosciences, Middle Tennessee State University, Murfreesboro, Tennessee. **Corresponding author:** Henrique G. Momm, 322G Kirksey Old Main, MTSU Box 9, Murfreesboro, TN 37132; phone: 615-904-8372; e-mail: henrique.momm@mtsu.edu.

consequently flow dispersion and deposition of sediment and attached nutrients and pesticides. Wetlands can also influence streamflow. Due to their capacity to store water beyond the water base level, wetlands have the potential to reduce peak streamflows and therefore reduce downstream surface flow energy (Hubbard and Linder, 1986). Another key characteristic of wetlands is their potential for nutrient sequestration by biological and chemical processes such as ammonia volatilization, denitrification, plant uptake (with biomass harvesting), ammonia adsorption, and organic nitrogen burial (Crumpton et al., 1994; Vymazal, 2007). One of the most important processes is denitrification, i.e., conversion of nitrates into nitrogen gas by microbial activity. Denitrification is mainly controlled by temperature, the amount of nitrate and organic matter, oxygen concentration, retention time, and flow intensity pattern (Crumpton et al., 2006; Burgin et al., 2007; Seitzinger, 1988). The last two factors can be estimated or evaluated using advanced topographic analysis at watershed scale. Additionally, wetlands should be located close to non-point pollution sources to properly intercept and filter sediment and nutrient loads. Placing wetlands in areas upstream in the watershed (small upslope drainage areas) can lead to inefficiency due to lack of pollution sources or transportation mechanisms. Conversely, placing wetlands in areas downstream in the watershed (large upslope drainage areas) can also lead to inefficiency due to the potential of high surface flows (Tanner and Kadlec, 2013). Methods for determination of potential wetland placement in agricultural watersheds have been proposed using different sources of spatial information. Trepel and Palmeri (2002) proposed a methodology for placement of wetland restoration based on a suitability index calculated from a set of eight geospatial layers: soil type, land use, relief features, terrain slope, distance to stream, socio-economic acceptability, elevation, and spatial location of historical wetlands. In their methodology, individual scores for each geospatial layer were calculated based on further discretization of each layer and varying weights assigned to multiple classes within that category. Dosskey et al. (2006) determined the optimal location for wetlands based on soil properties. Other studies investigated the concept of topographic indices as proxy descriptors for overland hydrological factors influencing the spatial positioning of wetlands. The wetland index is the most common compound topographic attribute used in determining potential locations for wetlands (Huang et al., 2010; Russell et al., 1997; Tomer et al., 2003). The wetland index is used in conjunction with land use and land cover information (Huang et al., 2010; Russell et al., 1997) or with other topographic indices (Tomer et al., 2003). Topographic indices are often adopted as a surrogate for describing overland hydrological forces due to the significant influence of these forces in defining the structure and performance of wetlands, the availability of topographic information in digital format, and the accessibility of topographic processing tools in standard geographic information systems (GIS) software packages (Russell et al., 1997).

We address the need for improved technology in watershed management through the development of tools for wetland analysis within the USDA-supported Annualized Agricultural Non-Point Source (AnnAGNPS) pollution and watershed management model (Yuan et al., 2008). AnnAGNPS is a comprehensive model that integrates a large number of components describing a variety of processes acting on watershed systems. Components can be used during the execution time or for input database development (characterization of watershed systems). AnnAGNPS contains the “Wetland Sediment and Nitrogen Removal” component for simulation of hydrologic and water quality processes within wetlands based on the mass balance approach. Input information for this component constitutes physical, hydrological, and spatial information for each wetland throughout the watershed, a labor-intensive and time-consuming database to assemble.

The objective of this study is to describe a new GIS-based AnnAGNPS component, referred to as AgWet, designed for placement and characterization of wetland properties within a watershed and automatic generation of the associated wetland input database for analysis of wetland impacts on water quality using AnnAGNPS. In AgWet, GIS procedures are integrated with topographic parameterization algorithms and compound topographic index analysis. The main capabilities of AgWet include: (1) automated watershed-scale characterization of individual wetlands, (2) automated generation of the AnnAGNPS wetland input database, (3) iterative assistance for watershed-scale determination of potential sites for new wetland implementation, and (4) user-defined criteria for filtering potential sites. Combining AgWet with other existing components within AnnAGNPS provides the means for spatiotemporal analysis of different types of sediment and agrochemical sources, farming practices, and conservation alternatives (Momm et al., 2012, 2014).

MATERIALS AND METHODS

AgWet capabilities are explained in detail in the following sections. The first section describes how the physical and structural characteristics of user-identified wetland sites are calculated and recorded into a database (characterization mode). The second section describes the topographic analyses performed to define potential sites for new wetland placement and their subsequent filtering based on user-defined criteria (siting mode). Outputs from the sitting mode were used as inputs in the characterization mode. In the third section, these modes of operation are evaluated through multiple AnnAGNPS simulations and their integration capabilities.

CHARACTERIZATION OF WETLANDS AND WETLAND INPUT DATABASE

AnnAGNPS modeling represents a watershed system with two basic modeling units: concentrated surface flow (referred to as reaches) and subcatchments (referred to as cells). Reaches and cells are hierarchically connected based on surface flow. The proposed AgWet component builds on the AnnAGNPS representation of watersheds as interconnected reaches and cells (fig. 1a). First, wetlands are defined to be located on reaches (concentrated flow paths).

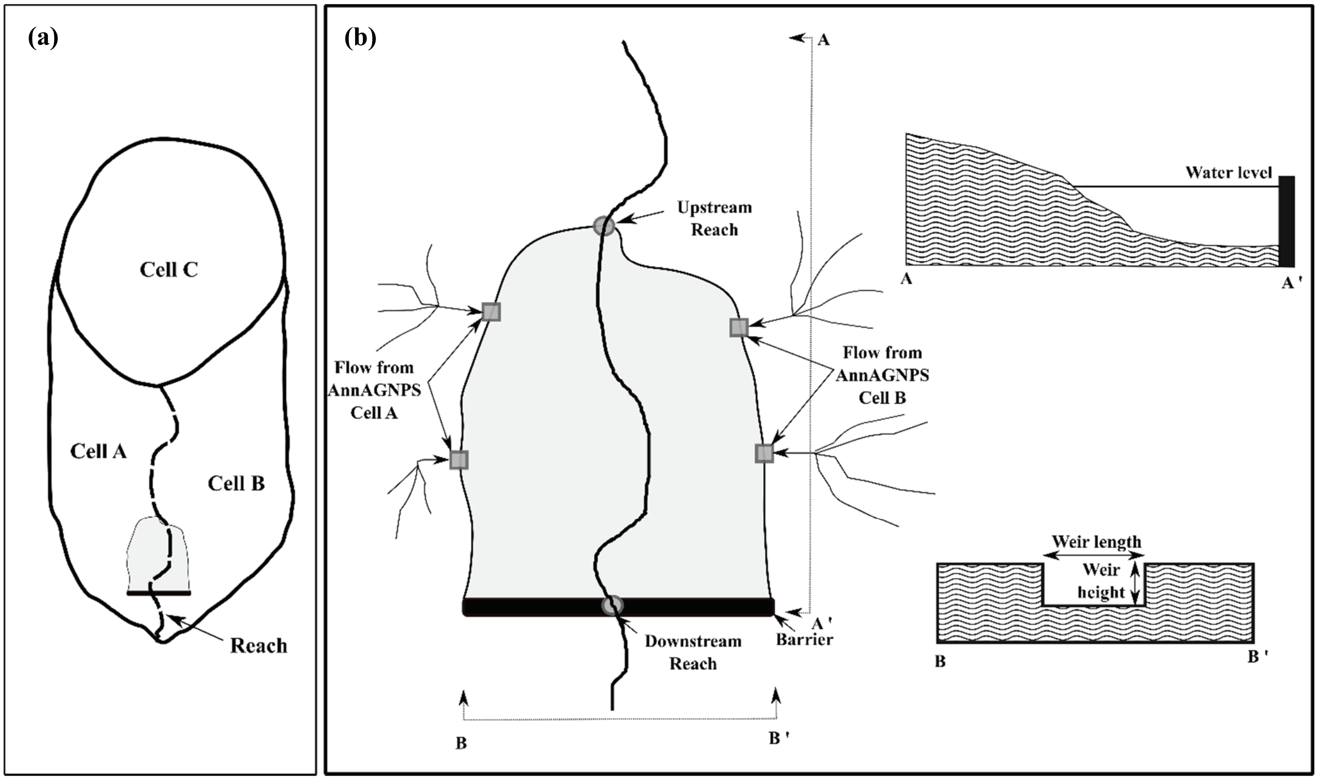


Figure 1. (a) Basic AnnAGNPS modeling units and (b) their use in AgWet for wetland analysis. AnnAGNPS represents watersheds as concentrated flow paths (reaches) and subcatchments (cells). AgWet uses GIS methods to characterize wetlands using cell and reach information to determine the wetland extent, profile, flow entering the wetland by cells and by reach, flow leaving the wetland by reach, and other geometric properties.

Second, every wetland has a barrier structure located downstream and intersecting a reach with orientation approximately perpendicular to the main reach flow. Third, wetlands receive surface flow through key entry points identified as flow from the upstream reach and flow from adjacent AnnAGNPS cells (fig. 1b). Finally, the outflow from each wetland is added to the same reach in which the wetland is located.

In the characterization mode, the user provides two sets of input information: (1) downstream locations of wetland barriers throughout the watershed and (2) topographic layers (fig. 2, boxes 1 to 7). Downstream locations of wetland

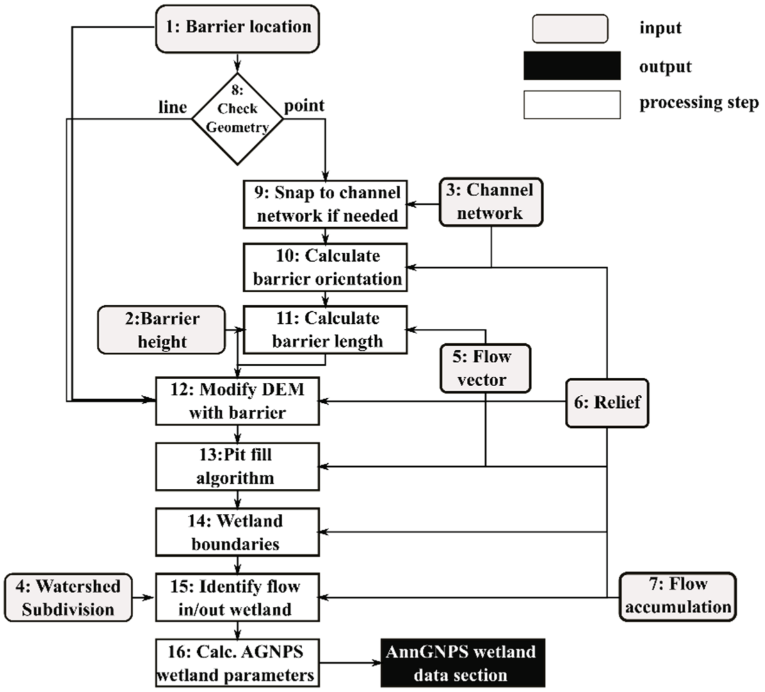


Figure 2. Flowchart of AgWet processing steps for automated watershed-scale wetland characterization.

barriers can be provided as either points or lines. Points denote the intersection between the barrier and the reach, while lines represent the digitizing of barriers. In addition to the barrier location (point or line), it is also necessary to provide the barrier's maximum height above ground (fig. 2, box 2). Barrier weir height and width are optional input information allowing for further description of barrier design characteristics (fig. 1, profile B-B′).

Topographic input includes the following raster layers: the channel network including reach locations and their unique identification numbers (box 3), watershed subdivision (box 4), flow vector (box 5), preprocessed relief (box 6), and flow accumulation (box 7). These layers are generated with the AnnAGNPS GIS component, TOPAGNPS. Any standard GIS-based software package with topographic capability could be used; however, the existing integration between wetland components and other AnnAGNPS components simplifies the input preparation. TOPAGNPS is a subset of the topographic parameterization (TOPAZ) program (Garbrecht and Martz, 1996) with incorporation of enhanced components to link spatial characterizations of ephemeral gullies and riparian buffers (Momm et al., 2012, 2014). TOPAGNPS uses digital elevation models (DEMs) in raster grid format to preprocess, identify, and measure topographic features, define the spatial extent of surface drainage, and depict the channel network pattern to support watershed hydrologic modeling and analysis.

Given a set of barrier locations, the algorithm starts by evaluating the feature type provided (fig. 2, box 8). If the user provided a set of barrier locations as points, the algorithm determines if the points are located on reaches. If not, the algorithm attempts to snap each point to the closest raster grid cell located on a reach (fig. 2, box 9; fig. 3a). Next, the orientation of each barrier is calculated based on the location of the barrier and the orientation of reach raster grid cells immediately upstream and downstream of that point (fig. 2, box 10; fig. 3b). The objective is to determine an orientation that is as close as possible to perpendicular to the flow direction in the reach. The orientation is limited to one of the eight angles defined by the raster grid data model. Using the calculated barrier orientation and the user-provided barrier height, the barrier length is then determined through an iterative procedure (fig. 2, box 11; fig. 3b). The barrier is iteratively extended one raster grid cell at a time (in both directions) until a raster grid cell with higher elevation than the barrier elevation is found. The original DEM is modified to add the wetland barrier (fig. 2, box 12). The wetland wet extent (wetland maximum area) upstream of the barrier is simulated through use of the pit-filling algorithm in TOPAGNPS (fig. 2, box 14; fig. 3c). Individual wetlands are assigned unique identifier numbers (fig. 3d). All drainage areas of raster grid cells identified as incoming or outgoing flow into the wetland wet area are recorded (fig. 2, box 15; fig. 4). A total of 21 parameters are recorded for each wetland (table 1) in AnnAGNPS wetland input database file format (fig. 2, box 16).

The ratio of wetland wet area to total drainage area flowing into the wetland wet area can be provided as an additional constraint to the generation of wetlands (Tomer et al., 2013a; Crumpton et al., 2006). An acceptable range of ratio values (as a percentage) can be applied to remove wetlands that do not meet this criterion. The definition of

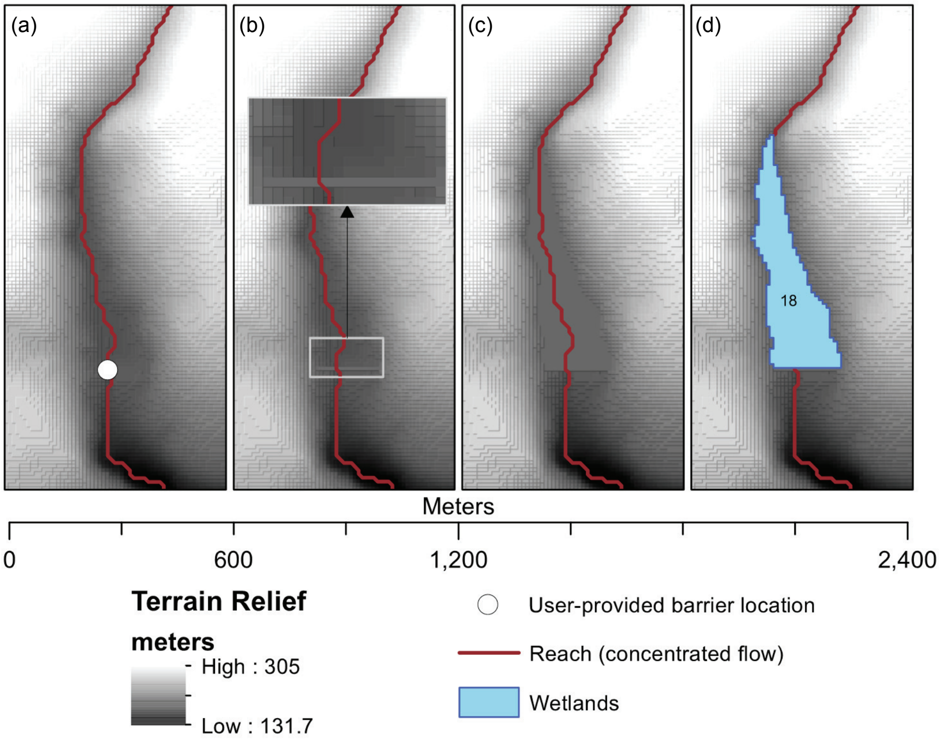


Figure 3. Procedure for determining wetland extent. Based on user-provided barrier location (white dot in a) and barrier height, the azimuth orientation of the barrier is determined, and the original DEM is modified to represent the barrier (b). Using pit filling algorithms in topographic parameterization, the upstream side of the barrier is modified to estimate the wetland's wet area (c). A unique wetland identification number is assigned to the wetland (d), and topographic attributes are calculated.

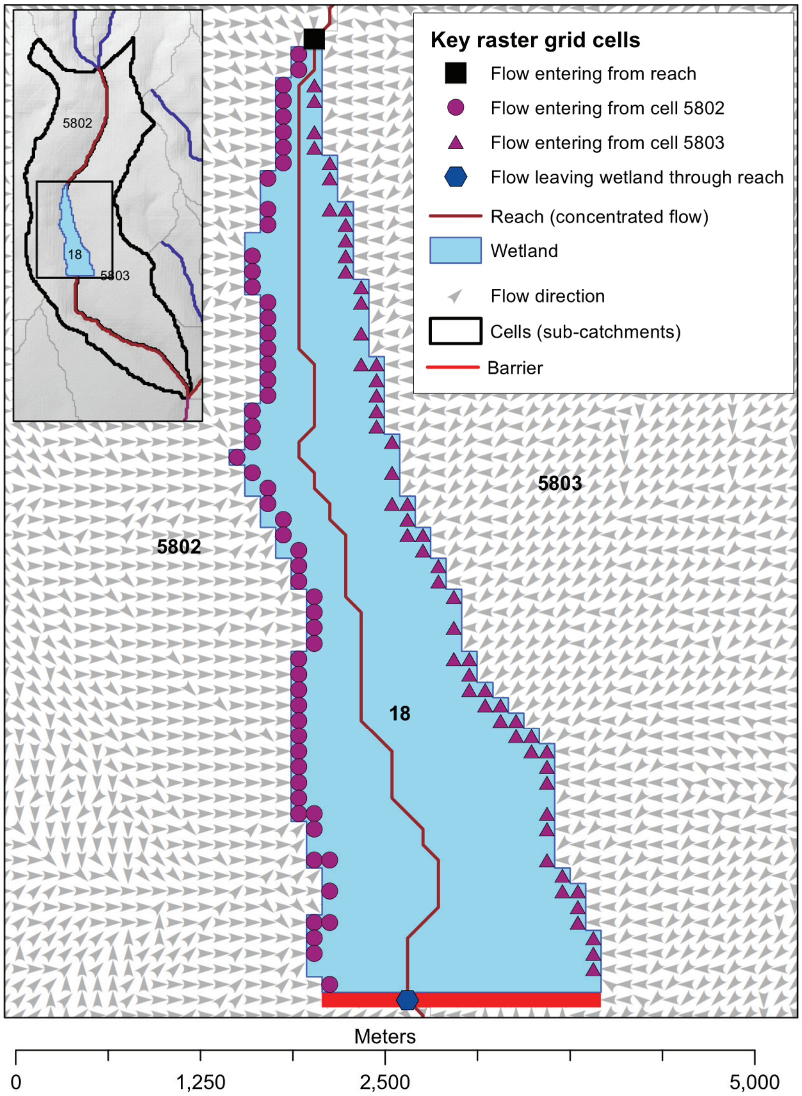


Figure 4. Identification of key raster grid cells for recording drainage area source and amounts. The drainage areas entering and leaving individual wetlands are recorded based on the flow direction and source. Two points are identified in the reach: flow leaving the wetland (blue hexagon) and flow entering the wetland (black square). Multiple points denote surface flow from AnnAGNPS cell 5802 (purple circles) and from AnnAGNPS cell 5803 (purple triangles). The drainage areas entering the wetland by cell (circles and triangles), by reach (square), and leaving the wetland (hexagon) are recorded in the output files.

these threshold values is based on studies comparing the wetland/drainage area ratio with nutrient removal efficiency. Accepted values range from 0.5% to 2.5% (Tomer et al., 2013a; Crumpton et al., 2006). Based on the calculated wetland area and the provided threshold values, the individual wetlands are identified as meeting or not meeting this criterion. Wetlands that do not meet the criterion are excluded from the database.

Another feature of the characterization mode is the option to determine the barrier height based on a user-provided range of values for the ratio of wetland area to drainage area. This is an iterative procedure that (1) increments the barrier elevation by a delta height value, (2) determines the maximum wet area, (3) calculates the ratio, and (4) compares it to the user-provided range. This procedure is iteratively repeated until the stopping criterion is met (fig. 5). A raster grid file with the extent of each wetland is generated for facilitating integration with standard GIS software for visualization of results and subsequent analysis.

SITING OF POTENTIAL WETLAND LOCATIONS

The objective of the siting mode is to identify candidate locations for artificial wetland implementations. The trapping performance of wetlands varies spatially according to hydrological, morphological, and biological factors. When designing watershed management plans, it is important to place wetlands at sites that maximize trapping efficiency while minimizing the disturbance of production areas. Among these factors, hydrological processes have been recognized as the main influences on the trapping performance of wetlands (Tanner and Kadlec, 2013). Hydrological processes can be estimated using compound topographic indices (secondary topographic attributes) as a surrogate to model how surface water flows in a landscape (Wilson and Gallant, 2000).

Candidate locations for wetlands should meet multiple conditions. First, wetlands should be located in areas that receive concentrated flow from upstream croplands, as sheet and rill erosion and ephemeral gullies are primary

Table 1. Example of TOPAGNPS-specific parameters recorded for each individual wetland.

Parameter	Units	Example
Barrier point UTM *X* coordinates	m	295,911.00
Barrier point UTM *Y* coordinates	m	4,599,846.00
Barrier height	m	0.90
Barrier identification number	none	18.00
Barrier number of raster grid cells	none	18.00
Barrier width	m	180.00
Barrier elevation	m	235.10
Barrier reach elevation	m	234.20
Barrier azimuth orientation	degrees	90.00
Wetland number of raster grid cells	count	644.00
Wetland wet area	m^2	64,400.00
Drainage area from AnnAGNPS cells	m^2	378,600.00
Drainage area from AnnAGNPS reach	m^2	2,525,700.00
Drainage area at the barrier	m^2	2,951,500.00
Average depth	m	0.53
Maximum depth	m	0.90
Reach number of raster grid cells	count	63.00
Average reach slope	none	0.004
Reach length through wetland	m	677.99
Reach ID entering wetland	none	580.00
Reach ID leaving wetland	none	580.00

sediment sources. Second, wetlands should be located at sites with sufficient drainage area to receive appreciable nutrients loads for processing. Conversely, wetlands should not be located in areas with large flows that limit sediment and nutrient residence times, which jeopardize the overall trapping performance. Third, the maximum wet area should be sized to allow optimal residence time for biological and chemical processes to reduce nutrient loads (Woltemate, 2000). Fourth, wetlands should be located in relatively flat terrain to reduce surface flow velocity and thus promote sediment deposition (Tomer et al., 2003). Finally, priority should be placed on locations adjacent to areas that are not prone to erosion (Tomer et al., 2003).

The topographic compound index commonly used for riparian conservation practices is the wetness index (Tomer et al., 2003; Huang et al., 2010; Russell et al., 1997). The wetness index is calculated as follows:

$$W = \ln\left(\frac{A_s}{\tan\beta}\right) \tag{1}$$

where W is the topographic wetness index (m), A_s is the specific catchment area (m^2 m^{-1}), and β is the local terrain slope in degrees. The specific catchment area represents an estimation of the runoff volume, and the local terrain slope represents the runoff rate or flow velocity (Wilson and Gallant, 2000). Combined into the wetness index, this relationship should allow identification of large drainage areas and small slopes in the watershed (Wilson and Gallant, 2000; Tomer et al., 2003).

Another important topographic index is the Revised Universal Soil Loss Equation (RUSLE) length-slope (LS) factor (Moore and Burch, 1986). The LS factor (Renard et al., 1997) is calculated for each individual raster grid cell using an automated procedure from a user-supplied estimate of when concentrated flow erosion begins and when sheet and rill erosion along any given flow path ceases, and from a user-supplied estimate of when deposition begins along any flow path (Bingner and Theurer, 2001a, 2001b). The distributed LS factor is calculated based on RUSLE science using the AGFLOW module within the AnnAGNPS TOPAGNPS component (Bingner et al., 1997). In the AGFLOW calculations, the slope is considered uniform at the point, but the area is defined by the upslope contributing area at that point, rather than a uniform slope width. Additionally, in the AGFLOW-calculated LS factor, the procedure accounts for the most distant hydraulic point where deposition may begin based on drainage area and the area that forms concentrated flow. The distributed LS factor for each raster grid cell is calculated as follows:

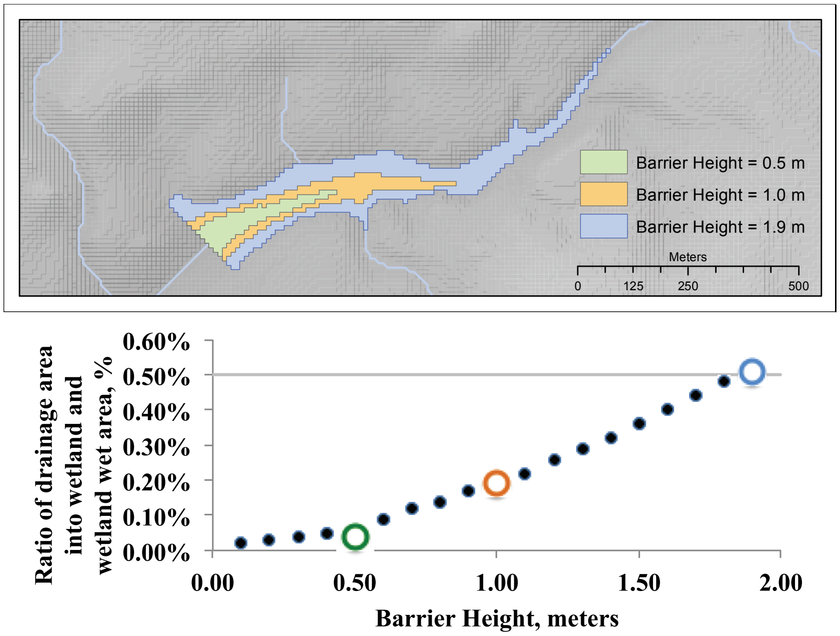


Figure 5. Iterative procedure to determine barrier height based on the ratio of wetland wet area to upslope drainage area entering the wetland. This procedure is repeated for all potential wetland points for which the user does not provide the height of the barrier.

$$LS = S \times L \tag{2}$$

where S is the slope steepness factor, and L is the slope length factor. The RUSLE slope steepness factor is calculated using:

$$\begin{aligned} S &= (10.8 \times \sin\theta) + 0.0310 \text{ for } \phi < 9\% \\ S &= (16.8 \times \sin\theta) - 0.5060 \text{ for } \phi \geq 9\% \end{aligned} \tag{3}$$

$$\theta = \tan^{-1}\left(\frac{\phi}{100}\right) \tag{4}$$

where ϕ is the slope in percent. The RUSLE slope length factor is calculated using:

$$L = \frac{(\lambda_d)^{m+1}}{(22.13)^m \times CS} \tag{5}$$

where m is the slope length exponent, CS is the raster grid cell size (m), and λ_d is the uniform slope distance from the top of the slope to the downstream end of the profile segment (m):

$$\lambda_d = \frac{CS + \left[0.4901 \times (A_s)^{0.39}\right]}{2} \tag{6}$$

$$m = \frac{\delta}{1+\delta} \tag{7}$$

$$\delta = \frac{\left(\dfrac{\sin\theta}{0.0896}\right)}{\left[3.0 \times (\sin\theta)^{0.8}\right] + 0.56} \tag{8}$$

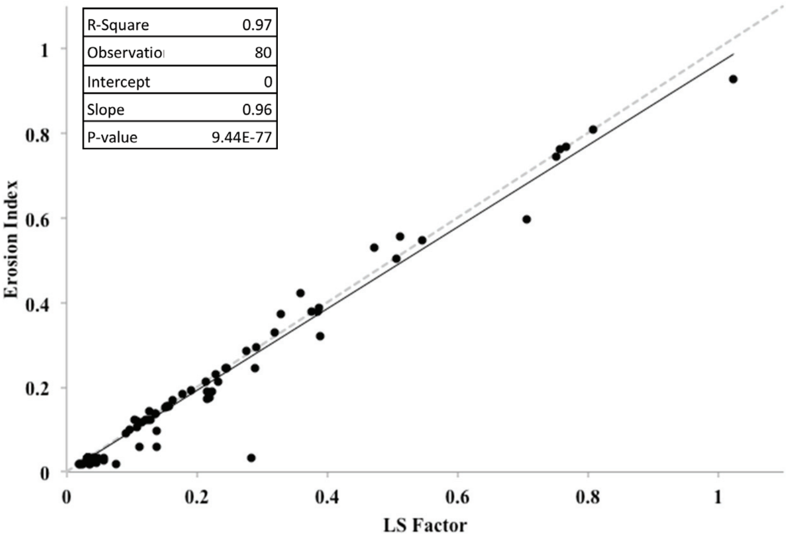
where δ is the ratio of rill and interill erosion.

The erosion index (EI) is an adaption of the LS factor by Moore and Burch (1986). The EI is valid for slope length <100 m and slope steepness <14°. This index is used to empirically calculate sediment transport capacity based on the RUSLE methodology (Moore et al., 1991):

$$\mathrm{EI} = (c_a + 1)\left(\frac{A_s}{22.13}\right)^{c_a}\left(\frac{\sin\beta}{0.0896}\right)^{c_b} \tag{9}$$

where c_a and c_b are unitless coefficients. One of the applications of the EI is to identify areas with high erosion potential. The values of coefficients c_a and c_b vary among authors. Moore et al. (1991) suggested $c_a = 0.4$ and $c_b = 1.3$. Use of the EI over the original LS factor is based on the RUSLE assumption of uniform slope and slope width in the area being investigated. Nonetheless, the EI and the LS factor can be used to identify points where erosion is low and where deposition may be occurring, resulting in low EI and LS values. There was positive agreement between the AGFLOW-calculated LS factor and EI (fig. 6). The EI values were calculated following the methodology described by Tomer et al. (2003).

In AgWet, compound topographic indices (wetness index and LS factor) are combined with local upstream drainage area to determine potential wetland locations. The following GIS layers are required as input for the siting mode: channel network (fig. 7, box 1), local terrain slope (fig. 7, box 2), flow accumulation (fig. 7, box 3), and LS factor (fig. 7, box 4). These layers are provided in raster grid file format. The user is also required to provide threshold values of the LS factor (fig. 7, box 5), wetness index (fig. 7, box 6), and drainage area (fig. 7, box 7). The wetness index is calculated using the local terrain slope in degrees and the drainage area per unit of cell width (fig. 7, boxes 8 and 9). Raster grid cells identified as concentrated flow paths (reaches) are used to mask out non-reach raster grid cells and generate another raster grid, referred to as the mask grid (fig. 7, box 10). The wetness index raster grid is calculated using equation 1 (fig. 7, box 11), and the drainage area is calculated by converting the drainage area per unit of cell width into an area based on the raster grid cell size (fig. 7, box 12). User-provided threshold values of the LS factor, wetness index, and drainage area are used to mask out raster grid cells that do not meet the criteria in the LS factor, wetness index, and drainage area raster grids,



R-Square	0.97
Observatio	80
Intercept	0
Slope	0.96
P-value	9.44E-77

Figure 6. Comparison of LS factor and erosion index values from manually determined wetland barrier locations. Dashed line is the 1-1 line, and solid line is the fitted line (goodness-of-fit summary statistics based on 99% observed confidence level are shown in the table).

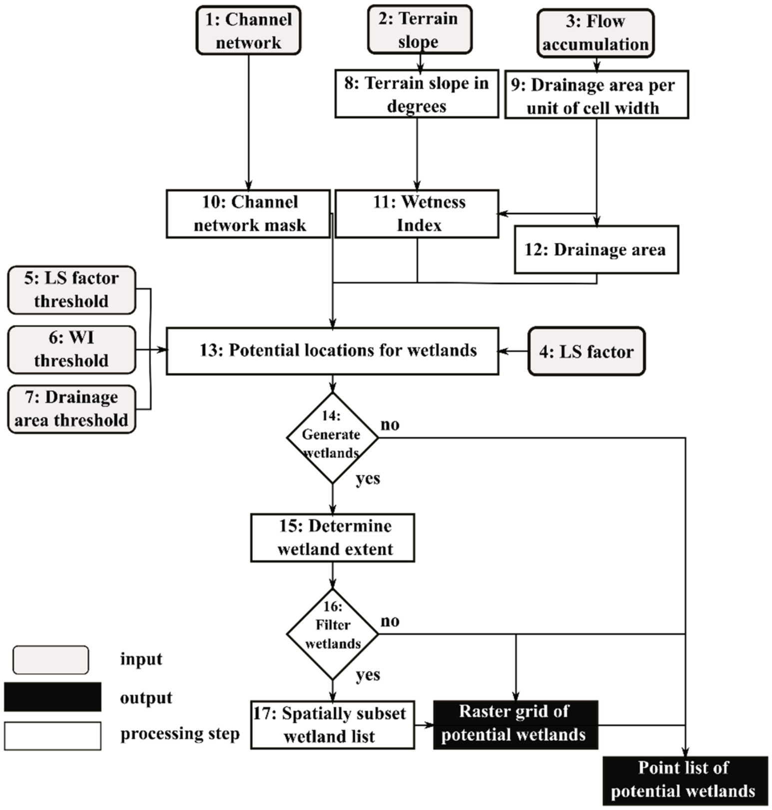


Figure 7. Flowchart of automated determination of potential wetland locations based on topographic analysis.

respectively. Three new binary raster grids are generated. Potential locations for wetland barriers are then defined by combining the mask raster grid with the three binary raster grids (fig. 7, box 13). Only raster grid cells in the mask raster grid that are marked as positive in all three binary raster grids are identified as potential locations. If the user does not estimate the wetland extent (fig. 7, box 13), the algorithm outputs these point locations as raster grid and *XY* coordinates in tabular file format. This option allows the user to visualize the candidate locations in a GIS environment and make changes based on auxiliary information. Alternatively, the candidate locations can be used as input to the characterization mode (fig. 7, box 15; fig. 2) to estimate barrier extent, wetland maximum wet area, and subsequently generate the AnnAGNPS wetland input database. If elected by the user, the set of wetlands can be further reduced based on the ratio of wetland wet area to total drainage area flowing into the wetland (fig. 7, box 17). The final set of wetlands is exported in raster grid file format.

EVALUATION OF PROPOSED METHODS

Description of Big Bureau Creek Watershed

The site selected for evaluating AgWet is the Big Bureau Creek (BBC) watershed in north-central Illinois. This watershed was studied in detail for the placement of artificial wetlands as part of a feasibility assessment for a nutrient trading market (Kostel et al., 2014). The majority land use and land cover of the BBC watershed is cultivated crops (approx. 77%). Additionally, this watershed contains significant animal agricultural activity. The watershed covers approximately 129,000 ha (499 square miles) at the confluence of Goose and Senachwine Lakes, which outflow to the Illinois River. For a detailed description of this watershed, refer to Kostel et al. (2014).

A multi-step approach was employed to simulate the implementation of artificial wetlands in this watershed. Topography was represented by a 10 m spatial resolution DEM. In the first step, areas of interest were defined based on soil, land use, and proximity to roads. A large number of areas of interest were defined. In the second step, these areas of interest were converted into wetlands and were further reduced based on wetland ratio, minimum and maximum water depth, drainage area, and land use/land cover based on independent GIS techniques (Kostel et al., 2014). A total of 80 potential wetland sites were determined after the filtering procedure and additional investigation using satellite imagery and field campaigns. This approach represented a labor-intensive analysis of the wetland locations to characterize each wetland for use within AnnAGNPS.

Evaluation of AgWet in Characterization of Wetlands

To illustrate the capabilities of AgWet to automatically characterize wetlands for application with AnnAGNPS when only downstream barrier locations of the wetlands are known, the 80 points representing the outlet locations of the wetlands determined by Kostel et al. (2014) for the BBC watershed were used as input to AgWet. This required that the *XY* coordinates in meters (in UTM projection) of the wetland outlet and a constant barrier height value of 0.9 m for each wetland location were used as input parameters to AgWet. Additional input raster grid layers derived by

TOPAGNPS for the BBC watershed included the watershed subdivision into AnnAGNPS cells and reaches, watershed boundaries, flow vectors, terrain slope, flow accumulation, preprocessed elevation, and LS factor.

Evaluation of AgWet in Siting Wetlands

In the siting mode, AgWet contains tools to identify potential locations for implementing artificial wetlands and/or restoring existing natural wetlands. The same watershed used to evaluate the characterization mode was used to evaluate the siting mode. The values of drainage area, LS factor, wetness index, and wetland area to drainage area ratio were calculated for the actual wetland points used in the characterization mode.

RESULTS AND DISCUSSION

The automated topographic threshold methodology of AgWet provides an easy-to-use and efficient method for generating potential wetland locations and input parameters for evaluating the impact of wetland characteristics and placement on pollutant loads with AnnAGNPS simulations. The proposed methodology is simple and computationally fast, allowing for iterative evaluation of multiple alternatives.

CHARACTERIZATION OF WETLANDS

The wetland extents (fig. 8) and parameters were determined using AgWet and compared to values from manually determined wetlands as described by Kostel et al. (2014) (fig. 9). Using the barrier point locations of 80 manually determined wetlands and a constant barrier height of 0.9 m, AgWet correctly determined the barrier orientation and extent, generated the maximum wet area, and recorded wetland topographic characteristics. Although the AgWet-determined wetlands are in agreement with the wetland wet extents determined through more elaborate methods involving aerial imagery analysis and field investigations (fig. 9; linear regression R^2 of 0.95, p-value of 8.69E^{-59}, and 85% slope between the two measurements), there were small differences between the automated and manual approaches (Kostel et al., 2014). This can be attributed in part to differences in the GIS software packages used in processing the DEM and the additional inspection of wetlands based on land cover/land use, aerial imagery, and field investigations.

SITING OF POTENTIAL WETLANDS

A wide range of variability was observed for drainage area, LS factor, and wetland area to drainage area ratio (fig. 10). For the 80 barrier points of manually determined

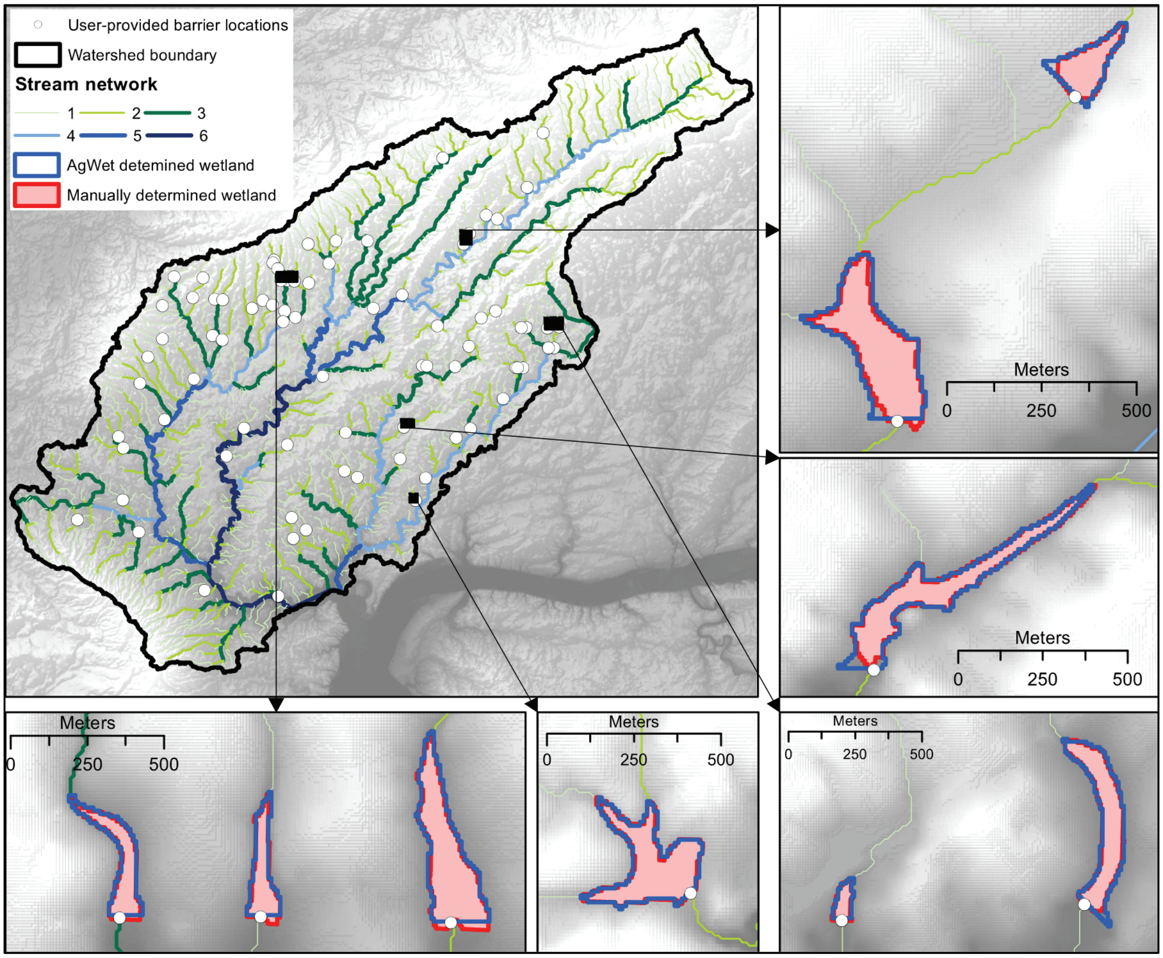


Figure 8. Comparison of manually determined wetlands (red polygons) and wetlands generated using AgWet (blue polygons). All AgWet wetlands were calculated from the user-provided barrier location (white dot) with a uniform barrier height of 0.9 m.

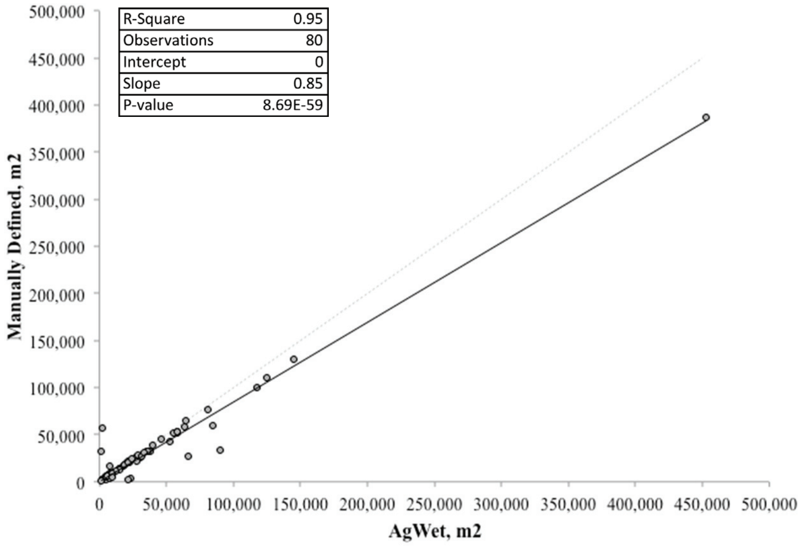


Figure 9. Comparison of surface area for manually defined wetlands and wetlands calculated with AgWet using a constant barrier height of 0.9 m. Dashed gray line is the 1-1 line, and solid line is the fitted line (goodness-of-fit summary statistics based on 99% observed confidence level are shown in the table).

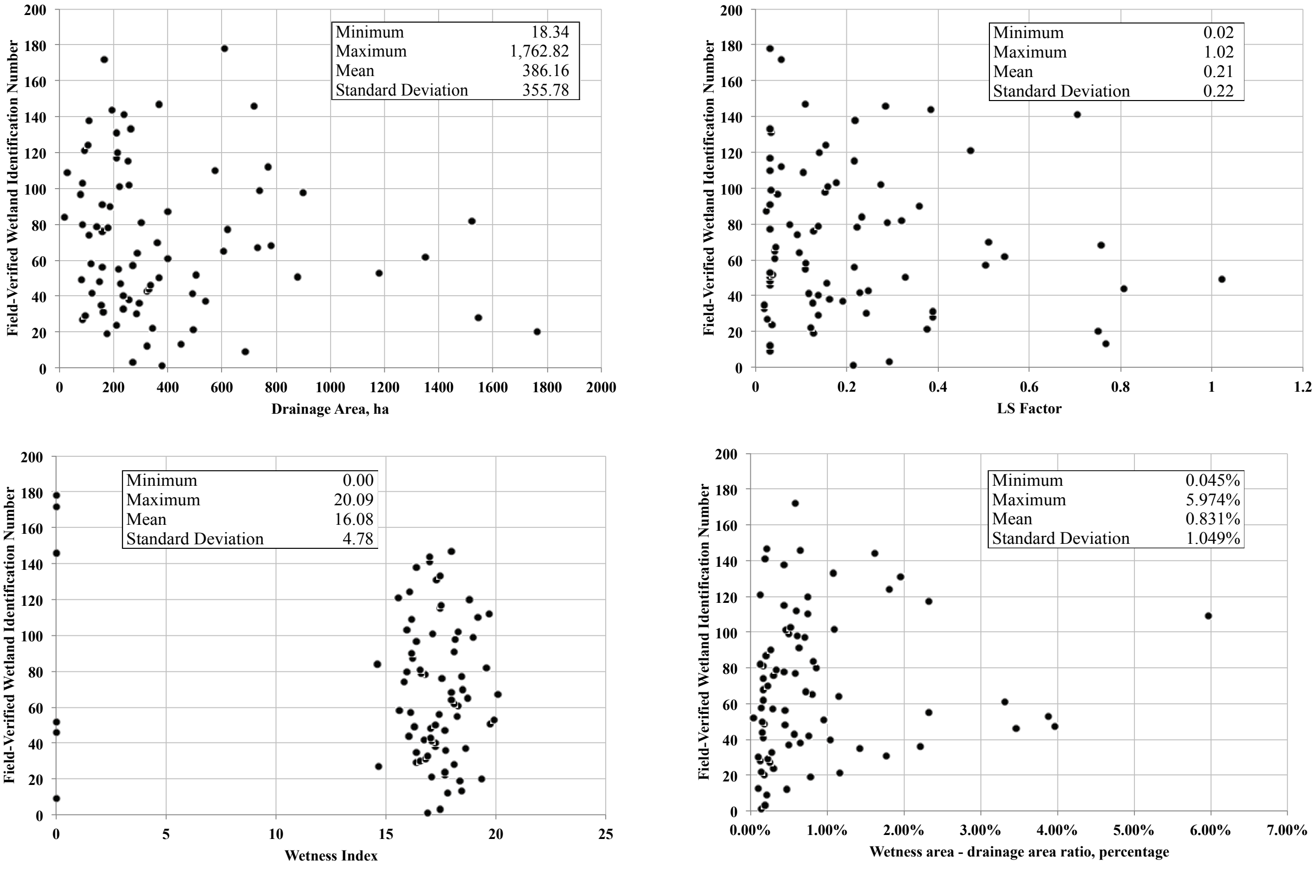


Figure 10. Topographic parameters used in the determination of locations with high potential for wetland implementation. These values were calculated for 80 actual wetland barrier locations that were determined based on field investigation.

wetlands, the wetness index varied between 15 and 20. Using these threshold values, a total of 9,244 potential sites for wetland implementation were generated (fig. 11a). These points were distributed throughout the watershed in concentrated flow paths. The drainage area threshold of 200 ha prevented the selection of potential sites at the most upstream parts of the watershed and with small upslope drainage area. Increasing the wetness index threshold to 21 reduced the number of potential sites to 1,356 (fig. 11b). The selected wetland locations were clustered in two main regions, representing locations with relatively large drainage areas and relatively small local terrain slopes. The points representing these potential wetland sites were used as input for the characterization mode. Additional filtering based on the wetland area to drainage area ratio was used to

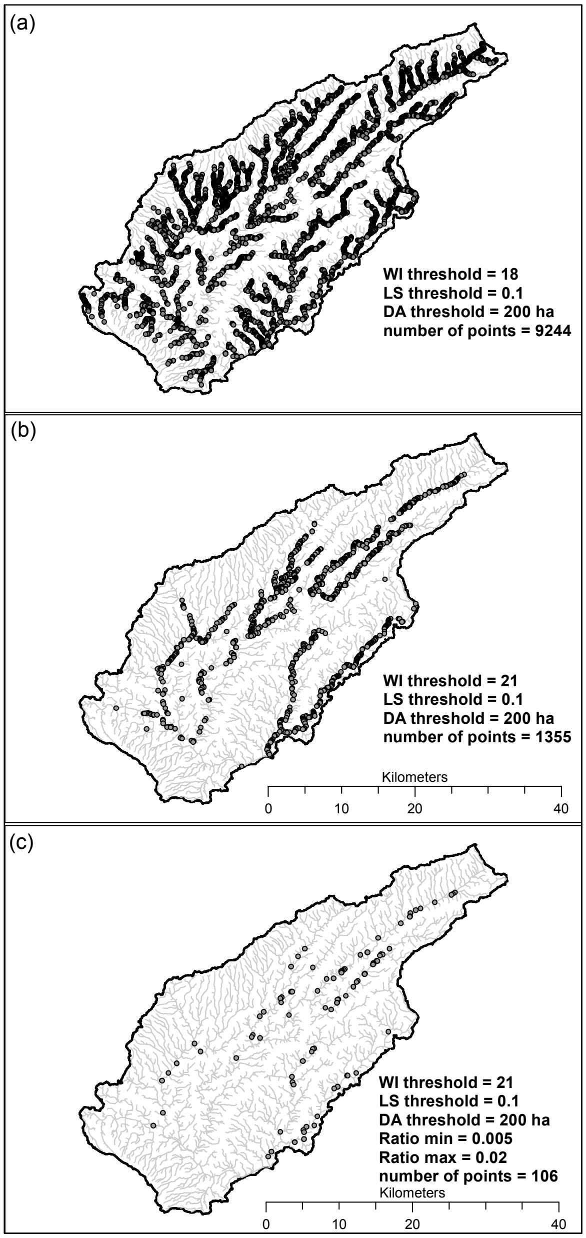


Figure 11. Determination of potential wetland locations based on three topographic criteria: upstream drainage area, LS factor, and wetness index. This example shows how the number of potential wetlands was reduced from (a) 9,244 to (b) to 1,355 by varying threshold values. Of these, only (c) 106 locations met the threshold value for the ratio of wetland area to upslope drainage area. Only barrier locations that had ratios between 0.5% and 2% were considered.

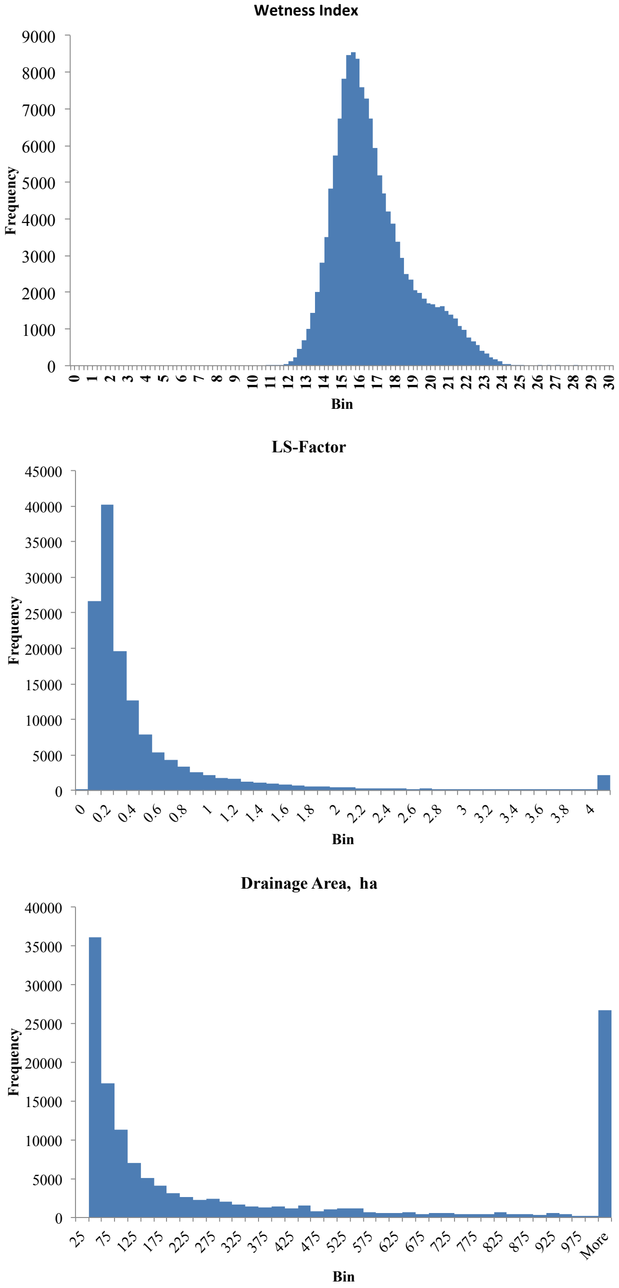


Figure 12. Histograms of parameters used in determining potential wetland locations. Only values for raster grid cells marked as AnnAGNPS reaches are shown here. The histogram of wetness index does not include values of zero. The distributions of drainage area and LS factor are distinct from the distribution of wetness index values.

demonstrate the versatility of this method. Using user-provided minimum and maximum ratio values, the number of potential wetland sites was further reduced to 106 (fig. 11c).

Small variations in threshold values can have a noteworthy effect on the number and location of potential sites. Different topographic indices have different cumulative distributions (fig. 12). The cumulative distribution of wetness index for raster grid cells located in the channel network and with values greater than zero has a proxy-normal distribution. Conversely, the same raster grid cell values for drainage area and LS factor are skewed toward small values. The generation and interpretation of these cumulative distribution plots can aid in determining threshold values to use. Additionally, the integration of the two modes of operation allows further filtering of candidate sites based on the ratio of wetland area and upslope drainage area entering the wetland. These methods can be used to select candidate sites away from upstream and downstream locations in the watershed.

Although the developed application allows for selection between two topographic indices of erosion potential for wetland siting (EI and LS factor), there is a small difference between these two indices for actual wetlands at the study site (fig. 6). These two indices share the same concepts rooted in the RUSLE2 LS factor. However, the small differences between them can be attributed to the calculation of the slope length factor; the coefficient varies with slope for the LS factor, whereas the same coefficient is fixed for the erosion index.

Although not within the scope of this study, the influence of DEM spatial resolution on topographic indices and their cumulative distribution functions is important (Momm et al., 2011, 2013). While the effect of DEM spatial resolution on drainage area is approximately linear, its effect on terrain slope is non-linear. As DEM resolution decreases, local terrain slope decreases due to diminishing ability to capture small relief variations. Conversely, high DEM resolution, on the order of millimeters to centimeters, has the ability to capture microtopography variations and therefore yields very high values of local terrain slope. Therefore, DEM spatial resolution influences compound topographic indices, including wetness index, erosion index, and LS factor. The evaluation of AgWet was performed using a 10 m spatial resolution DEM, which was the highest spatial resolution available for the study site.

SUMMARY AND CONCLUSIONS

This study described a GIS-based technology for placement and assessment of artificial wetlands in agricultural watersheds. This technology links topographic parameterization algorithms, GIS, and watershed modeling tools. The proposed technology has two modes of operation. In the characterization mode, user-provided downstream barrier locations are used to determine the maximum wetland wet area and corresponding parameters needed by the AnnAGNPS water quality and watershed management model. The siting mode aids in the identification of potential locations for wetland implementation based on second-order topographic indices. Integrating the two modes of operation allows further filtering of sites using wetland area to drainage area ratio and iterative determination of barrier height based on user-determined parameters.

Future enhancements of this technology include investigation of methods for identifying and characterizing topographic depressions (puddles) during DEM preprocessing. These topographic depressions could be automatically evaluated as possible wetland sites based on their location in the watershed and their potential for sediment and nutrient filtering. Another improvement would be the introduction of soil properties, such as soil transmissivity, into the decision-making process, which may have an influence on selecting suitable sites for wetland implementation.

Using this technology, potential wetland sites can be the first stage in generating watershed-wide management plans. Combined with remotely sensed imagery, field visits, and information on farming practices, the potential sites can be further evaluated and tailored to the development of site-specific alternatives. Integration of AgWet with other components in AnnAGNPS offers a unique opportunity to linking the characteristics and placement of wetlands to multiple pollution sources and conservation practices. This integration is key to developing watershed-wide precision conservation efforts. Multiple alternatives involving varying types and locations of conservation practices can be efficiently evaluated by tracking loads from multiple sources throughout the watershed and, more importantly, by estimating the efficiency of individual conservation practices in improving water quality.

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