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Modeling the Suitability of Potential Wetland Mitigation Sites with a Geographic Information System

ROBERT A. VAN LONKHUYZEN*
KIRK E. LAGORY
JAMES A. KUIPER
Environmental Assessment Division
Argonne National Laboratory
Argonne, Illinois 60439, USA

ABSTRACT / Wetland mitigation is frequently required to compensate for unavoidable impacts to wetlands. Site conditions and landscape context are critical factors influencing the functions that created wetlands perform. We developed a spatial model and used a geographic information system (GIS) to identify suitable locations for wetland mitigation sites. The model used six variables to characterize site conditions: hydrology, soils, historic condition, vegetation cover, adjacent vegetation, and land use. For each variable, a set of suitability scores was developed that indicated the wetland establishment potential for different variable states. Composite suitability scores for individual points on the landscape were determined from the weighted geometric mean of suitability scores for each variable at each point. These composite scores were grouped into five classes and mapped as a wetland mitigation suitability surface with a GIS. Sites with high suitability scores were further evaluated using information on the feasibility of site modification and project cost. This modeling approach could be adapted by planners for use in identifying the suitability of locations as wetland mitigation sites at any site or region.

In the United States, mitigation of wetland loss or degradation is frequently required by federal, state, and local governments for impacts to wetlands under their jurisdiction. With the continued loss of original wetland ecosystems, a high priority has been placed on identifying wetland mitigation projects that are likely to succeed and persist as functioning wetlands and that will replace the functions of the original wetland (Kusler and Kentula 1990; Kentula and others 1992; NRC 2001; USACE 2001; Interagency Workgroup on Wetland Restoration undated). Wetland functions are varied and complex and include hydrologic functions such as long- and short-term surface water storage, biogeochemical functions such as retention and removal of dissolved substances, and ecological functions such as maintenance of habitats, food webs, and species diversity (NRC 1995).

Many wetland mitigation projects fail because of poor planning and design (Mitsch and Wilson 1996; Pastorok and MacDonald 1996; Brown and Veneman 2001; NRC 2001; Perry and others 2001; Williams 2002). Failure is often a result of poor or inappropriate structural design, and also improper location of the mitigation site relative to other landscape features. Landscape context often determines hydrogeomorphic properties, wetland function, and the ability to persist as a functioning wetland system (Marble 1992; Brinson 1993; Davis 1994; Bedford 1996). The suitability of landscape position is sometimes related to specific wetland mitigation goals, such as habitat enhancement for a rare species, water quality improvement within a watershed, or enhancement of wildlife corridors. In this article, we present an approach that can be used to identify suitable potential mitigation sites using a geographic information system (GIS). The approach enables scientists and planners to develop a map for a site or region that identifies the degree of suitability of locations as wetland mitigation sites. The modeling process is flexible and can accommodate different planning goals, data sources, or refinements needed for a particular project.

KEY WORDS: Wetland mitigation; Wetland restoration; Suitability index; Geographic information system; Landscape; Spatial model

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*Author to whom correspondence should be addressed; *email:* rvan@anl.gov

Methods

A spatial modeling approach was developed for, and applied to, the Argonne National Laboratory–East (ANL-E) site, located in southeast DuPage County, Illinois. The ANL-E site is a federally funded research and development center operated by the University of Chicago for the US Department of Energy. Wetland mitigation at the site is performed in the context of the following: Section 404 of the Clean Water Act; Executive Order 11990, Protection of Wetlands; and Department of Energy guidance and policy (Title 10, Code of Federal Regulations, Part 1022 [10 CFR 1022]). It has typically been conducted in an ad hoc manner in response to proposed new developments. Impacts to wetlands are avoided and minimized if possible. When impacts to wetlands are unavoidable, compensatory mitigation is typically required; that is, new wetland areas must be established to compensate for wetland areas impacted.

DuPage County, within the Chicago metropolitan area of northeastern Illinois, USA, has experienced significanct urban development over the last two decades. Prior to European settlement, wetlands occupied more than 60% of the landscape (Lampa undated). Currently, wetlands occupy only about 12% of the county (DuPage County Department of Development and Environmental Concerns 1999). Top priority has been given to mitigating ongoing wetland loss in the county, and several large wetland banking projects have been established (Gazdaca 2000).

The ANL-E site was established at its present location in 1947. It occupies about 607 ha, of which 324 ha are developed and 283 ha are relatively undisturbed woodlands, old fields, and wetlands. Much of the ANL-E site is relatively level, with slopes typically between 2% and 5%. Numerous shallow depressions and drainages on the site support wetlands.

Thirty-five jurisdictional wetlands totaling 18 ha were delineated on the site in 1993 using the 1987 federal guidelines for wetland delineation (USACE 1987; Van Lonkhuyzen and LaGory 1994). Six palustrine emergent wetlands [using the classification system of Cowardin and others (1979)] totaling 1.5 ha and two palustrine forested wetlands totaling 0.4 ha are dependent on seasonally high groundwater levels and lack any significant surface water inflow. These wetlands are inundated early in the growing season for brief to extended periods. The remaining 27 wetlands, totaling 16.2 ha, occur along perennial and intermittent streams. Impacts to any of these wetlands would potentially require compensatory mitigation.

To identify the location of suitable sites for future wetland mitigation projects at ANL-E, we developed a spatial model of the site. A map of site characteristics was produced for each of the following variables: hydrology, soils, historic condition, vegetation cover, adjacent vegetation, and land use. The importance of each of these parameters and details of the modeling approach are described next.

Hydrology has perhaps the most important influence on project success because the magnitude and duration of inundation or saturation affects the success of hydrophytic vegetation establishment as well as hydric soil development (Niering 1990; Mitsch and Gosselink 2000). Mitigation project sites must be capable of providing an adequate and appropriate hydrologic regime.

Water quality also can affect project success because invasive species such as cattail (*Typha* spp.) and common reed (*Phragmites australis*) are more tolerant of poor water quality than are many less invasive plant species (Jaworski and Raphael 1979; Ehrenfeld and Schneider 1993). Sites with groundwater discharge or that receive surface water runoff from natural areas typically have better water quality (particularly lower nutrient loads) than do sites that receive surface water runoff from surrounding developed or disturbed upland areas (Pearson 1994; USACE 1998; Vivian-Smith 2001).

Restoring previously existing wetlands that have been altered or destroyed is often preferred over constructing new wetlands, because suitable soils and hydrology are either present or more easily reestablished and mitigation would restore important lost functions, such as flood control and water quality improvement (Kruczynski 1990; Richardson and Gatti 1999; Weinstein and others 2001). A determination of the distribution of historic wetlands can provide valuable input to wetland mitigation planning.

The presence of hydric soils may indicate the occurrence of wetlands in the past or a hydrologic regime that could support the establishment of a wetland ecosystem (Richardson and Gatti 1999). Hydric soils occur at a variety of locations on the ANL-E site and include Ashkum silty clay loam, Peotone silty clay loam, and Sawmill silty clay loam (Mapes 1979). These soils are poorly to very poorly drained and moderately to slowly permeable. Locations where these hydric soils occur would be better suited to wetland establishment.

The type of vegetative cover influences the suitability of a site for a wetland mitigation project. Forests and other relatively mature or valued habitats should be avoided because of their existing ecological value and, in some cases, increased cost of conversion to wetland habitat (Kruczynski 1990). In contrast, recently disturbed areas, mowed areas, old agricultural fields, or other early successional habitats are preferred because their current state has a somewhat lower ecological value, compared to mature native habitats.

The nature of adjacent vegetation can strongly influence wetland function (Mitsch and Gosselink 2000). Adjacent vegetation affects the quantity and quality of surface water runoff into a wetland, particularly nutri-

Table 1. Suitability scores and weights applied to variables in the GIS model

Variable	Weight	State	Suitability
Hydrology	3	Surface water (stream, pond)	1.00
		100-year floodplain	1.00
		Local topographic depressions	0.50
		Upland	0.10
Soil	3	Hydric soils (including water)	1.00
		Nonhydric soils	0.25
Historic condition	3	Historic wetland	1.00
		Historic depression	0.75
		All others	0.50
Adjacent vegetation	2	Forest	1.00
		Pine plantation	0.25
		Old field	0.75
		Wetland/open water	0.75
		Mowed lawn	0.25
		Disturbed	0.10
		Existing buildings, roads, etc.	0.10
Vegetation cover	1	Deciduous forest	0.00
		Pine plantation	0.00
		Old field (woody dominants)	0.50
		Old field (herbaceous dominants)	1.00
		Wetland/open water	0.00
		Mowed lawn	0.25
		Disturbed	0.10
		Existing buildings, roads, etc.	0.00
Land use	1	Open space	1.00
		Dedicated for development	0.25
		Existing buildings, roads, etc.	0.00
		Contaminated	0.00

ent and sediment loads. Adjacent upland habitats provide valuable habitat for wildlife that use wetlands for some, but not all, life requisites (e.g., foraging, drinking, reproduction) (Pearson 1994; Burke and Gibbons 1995).

Successful wetland mitigation requires a reasonable expectation of permanence on the landscape and freedom from residual or future impacts. Areas with existing buildings, infrastructure (e.g., roads, rail, or electric distribution lines), or soil contamination and areas of potential future construction generally are poor mitigation sites. In contrast, areas that are undeveloped and dedicated to open space may be more suitable as mitigation sites.

For each of these variables, we identified a suitability index based on professional judgment, data availability, and site-specific knowledge. GIS layers representing each variable were produced and then used to formulate the suitability model. Table 1 presents the suitability index values used for each of the variables in the model. Values of suitability for each variable ranged from 0 (no suitability) to 1 (optimal suitability). Composite suitability scores were obtained by determining the weighted geometric mean of the suitability scores using the formula

$$\text{Suitability} = \left(\prod_{i=1}^{n} \text{SI}_i^{W_i} \right)^{1/\Sigma_i^n = 1^{w_i}}$$

where SI_i is the suitability index score for variable i and w_i is the weight given to variable i.

For our model,

$$\text{Suitability} = \text{SI}_{\text{hydrology}}{}^{3}\text{SI}_{\text{soils}}{}^{3}\text{SI}_{\text{historic}}{}^{3}\text{SI}_{\text{adjacent vegetation}}{}^{2}\,\text{SI}_{\text{vegetation cover}}\text{SI}_{\text{land use}}{}^{1/13}$$

Weights were assigned to variables to represent their relative importance in determining the suitability of a site. The approach used is mathematically similar to the Habitat Evaluation Procedure developed by the US. Fish and Wildlife Service to evaluate the suitability of wildlife habitats (USFWS 1980a, USFWS 1980b, USFWS 1981), although our application is considerably different.

A GIS was used to perform the analysis. Spatial data sources used in the GIS are presented in Table

Table 2. GIS map layers used to determine wetland mitigation potential at ANL-E

Layer	Description
Elevation contours	0.6-m elevation contours derived by photogrammetric methods from 1995 digital orthophotography
Historic topography	Scanned 1946 USGS 7.5' quadrangle map with 1.5-m cell size
Soils	Soil polygons and points from 1976 DuPage County Soil Survey (Mapes 1979). Attributes include soil unit numbers and names
Historic wetlands	Polygons derived from wetland areas shown on 1946 and 1932 USGS 7.5' quadrangle maps
Historic depressions	Polygons derived from local depressions shown on 1946 USGS 7.5' quadrangle map
Vegetation	Vegetation-cover polygons based on field survey and photo interpretation of 1995 digital orthophotography; attributes include habitat type (e.g., marsh, old-field, scrub/shrub, immature deciduous woodland) and species lists for canopy, understory, and herbaceous layers; developed previously by the authors
Streams	Lines and polygons depicting streams derived from photo interpretation of 1995 digital orthophotography.
Land use	1998 Argonne master planning map; includes open space and environmentally sensitive areas in addition to programmatic and service areas

2. GIS layers for each environmental variable were compiled, and suitability scores were determined within these GIS layers (Table 1). A cell-based (raster) layer of suitability values was produced for each model input variable.

For land use, soil, historic condition, and vegetation cover, polygon areas from the GIS layers were converted to raster format with a cell size of 3 m $\times$ 3 m and coded with suitability values. The same approach was used to develop the hydrology layer using the boundaries of water bodies and streams from the streams layer and local depressions from the historical depressions layer. Areas adjacent to these hydrological features were included by calculating buffer areas within 15 m of water bodies and streams and 6 m of local depressions.

The adjacent vegetation layer was produced in two steps. First, a raster layer was produced from the vegetation cover layer, with suitability scores coded according to the values for adjacent vegetation in Table 1. For each cell, the suitability of adjacent vegetation was then determined by calculating the mean suitability score of all cells within a 15-m radius of each cell.

The GIS was used to calculate the overall suitability of each cell on the basis of all of the variables under consideration and the above formula. For example, a cell positioned within a local topographic depression (SI = 0.50, weight = 3), with hydric soil (SI = 1.0, weight = 3), that previously supported a historical wetland (SI = 1.0, weight = 3) is adjacent to old-field vegetation (SI = 0.75, weight = 2), supports old-field vegetation with woody dominants (SI = 0.50, weight = 1), and in an area reserved for open space (SI = 1.0, weight = 1) would have the following suitability index scores:

$$[(0.5)^3(1)^3(1)^3(0.75)^2(0.5)(1)]^{1/13}$$

The resulting composite suitability score is 0.77. In our study, we used ESRI ArcInfo 7.1.2 with the grid extension for GIS data preparation, modeling, and visualization; however, most GIS software with raster analysis capabilities could be used for similar work. Wayne (2003) provides a detailed discussion of the mechanics of preparing data and using it for suitability analysis with the ESRI ArcGIS software.

Results

Maps depicting suitability values for each variable across the ANL-E site are presented in Figure 1. On the basis of hydrology alone, the areas of highest suitability for wetland establishment are primarily located along intermittent and perennial streams in the northeastern and southwestern portions of the site. Numerous isolated depressions throughout the site have moderate suitability on the basis of hydrology.

Hydric soils occur in broad areas bordering the primary drainage systems on the site as well as in a number of areas along small intermittent streams (Figure 1). Many areas of hydric soils also occur in locations that are not associated with surface water features, particularly in the western portion of the site, and these areas currently support few wetlands.

The historic locations of wetlands are generally relatively small areas scattered throughout the ANL-E site (Figure 1). The larger of these are located on the periphery of existing wetlands in the western portion of the site or in areas currently occupied by buildings or other infrastructure.

Several large areas of the site are identified as suitable relative to the presence of adjacent vegetation (Figure 1). Areas of highest suitability are primarily

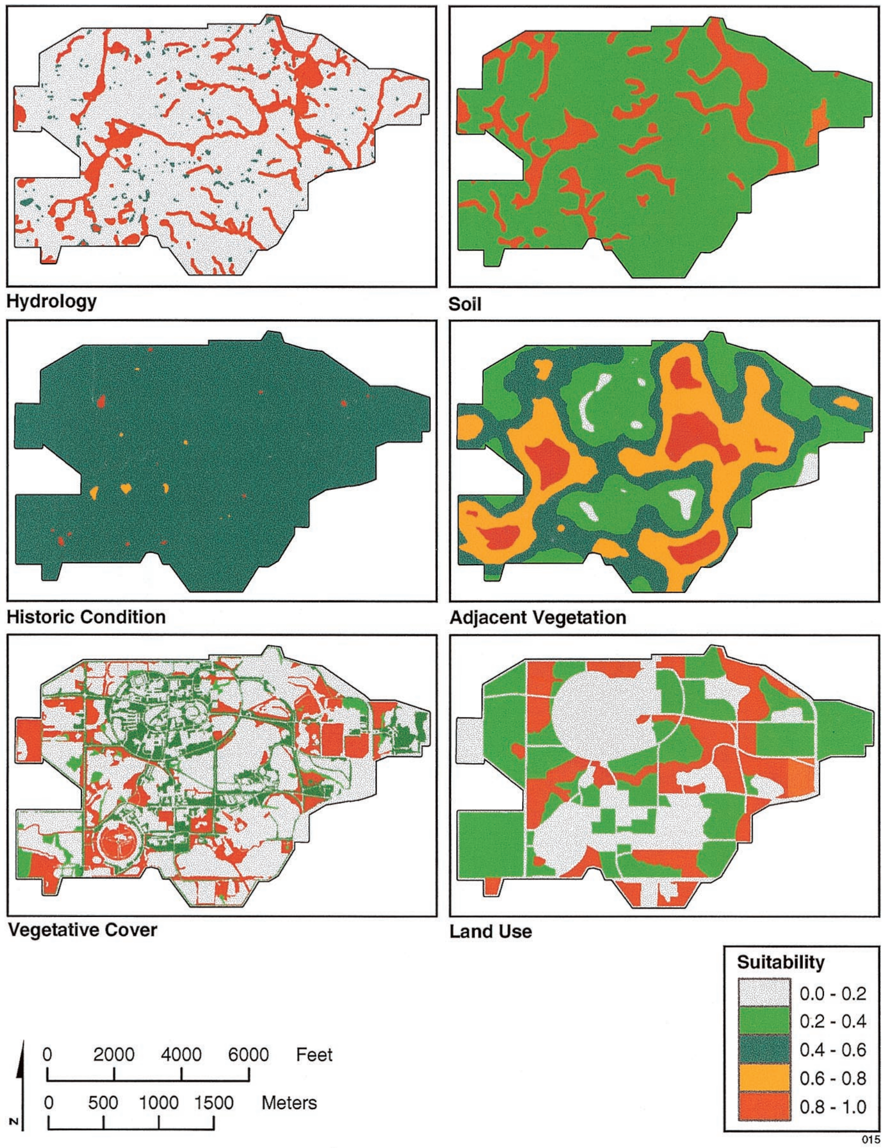

Figure 1. Suitability maps for individual variables on the ANL-E site.

associated with mature deciduous forest, which is the predominant native community type on the ANL-E site. Areas of high suitability in the western and southwestern portions of the site include a combination of woodland and open native grassland.

Areas identified as having the highest suitability for vegetation cover are predominantly located in the eastern, southwestern, and western portions of the site. Most of these areas are located in previously developed or cleared areas that now support old-field habitat. Some of these areas occur on former agricultural fields converted to cool-season grasses, and they have been mowed occasionally in the past.

The most suitable areas relative to land use generally occur in large blocks, and many are associated with the primary surface water drainages on the site (Figure 1). The areas of highest suitability have been dedicated to open space and are excluded from future facility development.

As can be seen in Figure 1, there is relatively little overlap in suitability among variables. For example, some areas that have high suitability for hydrology have low suitability for land use or for adjacent vegetation. Developing composite suitability scores takes these differences into consideration. Model results are shown as a wetland mitigation suitability "surface" in Figure 2. Composite suitability scores are mapped in classes of 0 to $<$ 0.2, 0.2 to $<$ 0.4, 0.4 to $<$ 0.6, 0.6 to $<$ 0.8, and 0.8 to 1.0. Specific locations with scores of 0.6 or higher on the suitability map were identified

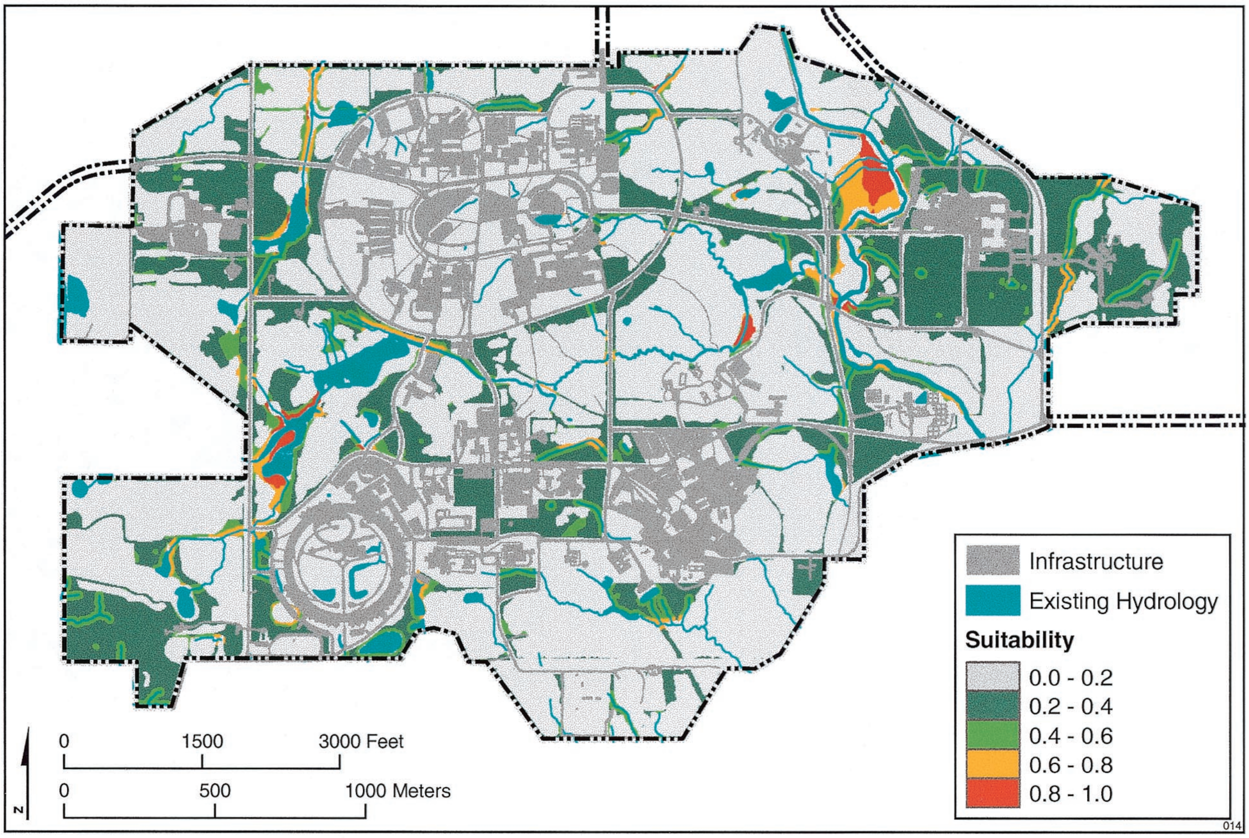

Figure 2. Composite suitability map for wetland mitigation on the ANL-E site.

for further consideration as potential wetland mitigation sites.

Figure 2 depicts the composite suitability scores output from the model. Several areas are identified as having the highest suitability for the development of wetland mitigation projects on the ANL-E site. These are primarily located in topographically low areas associated with the primary streams on the site and presently support a predominantly herbaceous vegetation community. Many of these areas are also located adjacent to mature deciduous forest and woodland. The largest of these areas are in the northeastern and western portions of the ANL-E site. A number of relatively small areas also identified as highly suitable are scattered throughout the site and are not associated with primary streams.

Discussion

The GIS modeling approach proved useful for objectively identifying several alternative locations for wetland mitigation projects at ANL-E. Our model is best viewed as a screening tool, and the mitigation suitability surface identified promising areas for further consideration. Each of the areas identified was subjected to additional evaluation before a final location was selected as the location of a wetland restoration site. Consideration was given to the combined area of contiguous suitable points because this determined potential project size. Feasibility of site modification and associated project costs also were incorporated into the decision-making process. Because of these additional important considerations, the final site selected may not be the site that appears most desirable on the suitability map.

Some researchers have used a similar approach (White and others 1998; Palmeri and Trepel 2002; Williams 2002). Palmeri and Trepel (2002) used elevation, slope, depressions, river network, soil type, land use, population density, and historical wetland presence as variables in two case studies that involved larger regions. In their study, the main focus was on locating sites for water quality improvement, whereas the focus of our study was primarily to improve ecological functions, such as providing wildlife habitat and supporting increased species diversity.

Model output and the suitability map produced will vary according to the data layers used, the suitability scores assigned to different variable states, the weights given to each variable, and the formula used to produce composite suitability scores. Weighted arithmetic means are most often used in suitability analysis (White and others 1998; Palmeri and Trepel 2002; Baban and Wan-Yusof 2003; Wayne 2003); however, we used the weighted geometric mean of suitability scores because we wanted to eliminate sites that had zero suitability for critical variables (e.g., wooded areas, contaminated areas). Because model output is sensitive to these factors, it is important to have good knowledge of the site and region under consideration and to incorporate this information into the model.

The decision-making step of assigning suitability indices to each variable is a key part of model formulation, and other researchers have noted the subjective nature of the process. Palmeri and Trepel (2002) formulated a model from three perspectives: economic/geological, geological/hydrological, and economical/ecological. This change in weighting strategies resulted in different model outcomes which can be used to examine different alternatives. Baban and Wan-Yusof (2003) noted that use of the GIS made decision-making more objective but that there was some subjectivity associated with map weights and scaling. Good knowledge of the site or region under consideration is critical to developing a useful model for site selection.

The sensitivity of our model to these various factors should not be viewed as a detriment to its application. Our model is a representation of our understanding of the ANL-E site and the important variables that would affect the success of wetland projects. It is a tool to identify possible wetland mitigation project sites, but it must be followed up with individual consideration of each location. Each site or region will be different and will require careful model construction and application.

We used the model to identify potential locations and then examined each location and the size and configuration of the final project (based mainly on topography of the site). We were interested in a minimum project size of at least 2 ha, but some of the contiguous areas with high suitability scores were not large enough. For these areas, the project boundaries extended into less suitable areas. Rather than eliminate smaller areas entirely, we made further comparisons by calculating a mean suitability score for the area within each proposed project boundary.

The modeling approach we describe has been applied to a variety of other natural resource management and planning problems and we expect that the trend will continue as the availability of spatial datasets increases and their value for planning becomes more apparent. The end result will be better planning that avoids conflicts, reduces cost, and results in more successful restoration projects.

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