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# A SYNOPTIC ASSESSMENT FOR PRIORITIZING WETLAND RESTORATION EFFORTS TO OPTIMIZE FLOOD ATTENUATION

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*Abstract:* The placement of wetland restoration projects in a landscape to optimize the functional performance of wetlands on a regional scale is often overlooked. To address this problem, the U.S. Environmental Protection Agency's Landscape Function Project developed the synoptic approach to assign restoration priority to landscape subunits according to selected functional criteria. The approach provides a flexible, ecologically-based framework for allocating limited restoration-resources and preserving valued wetland functions on a landscape scale. We conducted a synoptic assessment of the Prairie Pothole Region of the north-central U.S. to demonstrate application of the method for our assessment criterion—the marginal decrease in total downstream flood volume per restoration dollar. A criterion is often not directly measurable but can be represented by an index composed of measurements on related variables. In a synoptic assessment, these measured variables, referred to as indicators, are limited to variables for which data are existing, accessible, and uniformly available for the entire region. We developed a conceptual model to guide the development of an index of the assessment criterion. We then ranked landscape subunits based on index values and mapped the ranks to show relative priority for restoration among landscape subunits. We conducted a series of analyses to justify selection of indicators and some of our assumptions. The approach offers multiple options for processing and displaying information for use by wetland managers.

*Key Words:* synoptic approach, Prairie Pothole Region, wetland restoration, conceptual model, indicator, index, functional assessment, flood attenuation, geographic prioritization

## INTRODUCTION

Wetland management in the United States, including protection and restoration, has been dominated by site-specific concerns. Wetland protection under Section 404 of the Clean Water Act is initiated and driven by a permit application and is therefore reactive and limited in scope. Similarly, restoration efforts are often driven by opportunity (e.g., landowners can receive subsidies for enrolling in restoration programs). Unfortunately, neither process ensures that the benefits of wetland functions and values are optimized throughout the landscape.

In recent years, interest in managing wetlands more comprehensively and pro-actively has been increasing (Hirsch 1988, Preston and Bedford 1988, Abbruzzese and Leibowitz 1997). One approach that seems to be particularly useful for this kind of management is geographic prioritization of restoration and protection efforts, whereby resources are allocated to geographic areas where the functional benefits from restoration and protection are greatest. Geographic prioritization could be especially useful for subsidy programs like the Conservation Reserve Program (7 CFR Parts 704 and 1410) and the Wetlands Reserve Program (7 CFR Part 1467). Such programs are constrained, however, in their need to incorporate ecological criteria into decision-making under circumstances that do not allow for detailed and intensive analyses (e.g., due to funding limitations or time constraints). Unfortunately, there are few approaches to geographic prioritization that can operate under these constraints. Through stakeholder involvement, a greater emphasis is often given to social criteria than to ecological criteria. In an attempt to provide a more ecologically-based tool for geographic prioritization of wetland protection and restoration efforts, the U.S. Environmental Protection Agency's (EPA) Landscape Function Project developed the synoptic approach (Leibowitz et al. 1992, Abbruzzese and Leibowitz 1997).

''Synoptic'' refers to a general view of a whole, and a synoptic assessment, therefore, provides a broad perspective rather than a detailed analysis (Abbruzzese and Leibowitz 1997). The assessment calculates indices for functional criteria in subunits (e.g., counties, drainage basins) of a region and then ranks the subunits. Ranks enable wetland managers to produce regional or statewide maps useful for identifying areas where restoration or protection efforts should optimize functional performance on a regional scale. The synoptic approach was specifically designed as a proactive approach that could incorporate best professional judgment in cases where information and resources are otherwise limited. Its goal is to provide a general evaluation of a region as a whole. It is intended to complement procedures that are currently in place for siting restoration and protection efforts.

The synoptic approach was first proposed in 1992 (Leibowitz et al. 1992). Since then, several weaknesses of the original approach have been identified: benefits of ecological function were not defined in terms of a management constraint; the approach did not show how the proposed ecological indicators were linked to functional performance; the combination of indicators to evaluate functional performance did not have a firm mathematical basis; and alternatives to the selected indicators and the ways in which they were combined were not explored. The purposes of this paper are to show how we have addressed the shortcomings of the original approach and to demonstrate use of the new methods through a realistic application in the Prairie Pothole Region (PPR) of the United States.

A synoptic assessment is conducted in a series of five steps (Abbruzzese and Leibowitz 1997). This sequence of steps provides a framework for identifying the relevant ecological processes and deriving indicators so that decisions are based on the best ecological knowledge. These steps, which have been slightly reworded to reflect recent developments in the approach, are 1) definition of assessment objectives, 2) identification of relevant assessment concepts, 3) completion of the index and assessment, 4) presentation of results, and 5) application of the prioritization to management concerns. This paper follows a format prescribed by these steps. Within this format, we incorporate the following techniques, which we added to the approach to address the weaknesses listed above: use of a benefit/cost ratio to relate the benefits of ecological function to our management constraint (i.e., cost); use of a source/sink/transport schematic to illustrate the relevance of landscape processes to our management objective; development of a conceptual model, showing linkages between concepts and indicators and the mathematical basis for combining indicators into an index; and a series of analyses that test our assumptions, the use of alternative indicators, and alternatives for combining indicators. The discussion section that follows the five-step process focuses on how these techniques have improved the reliability and usefulness of the results.

## ASSESSMENT OBJECTIVE

Flooding that occurs in downstream flood plains, as well as in upland fields due to backup of artificial drainage systems, are concerns in the PPR. Recent flooding in 1993 (Allen 1993, SAST 1994, Hey and Philippi 1995, Kolva 1996) and 1997 caused extensive damage to crops, economic losses to landowners, and harm to fish and wildlife populations. These events created a renewed interest in floodplain management and the role of wetlands in flood attenuation. Given this interest, we chose to have our assessment address the following management question: if some level of funding were available for restoring pothole wetlands, where should restoration efforts be targeted so as to provide the optimal reduction in downstream flooding region-wide?

Hyman and Leibowitz (2000a) have shown that optimizing ecological function (Y) from a constrained level of management effort (E) can be accomplished by restoring in geographic subunits that have the highest marginal increase in function per unit effort, dY/dE, if dY/dE is considered independent across subunits. In our application, the function of interest is flood attenuation, and the effort (i.e., management constraint) is available restoration dollars. Thus, the function is specifically defined as the marginal decrease in total downstream flood volume per restoration dollar, dFV/dD. Our assessment objective was to estimate and rank dFV/dD, our assessment criterion, for subunits of the PPR. A ranking system provides a framework for addressing the management objective of prioritizing restoration efforts to optimize the benefits of flood reduction region-wide.

The PPR covers over 777,000 $km^2$ of the United States and Canada. We conducted this assessment only on the portion of the PPR within the United States, which covers 274,540 $km^2$ in the states of North Dakota, South Dakota, Minnesota, Montana, and Iowa. We used Mann's (1974) boundary to delineate the PPR of the United States. We divided the area within this boundary into subunits, which are the areal units for establishing ranks, making comparisons, and reporting results. Our subunits are the hydrologic cataloging units of the U.S. Geological Survey (USGS) classification. A hydrologic unit is a geographic area representing part or all of a surface drainage basin, a combination of drainage basins, or a distinct hydrologic feature (Seaber et al. 1984). Within the PPR boundary, we identified 119 hydrologic cataloging units (median area = 2,374 km²), which we used for the assessment.

## IDENTIFICATION OF RELEVANT ASSESSMENT CONCEPTS

To conduct the assessment, we used indicators to develop an index of dFV/dD. This was necessary because data for calculating dFV/dD directly were not readily available. Indicators are measurable variables used to estimate or represent related unmeasured variables. Indicator selection is often driven by data availability. Such an approach, which focuses on practicality, can be shortsighted because it does not identify potential redundancies or correlations between data layers, provides no guidance on how to mathematically combine the indicators, can allow use of variables that may not be ecologically relevant to the problem, and makes it difficult to determine whether important variables have been omitted from the analysis. To address these concerns, we used a conceptual model to guide indicator selection. We developed this conceptual model based on our understanding of how wetlands contribute to regional flood attenuation. The purpose of the conceptual model was to formalize our ecological understanding so as to guide the indicator selection process; it was not developed for the purpose of simulations, hypothesis testing, or direct analysis. In this section, we develop the conceptual model, showing the ecological linkages among the management objective, the assessment criterion, and the important related concepts that will be estimated with indicators.

### Hydrologic Background

Intact pothole wetlands generally tend to reduce the rate of overland transport of water and increase ground-water infiltration (Moore and Larson 1979, Hubbard and Linder 1986, Hubbard 1988, Schaefer and Brown 1992, Kolva 1996). Prairie potholes store and gradually release precipitation and snowmelt. The gradual release desynchronizes water delivery to streams during storm events, thereby helping to reduce the frequency and magnitude of flooding. Wetlands are most effective in flood attenuation when they have a high capacity to store additional water and when soils in the watershed are not saturated.

Numerous researchers have reported that extensive

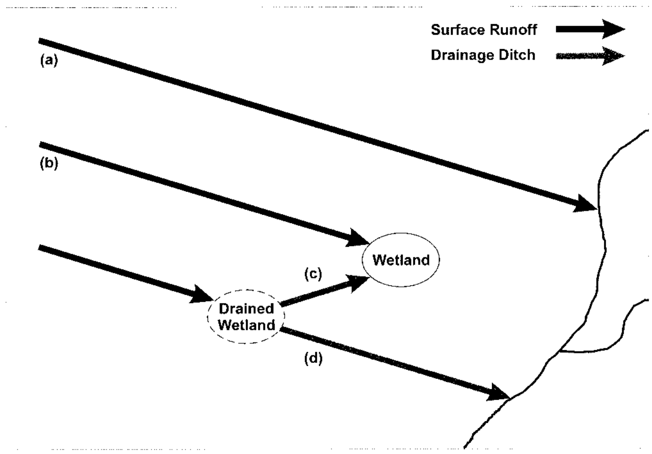


Figure 1. Potential pathways of surface runoff. Runoff can enter streams directly (a) or enter and be stored in wetlands (b). Stored runoff can be released from wetlands via drainage ditches or tiles and flow either into other wetlands (c) or into streams (d).

drainage of wetlands in the PPR has magnified peak flows and the incidence of flooding in areas of the PPR (Kloet 1971, Linsley and Franzini 1972, Campbell and Johnson 1975, Cernohous 1979, Brun et al. 1981, Vining et al. 1983). Other human-induced factors besides drainage, such as changing land-use patterns, tillage practices, reduction in beaver populations, and stream channelization, also contribute to flood frequency and intensity (Hey and Philippi 1995). In addition, the capacity of wetlands to function in attenuating flooding is limited and depends upon the volume of water flowing down slope and the rate at which it is delivered. These two factors are functions of natural factors such as rainfall intensity, antecedent soil moisture, rate of snow melt, and frost conditions.

The above principles led to the development of a schematic (Figure 1), which provided context for the conceptual model. The figure represents the hydrologic factors that we assume are important for flood attenuation. It describes the potential pathways for surface-water flow in the PPR, including relevant sources, sinks, and transport vectors (Leibowitz et al. 2000). Flood attenuation occurs when water that would otherwise contribute to flooding is temporarily or permanently diverted so that it does not enter surface waters during a flood event. Streams receive their water from several sources within a drainage basin; we focus on surface runoff as the source that, if uninterrupted, can enter streams and potentially cause flooding (Figure 1a). Because of their ability to store and gradually release water, wetlands can function as sinks and reduce flooding by intercepting surface runoff (Figure 1b).

Artificial drainage structures (e.g., ditching or tiling) act as transport vectors for stored water, effectively transforming a wetland into a source. However, drained water need not enter streams; much of the artificial drainage in the PPR terminates in another wetland (Figure 1c). While such drainage can cause local flood damage within the subunit to agricultural crops and communities, wetland drainage waters will have a significant effect on overbank flooding downstream only if they enter either a stream or a channel or ditch that empties into a stream (Figure 1d).

### Conceptual Model for Evaluating the Assessment Criterion

Since relating ecological function directly to restoration effort is difficult, we first expanded dFV/dD into a number of related terms that are more easily estimated (Hyman and Leibowitz 2000a):

$$dFV/dD = (dWA/dD) \times (dDV/dWA) \times (dFV/dDV) \quad (1)$$

where

dFV/dD = the marginal decrease in total downstream flood volume per restoration dollar;

dWA/dD = the marginal increase in area of restored wetland per restoration dollar;

dDV/dWA = the marginal decrease in drainage volume per area of restored wetland; and

dFV/dDV = the marginal decrease in total downstream flood volume per decrease in drainage volume.

The relationships among these various concepts is illustrated in the top portion of the conceptual model (Figure 2), which provides the basis for indicator selection (discussed in the next section).

## COMPLETING THE INDEX AND CONDUCTING THE ASSESSMENT

The purpose of this step was to finalize the conceptual model (Figure 2) by identifying the most suitable indicators to represent the individual terms of Equation 1, complete the index, and conduct the assessment. We emphasize that steps 2 and 3 are interactive processes; additional branching in the conceptual model (Figure 2) is necessary only if appropriate indicators are not identified. After finalizing the conceptual model, we conducted analyses to test alternative index components and some of the assumptions we made. These analyses, which are also summarized in this step, led to a final revision of the index.

Data and data sources for indicators in the conceptual model (Figure 2) are listed in Table 1. Indicators often had to be converted from their reporting format and re-expressed on a subunit basis. All initial data manipulations are summarized in the Appendix.

### Indicator Selection

We surveyed potential data bases to become familiar with the kinds of data available for deriving the indicators. We were limited to using data that were existing, accessible, and uniformly available for the entire PPR. This effectively restricted us to selecting data from a small number of existing data bases containing national or regional scale data.

The first term in Equation 1, dWA/dD, represents the area of drained wetland that can be restored per dollar. While this can be affected by a number of factors, including the methods used for restoration, we assumed that the cost of land (Figure 2) is the primary factor influencing this between subunits. We selected the inverse of farm property value as our indicator for this term; using a prime to represent the indicator of a variable, we denote this as $(dWA/dD)' = 1/PV$. Data were derived from the 1992 Census of Agriculture and include the dollar value of farmland and buildings per area.

The term, dDV/dWA, is the negative of the volume of water drained per area of drained wetland; this is equivalent to pathways (c) and (d) combined (Figure 1). The negative is needed because the term is defined as a decrease in drainage. We assumed that the amount of water drained from a wetland is proportional to total runoff into the wetland. This, in turn, is equal to the product of the total runoff depth and the wetland drainage basin area per area of restored wetland. We estimated total runoff depth using the Soil Conservation Service equation for predicting runoff on small ungaged watersheds (Kent 1973):

$$RD = \frac{[P - 0.2(1000/CN - 10)]^2}{P + 0.8(1000/CN - 10)} \quad (2)$$

where

RD = total runoff depth;

P = weighted storm precipitation (depth); and

CN = runoff curve number.

Curve numbers were originally applied only to small watersheds but have since then been used with Landsat digital data for large coastal watersheds (Slack and Welch 1980), using an averaging technique similar to the one we developed for this assessment. For each subunit, we derived average curve numbers based on hydrologic soil group and land use. Total runoff depth

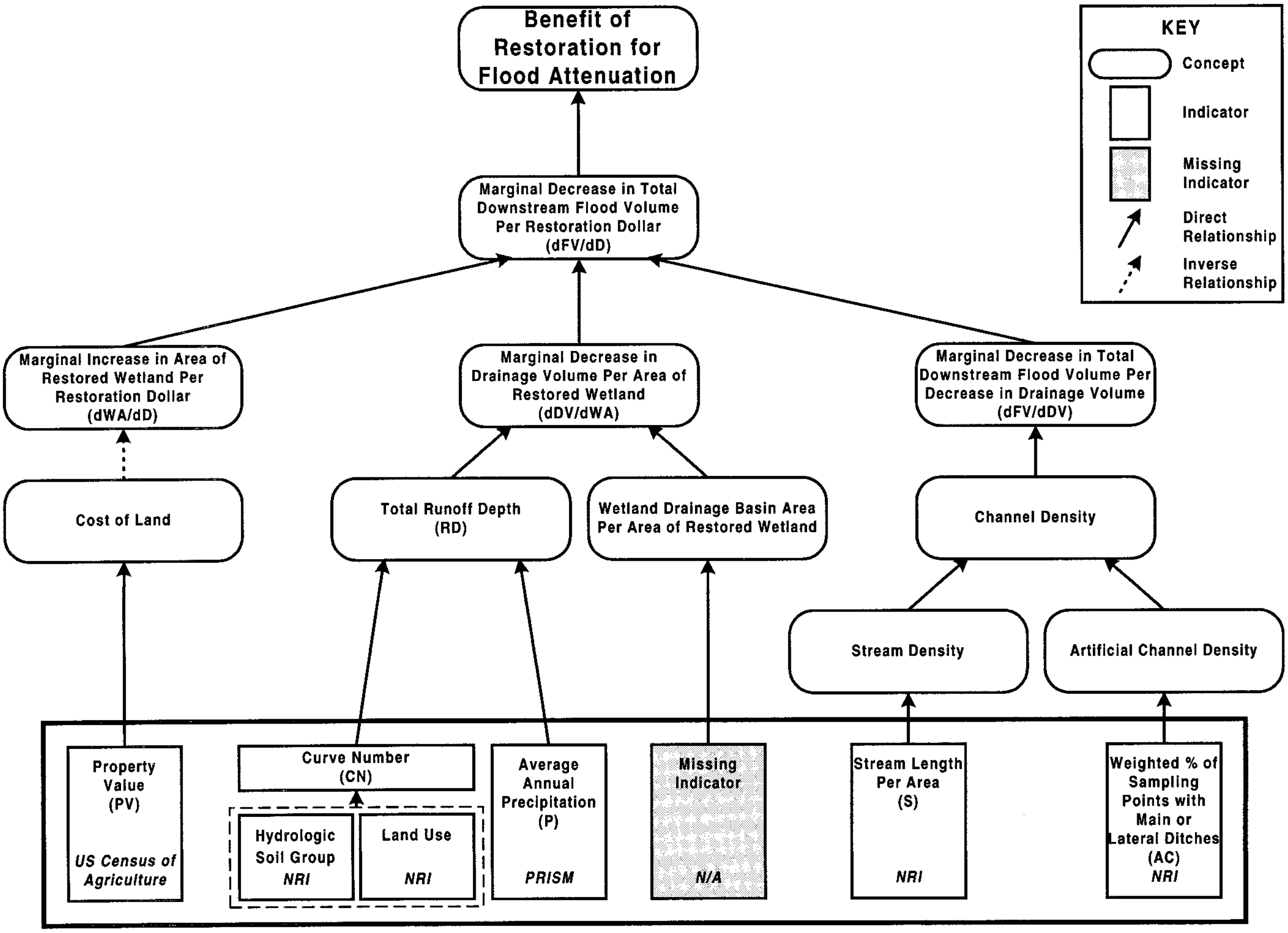


Figure 2. Conceptual model showing how ecological concepts and indicators are linked to functional performance. Functional performance is evaluated as the assessment criterion, dFV/dD, which is used to address the management objective of achieving the greatest benefit of flood attenuation through wetland restoration. Indicators selected for representing the concepts are shown in the area outlined in bold at the bottom of the diagram. Data sources, described in Table 1, are included with each indicator.

Table 1. Data bases, indicators, and indicator measurements used in the index of the assessment criterion, $I_{dFV/dD}$. N/A is indicated for descriptive indicators that do not have units of measurement; they were used for deriving curve numbers.

| Data Base | Indicator | Indicator Measurement |
|---|---|---|
| 1992 National Resource Inventory (USDA 1994) | Density of Ditches (main, lateral, field, tiles) | Percent of subunit |
| | Density of Streams | Percent of subunit |
| | Land Use | N/A |
| | Hydrologic Soil Group | N/A |
| Rawls et al. 1981, USDA 1986 | Curve Number | Ordinal value (0–100) |
| EPA Reach File—Alpha (RF3) (USEPA 1994) | Density of Streams | km stream length/km$^2$ of subunit |
| 1992 Census of Agriculture (USDC 1993, 1994) | Property Value | \$/km$^2$ of farmland |
| PRISM (OCS/SCS 1994) | Average Annual Precipitation | mm/yr |
| USGS Hydrologic Cataloging Unit GIS coverage (Seaber et al. 1984) | Subunit Area | km$^2$ |

was defined so as to reflect average annual precipitation and average antecedent soil moisture conditions.

We were not successful in identifying a suitable indicator for wetland drainage basin area per area of restored wetland. It therefore had to be omitted from our index. The consequence of this omission will depend on how much this term actually varies between subunits—the effect will not be significant if there is only minimal geographic variation. However, we included this variable in Figure 2 to make this omission explicit. This allows the variable to be incorporated into the analysis should an appropriate indicator become available. Thus, total runoff depth (Equation 2) was selected as the indicator, $(dDV/dWA)' = |-RD|$. Taking the absolute value allows for a positive expression of the index.

The third term of Equation 1, dFV/dDV, represents the reduction in downstream flood volume, given a unit reduction in drainage. This would be equal to one if all water drained down pathway (d) and would decrease to zero as the proportion traveling through pathway (c) increased (Figure 1). Thus, this term represents the probability of conveyence, which is a function of channel density. We defined channels as all streams plus artificial channels that can drain wetlands into streams. We used a measure of stream length per area, derived from the EPA Reach File (RF3) data base, as an indicator of stream density in a subunit. For artificial channel density, we used the Natural Resources Inventory (NRI), which reports on three forms of artificial drainage: main/lateral ditches, field ditches, and tiling. We used the density of main and lateral ditches as our indicator of artificial channel density, assuming that these ditch types are most important for delivery of water to streams. We estimated the density of each of these indicators as the percentage of NRI sampling points at which each occurs.

The physical units for our indicators of stream and artificial channel densities were different and could not be added together to obtain channel density. To combine these two indicators, we first standardized each to a common scale from zero to one (Appendix). The addition also required that we factor in a coefficient, *k*. The *k*-coefficient is required as a weighting and conversion coefficient when adding two indicators (Leibowitz and Hyman 1999) and has several functions: 1) it adjusts for differences in the ways the indicators are scaled with their concepts; 2) it assigns appropriate weighting factors to the concepts being combined; and 3) it adjusts for differences in unit measures between the indicators. Unless specific information is available about the relationship between the indicators and their concepts and the relative contribution of each concept to the assessment criterion, *k* must be estimated from assumed or inferred relationships. For our index, we assigned *k* a value of one (i.e., the indicators were weighted equally), since we had insufficient information to support the selection of an alternative *k*. Thus, our indicator for the final term in Equation 1 was $(dFV/dDV)' = kS^* + AC^*$, where $S^*$ and $AC^*$ are the standardized stream and artificial channel densities, respectively (Appendix). Given the indicators for the three components of Equation 1, the final index for the marginal decrease in total downstream flood volume per restoration dollar, $I_{dFV/dD}$, was defined as

$$I_{dFV/dD} = (dWA/dD)' \times (dDV/dWA)' \times (dFV/dDV)' = \frac{|-RD| \times (kS^* + AC^*)}{PV} \qquad (3)$$

Subunits were assigned to standard quintiles based on $I_{dFV/dD}$, with a rank of one representing the highest restoration priority.

## Limitations of the Index

The index was constructed with the following restrictions. (1) It pertains only to overbank flooding downstream and not local flooding of farm fields or lakes. (2) It accounts for the delivery of water to streams but does not predict whether flooding occurs within the same subunit or in a downstream subunit, which would require detailed routing and timing information. (3) It explains the contribution to downstream flooding resulting only from the drainage of wetlands. It does not address the significance of this source of flooding relative to other sources (e.g., tillage, channelization, land use). (4) It does not pertain to restoration of riverine wetlands. We chose to focus on pothole wetlands because they are reported to decrease flooding to a greater extent than do riverine wetlands (SAST 1994). (5) It incorporates flood volumes but not discharge velocities. Estimating velocities requires an analysis of the timing of water movements within a drainage basin, which, because of the high costs and data requirements, is beyond the scope and purpose of a synoptic assessment.

We emphasize that the synoptic assessment is a regional prioritization tool; its purpose is not to prioritize individual wetlands but, rather, to identify candidate groups of wetlands (i.e., wetlands in a subunit) based on average condition. At the individual wetland scale, it is possible that restoring a particular wetland in a low priority subunit could actually result in greater functional benefit than restoring a wetland in a high priority subunit. The use of average condition means that restoration within highly ranked subunits should, on average, provide more flood attenuation benefit per cost than restoration in lower ranked subunits. A regional approach sacrifices detailed information about individual wetlands for tractability of analysis and broader scope. Targeting individual wetlands that contribute the most benefit would require site-specific approaches, which would be impractical for a large region. However, site-specific prioritization in high ranking subunits would be a logical follow-up to a synoptic assessment.

We caution that the inclusion of cost in the index might mean that subunits where restoration could greatly reduce flood volumes might receive low priority because of high land costs. Removing cost from the assessment would alleviate this, but the assessment would no longer optimize the distribution of limited resources for achieving the greatest amount of flood attenuation region-wide. This factor was incorporated because regional scientists and managers at a workshop suggested that cost of restoration is an important consideration that should be included. However, our approach can allow a comparison of the ranks derived from assessments with and without cost as a factor; this could reveal geographic areas where further investigation may be necessary before a final decision about resource allocation can be made.

## Analysis of the Index

The appropriateness of the indicators used in the index, the effect of the *k* value on ranks, and the validity of our assumptions were uncertain because they are conceptually based on professional judgment. Because of our uncertainty related to these factors, we conducted several analyses to evaluate our judgment for this assessment. In this section, we describe a series of analyses with which we explored index alternatives and tested assumptions. We emphasize that these kinds of analyses are a necessary component of a synoptic assessment, since decisions must be made based on limited information, and assumptions are often necessary.

*Use of Alternative Indicators.* The NRI data base reports presence or absence of streams at each sampling point. Therefore, an alternative to the RF3 indicator for stream density would be the number of NRI sample points where streams are present as a percentage of total sample points in a subunit. Correlation analyses revealed no significant correlation between the NRI and RF3 indicators of stream density or between the ranks of $I_{dFV/dD}$ derived using these different indicators. Investigation of the data revealed that the NRI data represent only perennial streams, whereas the majority of PPR streams are intermittent streams, which are particularly significant during storm events. The RF3 data include both perennial and intermittent streams. This suggests that the NRI-derived indicator is probably not an accurate representation of stream density. We therefore eliminated the NRI stream density as a potential indicator.

We were also uncertain about the relative contributions to flooding from the different forms of drainage reported by the NRI and whether one or a combination of these drainage types should be used as an indicator of artificial channel density. As an alternative to using main and lateral ditching as an indicator for artificial channel density, we considered all drainage types reported in the NRI data base (i.e., main/lateral ditches, field ditches, and tiles). Mapped ranks of the assessment criterion, calculated using the two different indicators, showed very similar patterns. A correlation analysis on the values of the two alternative indicators revealed that they are highly correlated ($r = 0.74$; $P \leq 0.0001$). A correlation analysis on the quintile ranks of $I_{dFV/dD}$ also showed high correlation ($r = 0.81$; $P \leq 0.0001$). We concluded that field ditches and tiling either do not contribute substantially to artificial channel density or most frequently co-occur with main and lateral ditches at NRI sample points. Since the selection of either indicator produces similar results, the potential for error from selecting the wrong indicator is small.

*Investigation of Geographic Assumptions.* Geographic prioritization is appropriate only when concepts and indicators are influenced by geographic location (Hyman and Leibowitz 2000a). In our analysis, variation within a subunit should be small compared to variation between subunits, justifying the use of average conditions within subunits. We therefore wanted to test whether use of 119 USGS hydrologic cataloging units reduced total variance, compared to variability for the PPR as a whole. We also wanted to compare the reduction in variance for the 119 subunits with some alternative subunit classification. For the alternative, we selected the 14 Major Land Resource Areas (MLRAs) in the PPR. The USGS and MLRA subunits are defined by two completely different classification systems and do not share any common boundaries. We compared the error sum of squares of land capability, a NRI indicator related to property value, for the entire PPR with the error sum of squares remaining after variance reduction by division into MLRAs or USGS hydrologic cataloging units. We conducted this analysis on land capability for several reasons: land capability is highly correlated with property value; the data for land capability are represented by quantitative data rather than presence/absence data, which allows for a more realistic calculation and use of the variance estimate; and we needed a variable that is derived for the USGS subunit.

The division into either MLRAs or cataloging units

| Rank B ($k$=1/100) \ Rank A ($k$=100) | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1 | 1 (1) | 2 (2) | 3 (4) | 4 (7) | 5 (11) |
| 2 | 2 (2) | 2 (3) | 3 (5) | 4 (8) | 5 (12) |
| 3 | 3 (4) | 3 (5) | 3 (6) | 4 (9) | 5 (13) |
| 4 | 4 (7) | 4 (8) | 4 (9) | 4 (10) | 5 (14) |
| 5 | 5 (11) | 5 (12) | 5 (13) | 5 (14) | 5 (15) |

Figure 3. System for combining ranks. For a given cell, the maximum (i.e., lowest priority) of Ranks A and B represents the primary rank (upper number in each cell). Cells having the same primary rank are then given a secondary rank based on the minimum (i.e., highest priority) of Ranks A and B. These are then renumbered from 1 (high restoration priority) to 15 (low priority), shown as the lower parenthetical number. Finally, subunits are re-assigned to quintiles based on these ranks.

resulted in a significant ($P \leq 0.0001$) reduction in error sum of squares (21% and 23%, respectively). The variance reduction achieved by division into cataloging units is only slightly greater than that for MLRAs. While this justifies use of either type of subunit, hydrologic units are more appropriate for managing hydrologic functions.

Another assumption we made is that indicator values are homogeneous across reporting units. This assumption is necessary for pro-rating (see Appendix). To assess the validity of this assumption, we compared the ranks, via a correlation analysis, of two related indicators: 1) property value, which is reported at the county level and must be pro-rated to the subunits; and 2) land capability, which is derived from samples of the NRI at the subunit level. The analysis showed that the ranks of the two indicators are highly correlated ($r = 0.81$; $P \leq 0.0001$). We concluded that the assumption of the representativeness of the county-derived data values is reasonable.

*Effect on Ranks of the* k*-coefficient.* Because we had insufficient information to select a $k$-coefficient for adding the indicators of channel density, we were interested in the extent to which the $k$ value would affect ranks. Two alternative sets of ranks were generated (Equation 3) using $k$-coefficients of 0.01 and 100 and compared with the results obtained using a $k$-coefficient of one. Correlation analyses were conducted on the $I_{dFV/dD}$ estimates and on the quintile ranks of $I_{dFV/dD}$ to compare the three $k$ alternatives. Results showed a stronger correlation between the $k = 1$ and $k = 100$ alternatives for both the estimates ($r = 0.85$, $P \leq 0.0001$) and the quintile ranks ($r = 0.69$, $P \leq 0.0001$) than between the $k = 1$ and $k = 0.01$ alternatives ($r = 0.20$, $P = 0.030$ for the estimates; $r = 0.33$, $P = 0.0002$ for quintile ranks). We concluded from these results that the selection of $k$ is important in determining the way subunits are ranked. This analysis alone, however, does not suggest which of these $k$-coefficients is more appropriate.

## Final Revisions to the Ranking Procedure

Because of the effect of the $k$-coefficient on rankings and the uncertainty in its value, it was necessary to reduce the potential for assigning incorrect ranks due to a poor choice of $k$-coefficient. We thus developed a procedure for combining two sets of ranks derived with $k$ coefficients at the extremes of a range.

We began by computing subunit ranks based on values of $I_{dFV/dD}$ (Equation 3) using 11 $k$-coefficients between 250 and 1/250. We then identified the range of $k$ values where most of the variation in ranks occurred; there was minimal variation in ranks on either side of this range. The range was defined by $k = 100$ and $k = 0.01$. We used these two $k$ values to derive minimum and maximum ranks for each subunit. This approach assumes that the relationship between ranks and $k$-coefficient is monotonic. Based on the $k$ values we used to produce this range of ranks, the assumption of monotonicity is valid. We refer to the maximum (i.e., lowest priority) rank as the "primary" rank and the minimum as the "secondary" rank. To minimize the risk of assigning an inappropriately high priority to a subunit, we ranked the subunits by their "primary" ranks. Then, if two or more subunits had the same "primary" rank, we assigned a new rank, in sequence, based on the "secondary" rank (Figure 3). Thus, if two subunits had the same primary rank, but different secondary ranks, the subunit with the lowest secondary rank would receive a lower rank in the sequence than the subunit with the higher secondary rank. This method produced a potential for ranks of 1 to 15 (Figure 3). Based on these ranks, the subunits were assigned to standard quintiles and then re-ranked from one to five.

Table 2. Example format for tabular display of results, including indicator values, index ($I_{dFV/dD}$) estimates, and ranks. The table organization corresponds to Figure 2; entries for only the first five subunits are shown. To estimate $I_{dFV/dD}$, indicator values below were converted to the proper physical units and/or standardized, and then substituted into Equation 3. Estimates and ranks below are for a *k* coefficient of 1.

| **Benefit of Restoration for Flood Attenuation** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Marginal Decrease in Total Downstream Floor Volume per Restoration Dollar **dFV/dD** | | | | | | | |
| | Marginal Increase in Area of Restored Weland Per Restoration Dollar **dWA/dD** | Marginal Decrease in Drainage Volume Per Area of Restored Wetland **dDV/dWA** | | | Marginal Decrease in Total Downstream Flood Volume Per Decrease in Drainage Volume **dFV/dDV** | | | |
| | Cost of Land (reciprocal) | Total Runoff Depth | | Wetland Drainage Basin Area Per Area of Restored Wetland | Channel Density | | Criterion | |
| | | | | | Stream Density | Artificial Channel Density | | |
| Subunit | Property Value | Curve No. | Avg. Annual Precip. | N/A | Stream Length per Area | Weighted % of Sampling Points with Main/Lateral Ditches | $I_{dFV/dD}$ | Rank |
| 7010104 | 144000 | 64 | 690 | | 0.98 | 0.0 | 2.69 | 1 |
| 7010106 | 138000 | 68 | 675 | | 0.37 | 0.0 | 1.06 | 5 |
| 7010107 | 137000 | 61 | 665 | | 0.50 | 0.0 | 1.33 | 4 |
| 7010108 | 153000 | 62 | 666 | | 0.75 | 0.0 | 1.82 | 3 |
| 7010201 | 187000 | 61 | 697 | | 0.90 | 1.6 | 2.37 | 2 |

## RESULTS AND DISCUSSION

Results of a synoptic assessment are most useful if displayed in a format beneficial to interpretation and decision-making. A tabular display preserves intermediate data, such as individual indicator values, or intermediate calculations (e.g., dWA/dD). An example of a tabular display of indicator data and the assessment criterion ranks is shown in Table 2. Presentation of the data in map form is usually most useful for identifying locations and spatial patterns of the ranks. The mapped ranks of $I_{dFV/dD}$ are shown in Figure 4.

### Management Applications

Synoptic maps and subunit ranks could provide federal agencies, such as the U.S. Department of Agriculture (USDA), with regional information to complement the approach currently used to allocate limited resources for wetland restoration. The Natural Resources Conservation Service (NRCS) assists the Farm Service Agency in administering the Conservation Reserve Program (CRP) and is the lead agency for administering the Wetland Reserve Program (WRP). These programs provide incentives for improving natural resources on the nation's private lands.

The current system for determining the allocation of available funding evaluates offers from farm operators to enroll land in CRP or WRP. The NRCS uses national ranking factors of the Environmental Benefits Index (EBI) to rank individual sites for land enrollment in the CRP and WRP (David Dewald, personal communication, NRCS, Bismarck, ND, 1997). Bids from landowners are then ranked in comparison to all other bids offered and selections made from that ranking.

A decision-maker could use synoptic maps to screen and reduce the number of subunits to be considered for site prioritization using the EBI. Areas where wetland restoration could achieve the greatest reduction in flood volume per dollar (or effort) are ranked high. A manager could identify landscape subunits within the region, or a particular state, to be considered high pri-

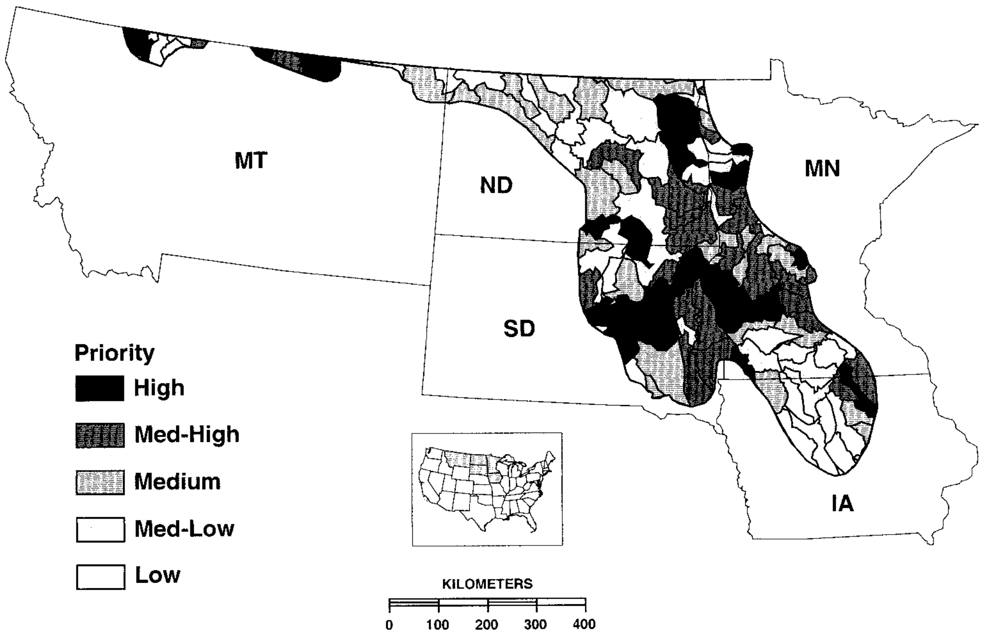


Figure 4. Mapped ranks of the assessment criterion, $I_{dFV/dD}$. Ranks were reassigned from combined primary and secondary ranks, based on Figure 3 (see text). Low ranks indicate high criterion values and high priority for restoration, whereas high ranks indicate low criterion values and low restoration priority.

ority for funding. For example, Figure 4 shows several areas of high ranks: east-central South Dakota, including an extension into western Minnesota, the Red River Valley between North Dakota and Minnesota, and northern Montana. This initial selection could serve as a first cut to help direct the site-level allocation of funding under the NRCS programs.

State agencies that have developed their own prioritization schemes for wetland protection, restoration, and enhancement may be reluctant to adopt another approach. Land managers and decision-makers often require specific information and greater flexibility of interpretation. In such cases, statewide rankings of specific indicators may be used to target areas within the state or to complement information derived from the state prioritization. Statewide rankings are a readjustment that allow the quintiles to be defined over a smaller sub-region. This can provide better discrimination of differences between subunits in the selected sub-region.

North Dakota has two site-level ranking systems for allocating resources for its WRP. Site-level criteria, however, might not provide information about landscape factors that influence characteristics (e.g., total runoff) of a broader area surrounding sites. Managers could refer to synoptic maps to select land for easements specifically for downstream flood attenuation benefits. By referring to a synoptic state map showing ranks for total runoff depth (Figure 5a), the manager could evaluate the need for restoration in a state-wide or watershed context. It would also be possible to identify areas where specific land practices affecting downstream flood volume, such as density of main and lateral ditches (Figure 5b), may need special attention in order to ensure successful restoration of the function.

In some states or other geographic portions of the PPR, more reliable or more pertinent data might be available. There are, in fact, numerous data sets compiled for smaller sections of the PPR that are often more reliable than the national data bases we used. Our approach allows alternative indicators to be substituted without the need for changes in the conceptual model (Hyman and Leibowitz 2000a, b). Although a smaller-scale assessment could be an advantage in terms of data availability and ranking accuracy, it would not be as effective in addressing regional functional performance.

## Improvements to the Assessment Approach

The synoptic assessment presented here incorporates several new techniques, not used in earlier versions of the approach, that are aimed at improving assessment quality. These include 1) structuring the index as a benefit/cost ratio, 2) use of a source/sink/transport schematic, 3) development of a conceptual model, and 4) incorporating analytical improvements. This section discusses how the use of these techniques has im-

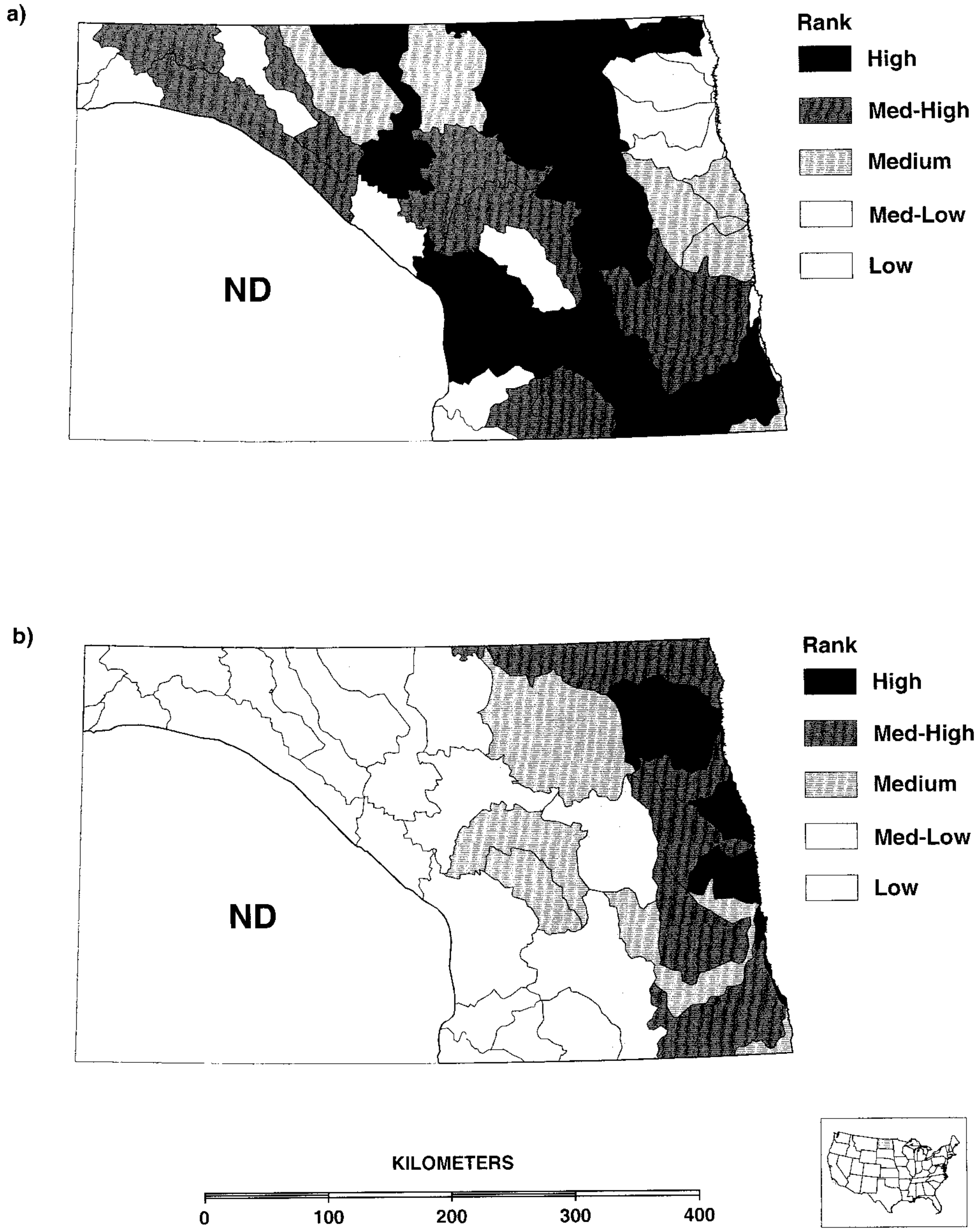


Figure 5. Ranks for total runoff depth (a) and density of main and lateral ditching (b) for subunits of North Dakota. Low ranks indicate high criterion values and high restoration priority, whereas high ranks indicate low criterion values and low restoration priority. A preponderance of zero values for density of main and lateral ditching (b) resulted in an unequal distribution of ranks.

proved the reliability and usefulness of synoptic results and how the method could be further improved in the future.

*Benefit/Cost Ratio.* The formulation of our assessment criterion as a benefit/cost ratio readily allows expression of the criterion as a function of related terms (Equation 1), which may be more easily evaluated than the ratio. Explicitly incorporating the management constraint (i.e., cost) into the assessment criterion helps to define the circumstances under which the results are applicable. The usefulness of our prioritization requires that the cost of restoration is a constraining factor. If the constraining factor were the number of landowners willing to enlist in restoration programs, then prioritization by the benefit/cost ratio would be inappropriate because the constraint—willing landowners—is geographically fixed and cannot be distributed among subunits so as to optimize benefit. In such cases, active recruitment of anyone willing to enlist would be the appropriate strategy.

*Source/Sink/Transport Schematic.* The source/sink/transport schematic (Figure 1) improves the assessment procedure by illustrating the relevance of the landscape processes to the specific management objective. We made explicit conceptual links between the ecological benefits desired by the manager and the ecological processes thought to control and influence them. Approaching landscape function in this manner simplifies the problem by eliminating details specific to the particular function and allowing the initial focus to be on the processes that are most directly linked to addressing the management objective (Leibowitz et al. 1992). For example, a reasonable initial assumption would be that all artificial drainage of wetlands ultimately contributes to downstream flooding. If that were the case, then subunits with the most drained wetlands would automatically be ranked highest. Incorporating the transport dynamics into the assessment forced us to consider how drained water actually enters streams. This led to the recognition that, in the PPR, many subunits contain wetlands that are drained locally into other wetlands and therefore contribute very little to downstream flooding; these subunits should not be considered high priority for restoration to reduce downstream flooding. These conclusions helped us focus on particular concepts to develop the conceptual model.

*Conceptual Model.* Indicator development is often driven by data availability, rather than by ecological considerations (i.e., relationships between the indicator and endpoint). Our top−down conceptualization (Figure 2) required that we identify important concepts first and find suitable indicators and data sources afterward. If suitable data sources do not exist, the conceptual model reflects the missing data while retaining the ecological concepts. This structure helps prevent duplication of distinct but related measures to represent the same concept (Hyman and Leibowitz 2000b). It allows us to separate the effects of measurement error from error in the hypothesized structure of the conceptual model, to compare the performance of different indicators (e.g., RF3 vs. NRI streams), or to add new indicators as they become available without needing to change the conceptual model.

While important individually, the combined use of the three techniques—the benefit/cost ratio, source/sink/transport conceptual model, and concept/indicator diagrams—provides a mechanism for formalizing the management objective and our understanding of the ecological factors and data issues relevant to that objective. This allows us to communicate this understanding with others and ensure that all parties share the same understanding of the problem. We believe the manager needs to be an active participant in the development of the index. The three techniques mentioned can facilitate that involvement.

*Analytical Improvements.* The analytical techniques we employed examined how alternative indicators, weighting factors, and geographic assumptions affected results. These analyses and the above conceptual modeling improvements allowed us to examine the effects of uncertainty and to quantitatively compare how results respond to differences in management objectives, conceptual model formulation, and indicator selection. We also employed an approach that conservatively combined extreme results in cases where uncertainties could not be resolved (i.e., the value of the *k*-coefficient). All of these techniques are aimed at producing more reliable results along with a better understanding of the limitations of the assessment. We note, however, that the use of these analytical improvements in the current study was meant to be illustrative, rather than exhaustive.

*Opportunities for Further Improvement.* The reliability of our results could be improved if new region-wide data sets become available in the future. Determining the degree to which average wetland drainage basin area per area of wetland varies by subunit would help us to better estimate the error resulting from omission of the indicator. Determining the relative weight for scaling density estimates of streams and artificial channels would further reduce the uncertainty of results. The development of additional indices that address other PPR functions—such as water quality and habitat—would contribute to a more complete picture of restoration targets and options. Areas with low priority ranks for flood attenuation (Figure 4) may have considerable restoration value for wildlife habitat or water quality improvement functions. The availability of ranks for multiple functions would allow managers to decide which functions to optimize within a given subunit. Most importantly, further verification of the results, via field studies and testing of assumptions, could provide guidance for future improvements.

## CONCLUSION

A synoptic assessment is a management tool that can assist in making decisions about resource allocation for functional restoration on a regional level. The approach described here for the flood-attenuation function of wetlands in the Prairie Pothole Region is the result of numerous changes that have been implemented since the method was originally introduced. It now has a stronger scientific base, and the calculation of the assessment criterion is better supported with mathematical principles. The results show that our index is generating ranking patterns that seem reasonable. We believe that the results of the synoptic assessment can be a valuable complement to existing wetland restoration and protection programs by providing information for optimizing wetland functions on a regional scale. The biggest obstacle may be incorporating the scheme into current programs and institutions, which operate primarily by restoring opportunistically with little attention to regional functional performance.

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## APPENDIX

Each of the indicators was created by performing one or more of the following operations on data extracted from the source data bases.

- *Pro-rating.* Indicators are derived from data reported by spatial units other than the subunit. They are calculated using the following formula:

$$Value_S = \sum_R \left[ \frac{Value_R \times Area_{RS}}{Area_S} \right]$$

  where $Value_S$ is the indicator value for the subunit, $Value_R$ is the indicator value for the reporting unit (e.g., county), $Area_{RS}$ is the area of the intersection of the reporting unit with the subunit, and $Area_S$ is the area of the subunit. Use of this technique requires the assumption that the indicator value is uniform across the reporting unit. Property value was derived by pro-rating the Census of Agriculture data, reported by county, to subunits.
- *Aggregation.* Indicators are derived from variables that represent presence/absence of a particular attribute (e.g., 1 = ditching present, 0 = ditching absent) at a sample point in the subunit. Aggregation-derived indicators, expressed as a percentage of the subunit, are calculated as follows:

$$Indicator\ Value = \frac{\sum Value_S \times Areal\ Weight}{\sum Areal\ Weight} \times 100$$

  where $Value_S$ is the value of the attribute recorded at a sample point and *Areal Weight* is the number of hectares that the sample point represents. All NRI-based indicators were created by the *aggregation* of attribute values across all sample points in a subunit. Each of the observations in the NRI data base includes an expansion factor, or areal weight, that specifies the number of hectares represented by a sample point. Since each value at a sample point is weighted by its areal representation, the correct interpretation of percentage indicators so derived is ‘‘weighted percentage of all sampled land in the subunit that possesses the attribute’’ (White et al. 1989). Estimates of annual precipitation were generated by the PRISM model and a Geographic Information System was used to clip, aggregate, and average the estimates to derive an average annual value for each subunit.
- *Derivation with Existing Function.* Indicators are created either as mathematical functions of two or more variables, or by linking variables (e.g., land use and hydrologic group) with information from an additional resource (e.g., tables of curve numbers). The curve number was function derived.

In addition, stream density and artificial channel density were standardized to help adjust for differences in scale and permit their addition. The two indicators were standardized by their observed maximum value across all subunits:

$$Standardized\ Indicator = \frac{Indicator}{Indicator_{MAXIMUM}}.$$