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Development of a Multi-Attribute Utility Analysis Model for Selecting Aquatic Plant Restoration Sites in Reservoirs

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PURPOSE: This technical note describes development of a decision support tool that uses multi-attribute utility analysis to aid resource managers in selection of suitable sites for establishing native aquatic vegetation in large, multi-purpose reservoirs.

BACKGROUND: There is increasing awareness that a diverse native aquatic plant community is a valuable, but often missing, component of aquatic habitat in reservoir ecosystems (Smart et al 1996). As a result, there is a need for technical information on methods for establishing native aquatic plants in reservoirs. Because the presence of a diverse native plant community has been shown to enhance weed management efforts, especially in the presence of capable herbivores, native vegetation establishment may also be an important consideration when designing weed biocontrol projects (Grodowitz et al. 2007; Smart et al. 1996). Such is the case for management of submersed aquatic plants; i.e., greatest hydrilla (*Hydrilla verticillata* L. f. Royle) declines occur in the presence of both a diverse native plant assemblage and sustained herbivory by the hydrilla leaf-mining fly (*Hydrellia pakistanae*; Grodowitz et al. 2007).

While progress has been made in developing techniques for native aquatic plant culturing/planting (Dick et al. 2005), only limited information is available describing methodologies for selection of suitable in-lake sites for revegetation efforts. To solve this problem, a decision support model was developed using multi-attribute utility analysis (MAU) (Clemen and Reilly 2004) where revegetation experts initially identified 10 important characteristics to allow for selection of sites suitable for revegetation. For each characteristic, utility functions were developed that incorporate probabilities for site selection across a wide range of site characteristic values and each was weighted using swing-weighting techniques.

Establishment of native aquatic plants is not an exact science, but several common limitations have been documented in many reservoir systems. For instance, protection from herbivory, most notably from the ubiquitous common carp (*Cyprinus carpio*) and semi-aquatic turtles (Emydidae), is usually required to ensure survival of transplants. The use of simple exclosures has proven effective as a means of overcoming this limitation (Dick et al. 2005). For this reason, selection of sites is not dependent strictly upon environmental factors that directly support aquatic plant growth (i.e., sediment type, turbidity, etc.) but also those that affect exclosure construction/placement. For example, sites with steep slopes and excessive existing structure such as rocks or snags may be otherwise well suited for aquatic plant establishment, but these conditions may hamper or even preclude exclosure installation, thereby decreasing the suitability of the site.

MATERIALS AND METHODS: To develop the model, experts were interviewed about site characteristics used to select revegetation areas. Based on these discussions, 10 site characteristics were initially identified. Subsequently, probabilities were assigned to a range of site characteristic values resulting in probability curves or utility functions, which describe site suitability based on

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specific values for the characteristic. Site characteristics were then ranked according to importance. Finally, MAU techniques (Clemen and Reilly 2004) were applied, resulting in site rankings based on the weighted probability of all characteristics.

The model was then calibrated by using the 10 characteristics to rate 15 sites on Lewisville Lake, Texas, during November 2006 and then again during May 2007. For comparison, two experts rated the same sites. In addition to individual comparisons with expert rankings, the two were averaged and the resulting ranks used to compare model output. Expert averages were determined by adding the two expert ranks and then dividing by two. Based on differences in the rankings of the two validation data sets, additional model adjustments were applied to lessen the observed differences between the model and the experts and force the model to a closer approximation of the actual decision process. Ranking of a specific characteristic was given a predetermined weight prior to field testing. However, subsequent discussions on which characteristics played the most important roles in the experts' decision-making process allowed factor-weighting values to be reevaluated and adjusted.

RESULTS AND DISCUSSION: The 10 original characteristics with corresponding in-depth descriptions and rationales for selection are presented in Table 1. Associated selection probabilities identified by the experts are presented in Table 2 for categorical characteristics and in the following six graphs (Figures 1 through 6) for continuous variable characteristics. In most cases, probabilities for continuous variables were determined by interpolation and, where possible, via regression.

The 10 original characteristics can be broken down into four major groupings including sediment, physical, plants, and water characteristics. For example, under the sediment grouping, two characteristics were described including type and depth, both of which are essential for planting success. Under the physical grouping, four characteristics were identified including shoreline gradient, human presence, cage placement, and fetch. The plant groupings mainly involved presence of aggressive natives or exotic plant species known to interfere with revegetation efforts. Finally, the water grouping included water clarity as measured by Secchi disk and water flow, which has been shown to interfere greatly with plant establishment and cage disruption.

Characteristics within each major group were varied and included sediment penetrability, shoreline gradient to the 3-ft depth contour, turbidity (as measured by Secchi disk), and fetch, among others. In addition to probabilities, importance was assigned based upon expert judgment for each characteristic using a weighting factor (as determined by swing-weighting techniques) on a scale from 0 to 100 percent (Table 2). Characteristics with weights greater than 70 percent have a greater bearing on model output and hence, site selection. These included presence of exotics, sediment penetrability, and shoreline gradient.

Table 1. Site selection characteristics used for model version 1.0 with corresponding descriptions, short rationale for their importance, and possible selections and methods for their collection.

Characteristic	Description	Possible Selections
Existing Structure	Excessive structure such as rocks, snags, or made-made objects may hamper placement/anchoring of protective exclosures.	This is determined by estimating the percentage of existing structure at the site.
Sediment Type	The most preferential sediment types are those classified as fine. Unsuitable sediment types can severely limit plant growth.	Four sediment types are recognized including: 1. Fine: soft clay to sandy-clay mix with some organics present 2. Coarse: heavy sand to gravel 3. Muck: unconsolidated with high organic content 4. Rock: hardpan clay to shale, sandstone, or other rock materials
Human Presence	Human presence includes close proximity of marinas, boat docks, parks, hiking trails, etc. The primary concern is exclosure vandalism.	Three levels of human presence are recognized including: 1. High: swimming areas, parks, and marinas/boat docks present 2. Moderate: bulkhead may be present and some housing visible in the immediate area 3. Low: only limited signs of human presence observed
Presence of Exotics	Presence of aggressive exotics (e.g., hydrilla) can be highly detrimental to native plant establishment because they may overwhelm newly planted species.	Three levels of exotic presence are utilized: 1. No history 2. History/propagules: sites where historical accounts indicate their presence or propagules such as plant fragments observed 3. Present: sites where exotics are identified in the immediate area
Storm Water Flow	Increased water flow during rain events might damage protective exclosures, especially at sites where runoff is channeled into narrow areas.	Four possible answers are allowed including none, low, medium, and high. These are determined by visual estimates of potential storm water effects based primarily upon signs of erosion and general topography of the site.

Distance to 3-ft Depth Contour	Shallow runs to the 3-ft depth contour are most suitable for cage placement and may aid in plant expansion.	This was estimated by running three transects perpendicular to the shoreline at equal distances along the site's shoreline and measuring the distance to the 1-ft, 2-ft, and 3-ft depth contours. For each transect, calculate an average using the following formula: For each transect - 3 X 1 ft distance + 1.5 X 2 ft distance + 3 ft distance) / 3. Then average the three transects.
Secchi Depth	Sufficient light penetration into the water column is necessary for growth of submersed and some other plant species. Light penetration is determined by using a standard Secchi disk with depth measured in inches.	Secchi disk depth (in) measured at 3- to 4-ft water depth.
Fetch	Fetch is the distance to the opposite shoreline from the site and represents potential wave and wind energy. Higher energy associated with greater fetch may disrupt plantings and damage exclosures.	A visual estimate of the unimpeded distance to the opposite shore in miles
Sediment Penetrability	Sediment depths that are too shallow (low penetrability) may be too dense to allow for adequate root development while sediments that are too deep (very high penetrability) may be too unconsolidated to allow for adequate anchoring by roots, leaving plants susceptible to washout.	Measure by pressing one end of a 6-ft-long, ¾-in.-diameter schedule 40 PVC pipe into the substrate with 30 to 40 lb pressure (or until the pipe begins to bend). Measure penetration (in inches) at the 1-ft, 2-ft, and 3-ft depth contours along three transects (both ends and the center of the site). The average of these readings gives the sediment penetrability of the site.
% Aggressive Natives in Open Water and Along Shoreline	Some native plants are aggressive (e.g., cattails), can dominate communities, and may hinder establishment of other native species.	This characteristic uses a simple relationship between a visual estimate of the percent cover of aggressive natives in the open water and linear percentage of the occupied shoreline of the site. Aggressive natives include American lotus, cattails, water willow, and giant cutgrass, among others.

Table 2. Categorical site characteristics and associated probabilities for selection used for model version 1.0 development effort.

Characteristic	Answers	Probability of Selection
Sediment Type	Fine	1.00
	Coarse	0.67
	Muck	0.33
	Rock	0.00
Human Presence	High	0.00
	Moderate	0.50
	Low	1.00
Presence of Exotics	Present	0.00
	History/Propagules	0.50
	No history	1.00
Storm Water Inflow	None	1.00
	Low	0.67
	Medium	0.33
	High	0.00

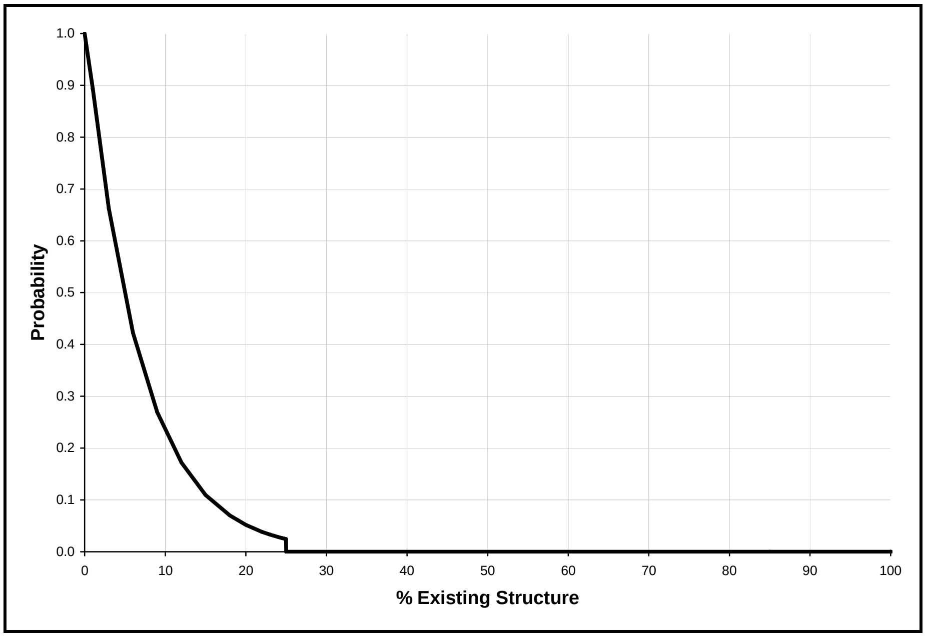

Figure 1. Utility function for percent existing structure at a site.

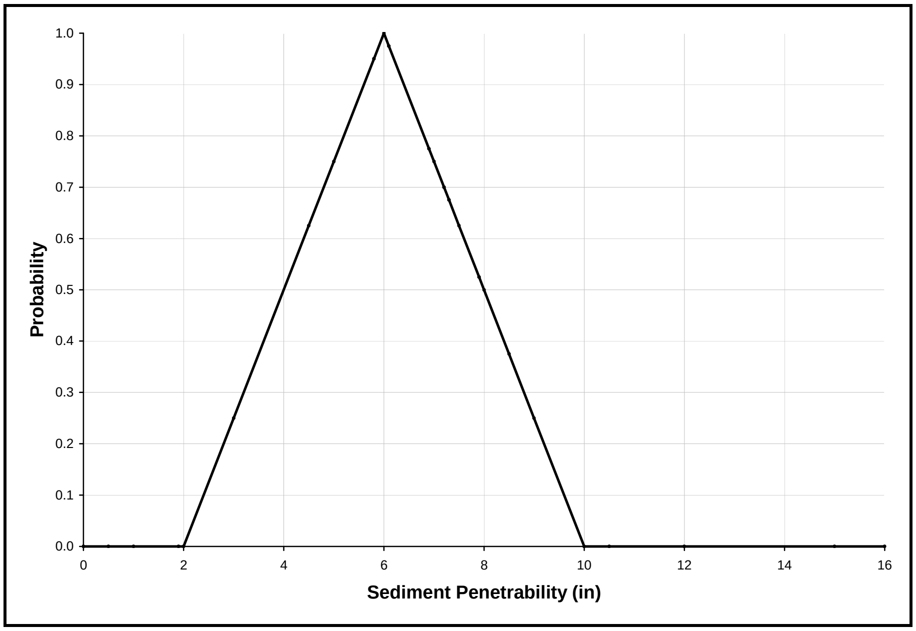

Figure 2. Utility function for sediment penetrability.

Figure 3. Utility function for distance to 3-ft depth contour.

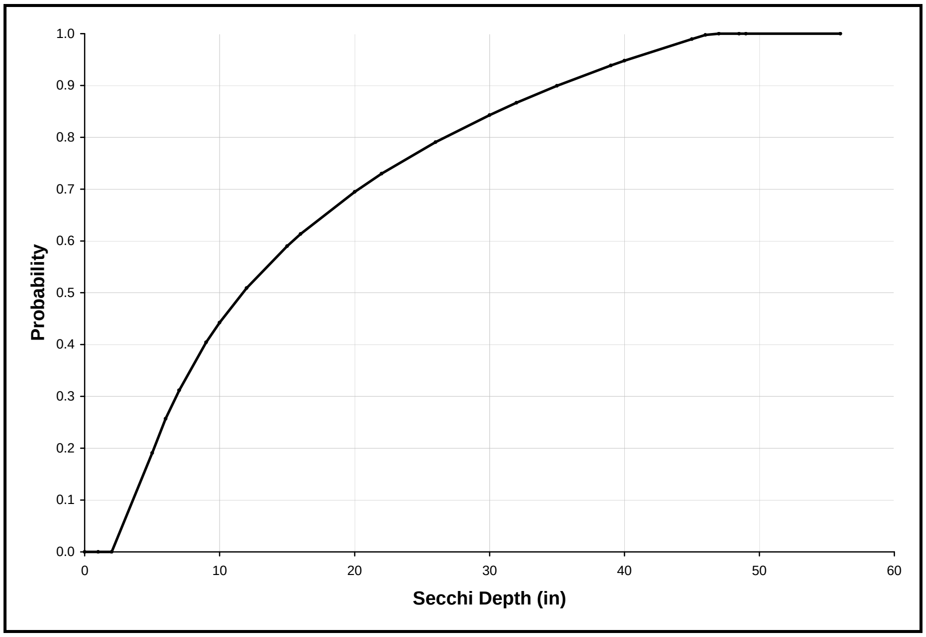

Figure 4. Utility function for light penetration as indicated by Secchi depth.

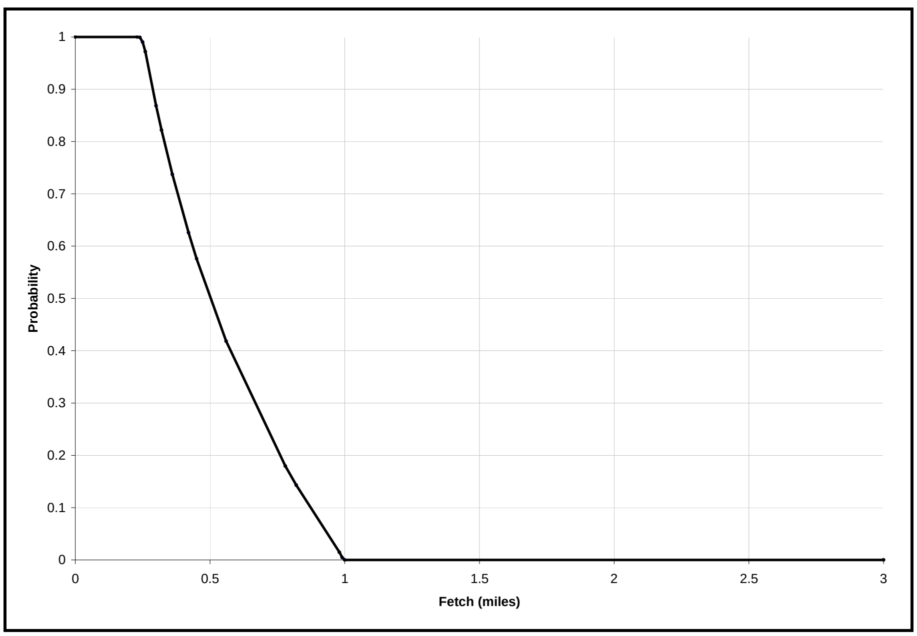

Figure 5: Utility function for fetch or distance (in miles) to opposite shoreline.

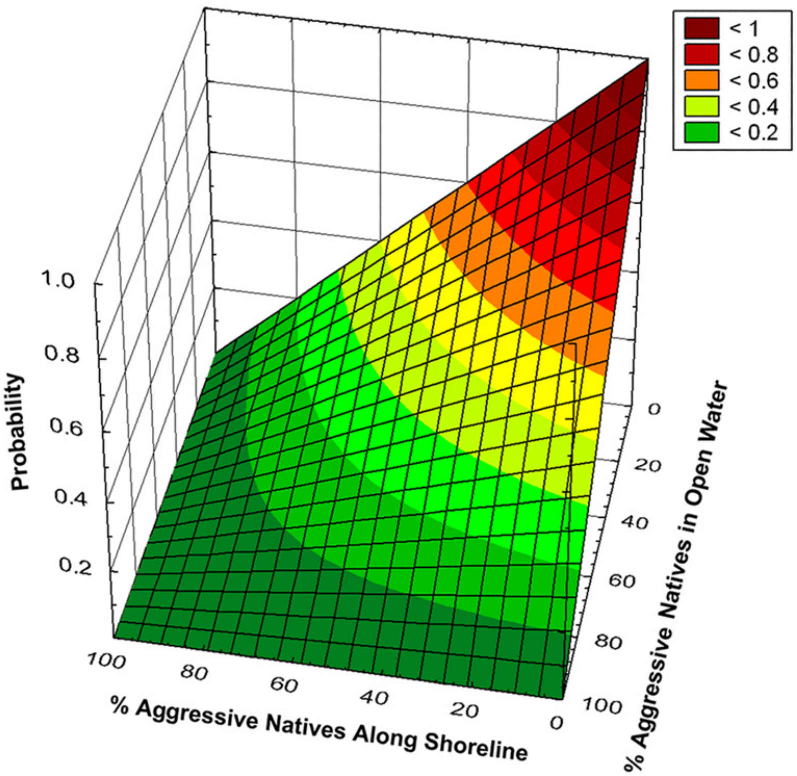

Figure 6. Utility function for the relationship between the percent of the shoreline and percentage of open water occupied by aggressive native plants.

Table 3. Weights of each characteristic used in model version 1.0 and modifications made after examining the November 2006 validation data set.

Characteristics	Weight (%) Ver. 1.0	Weight (%) Ver. 1.1	Weight (%) Ver. 1.2
Presence of Exotics	100	100	100
Sediment Penetrability	80	80	80
Shoreline Gradient	70	70	70
High Water Flow	60	No weight[1]	No weight[1]
Aggressive Natives	50	50	50
Fetch	40	40	60
Human Presence	40	40	70
Existing Structure (Cage Placement)	40	No weight[1]	No weight[1]
Sediment Type	30	30	30
Secchi Disk	10	10	10

[1] "No weight" indicates that these variables were either eliminated from the model or they were evaluated prior to running the model as to eliminate the site from consideration.

The original model (version 1.0) accurately selected the two sites ranked most suitable by the experts in Lewisville Lake (numbers 4 and 14) and the overall expert average (Table 4). However, only the first two sites were selected (not a very viable fit) and there was considerable variation in ordering of the remaining sites. This prompted additional discussions with the experts, resulting in modifications to the model. The most important modification included the addition of situations where sites were eliminated based on specific site values. These included sediment penetrability, where sites were eliminated when penetrability was less than 2 in. and greater than 18 in.; situations where storm water flow was high enough to impact exclosures; sites where existing structure (i.e., trees, rocks, etc.) was great enough to interfere with exclosure placement; presence of rock or very hard substrates; and high human presence. Another change to the model was shifting shoreline gradient so that a 10:1 average slope (30-ft horizontal distance to the 3-ft depth contour) had a probability of only 0.5 in comparison to the maximum value of 1.0 in earlier model designs (Figure 7) – essentially extending the utility function so that maximum suitability of 1.0 occurs with a slope of 20:1. These changes resulted in stronger agreement between the model's top four sites and that of the experts' average rankings. Note that in Table 4, sites highlighted in gray were eliminated under the revised model criteria because of one or more site characteristics.

Table 4. November 2006 aquatic plant establishment suitability ranks of 15 sites (numbered 1 to 15) on Lewisville Lake, Texas. Ranks are given for each expert, the average of the experts' scores, and ranks predicted by the original and final modification to the model based on the first validation data set. Sites shaded in gray were deemed unsuitable based on refined definitions of site suitability characteristics.

Rank	Expert 1	Expert 2	Expert Average	Model – Ver. 1.0	Model – Ver. 1.1
1	14	14	14	14	4
2	4	4	4	4	14
3	10	6	10	11	6
4	8	10	6	15	10
5	1	12	1	9	8
6	6	1	8	10	1
7	11	7	12	12	12
8	13	11	11	13	2
9	12	8	7	1	3
10	7	9	13	3	7
11	5	13	9	5	13
12	15	2	5	6	5
13	3	3	2	7	9
14	9	5	3	8	11
15	2	15	15	2	15

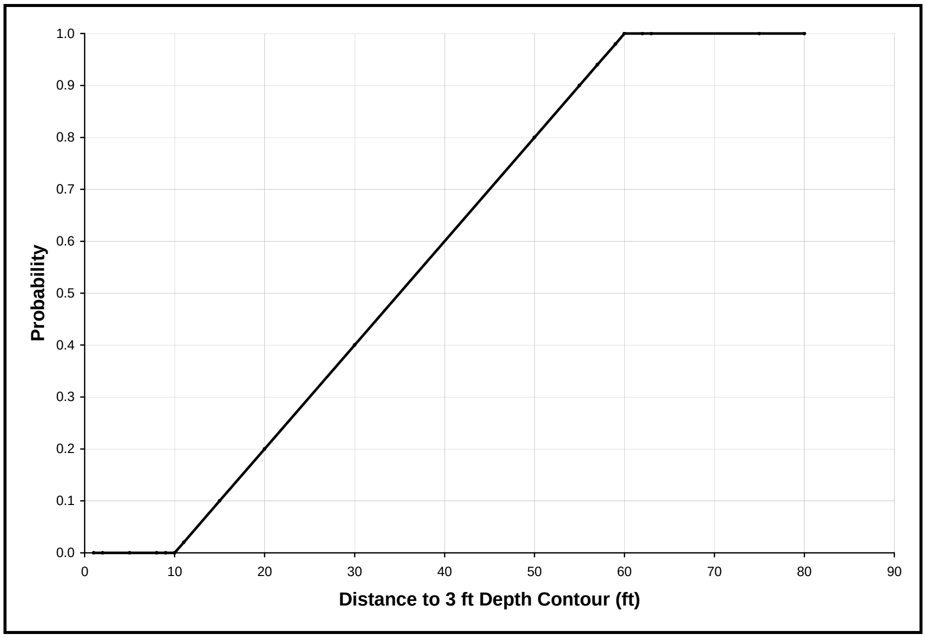

Figure 7. New utility function developed for average slope (dh/dz) and used in model version 1.1. The plotted values are the horizontal distance (dh) to the 3-ft depth contour. The term dz represents depth.

In May 2007 another 15 sites were evaluated on Lewisville Lake, Texas to further validate model output. Based on comparisons to model version 1.1, major discrepancies were noted between expert rankings and model output and further modifications were made to lessen these discrepancies. These included changes in the sediment penetrability utility function and weights assigned to human presence and fetch. In addition, efforts were made to standardize procedures for field measurements of sediment penetrability and shoreline gradients. In this case a series of points that were later averaged by the model resulted in better overall characterization of these variables.

Changes to sediment penetrability included widening the curve shown in Figure 2 to allow minimal selection probabilities at penetrations greater than 1.5 in. (Figure 8) instead of 2.0 in. for the original model. Sediment penetrability appears to be problematic since it has been modified to adjust model output for both validation data sets. Part of the problem is the result of difficulties in accurately measuring penetration that is not biased from person to person and from device to device. More research is warranted in developing a device for consistent, rapid field assessment of sediment penetrability.

Table 3 shows the weights assigned to each characteristic for model version 1.3. Changes from earlier versions were made to the human presence factor by increasing its importance from 40 to 70 percent. In addition, the importance of fetch was increased from a weight of 40 to 60 percent to align its weight more closely to that of what the experts agreed they used when evaluating site suitability.

Based on the latest model adjustments (version 1.2) there is excellent agreement between the experts' average score and model output (Table 5). The top three sites were selected accurately with minor discrepancies in the remaining sites. Two sites did not match with model output (i.e., sites 13 and 7), but reasons for these discrepancies are not readily apparent - more validation data sets are needed for understanding. However, it is important to note that the scores indicate a relatively small disagreement between these sites with an average score difference of only 0.14 (14 percent). This represents relatively minor differences for selection criteria and is probably within the accuracy one could expect from such a model. In essence, it appears that non-technical users could easily use the model to evaluate and group sites in decreasing order of desirability. This would allow users to select the most favorable sites and be reasonably certain that these would likely also be selected by the experts.

Table 5. Ranks for each of 15 sites (numbered 1 to 15) on Lewisville Lake, Texas (based on May 2007 validation data set) examined for suitability for aquatic plant revegetation. Ranks are given for the average of the experts' scores and the ranks predicted by model version 1.2. Probability scores as output by the model are also provided for comparison. Sites shaded in gray were eliminated based on site characteristics.

Rank	Expert Average	Model – Ver. 1.2	Score
1	14	14	0.80
2	2	2	0.78
3	8	8	0.77
4	11	13	0.69
5	1	11	0.68
6	15	12	0.68
7	10	1	0.67
8	7	15	0.65
9	12	10	0.64
10	9	6	0.58
11	13	7	0.53
12	6	3	0
13	3	4	0
14	4	5	0
15	5	9	0

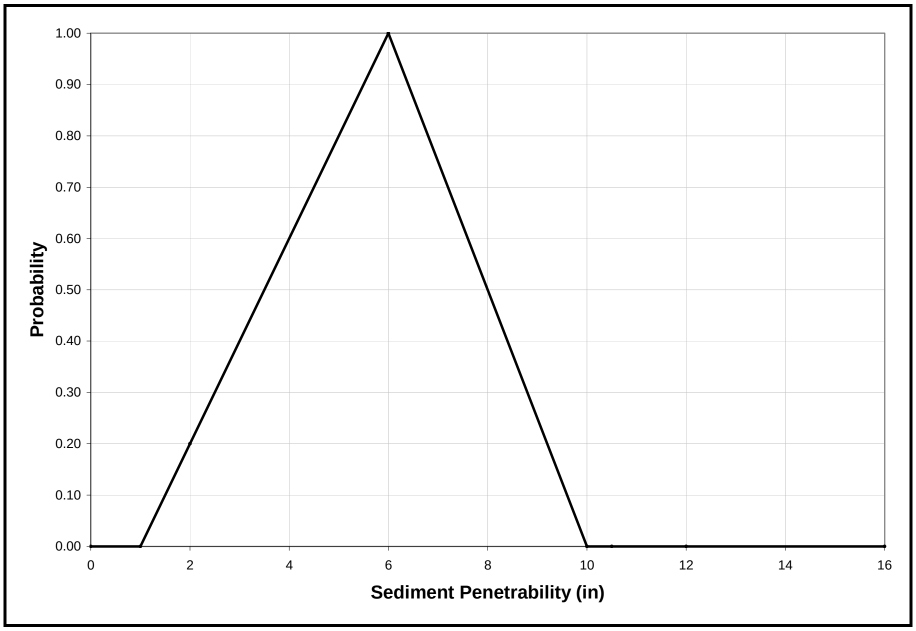

Figure 8. Sediment penetrability utility function where the lower limit was shifted to 1.5 in. after the second validation data set comparisons.

SUMMARY AND FUTURE DIRECTION: More work is warranted. Additional validation data sets from different geographical regions and different reservoir types are needed to further test the validity of the model and allow for continued refinement. Several validation data sets from more northern large reservoir systems have been collected and are waiting to be processed with results incorporated into more recent model versions. Additional MAU models are also needed to allow for the selection of suitable protective exclosures and plant species depending on a variety of site characteristics. Additional work is needed as well on developing efficient and accurate tools for measuring sediment penetrability, determined by the experts to be an important site characteristic necessary for successful revegetation efforts. Finally, the system will be incorporated into a web-based tool allowing efficient and easy access for non-technical users.

In addition, while these techniques provide a framework for revegetation site selection, the output is based solely on expert opinion, which may be questionable. Hence, the final model version should be used to examine expert opinion (and therefore model value) by evaluating the success of plant establishment efforts conducted at sites deemed suitable by the model.

Based on this work, MAU techniques should enable non-technical personnel, using easily measured site characteristics, to effectively select appropriate sites for aquatic plant restoration.

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