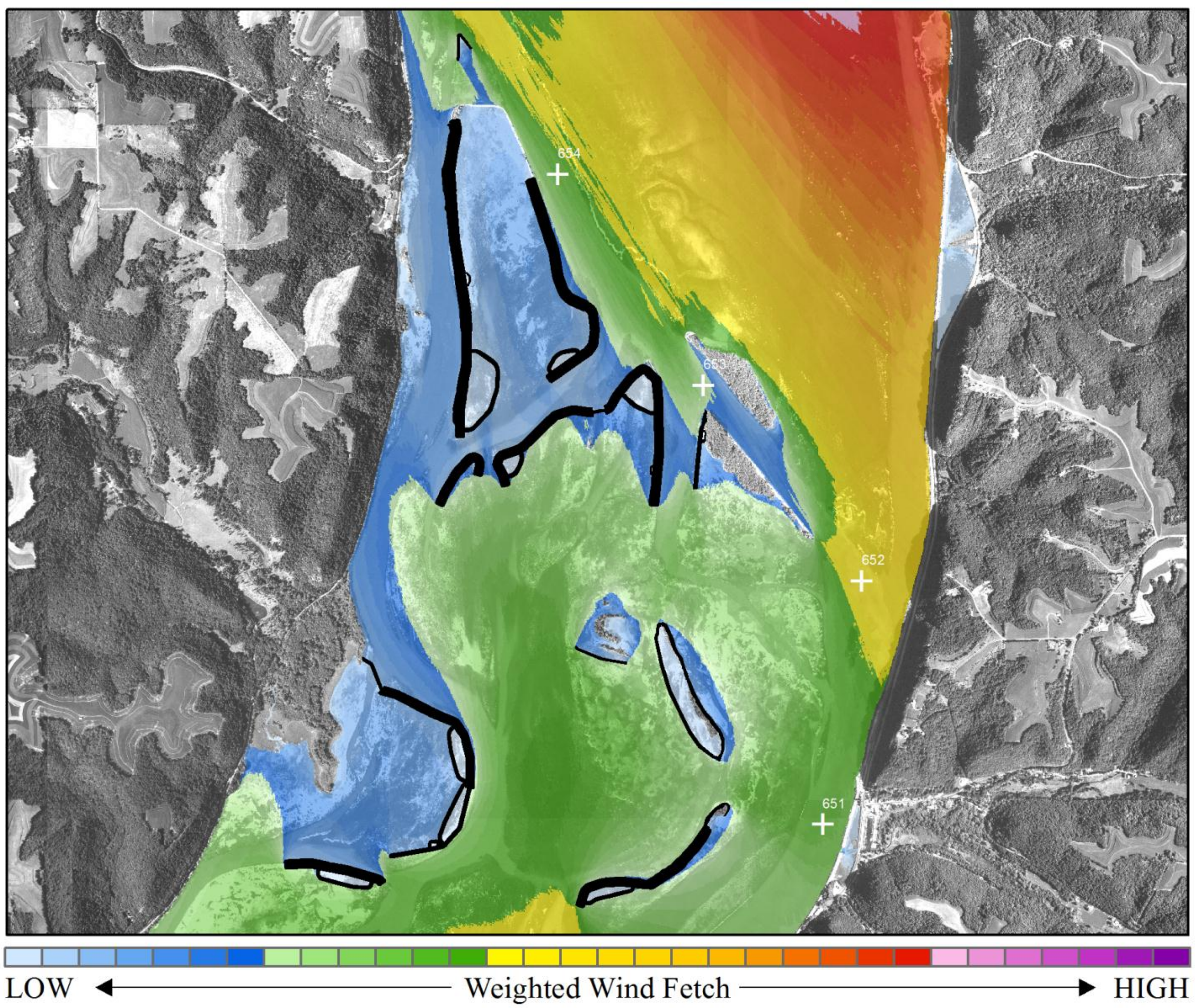
U.S. Department of the Interior
U.S. Geological Survey

Application of Wind Fetch and Wave Models for Habitat Rehabilitation and Enhancement Projects – 2012 Update



Suggested citation:

Rohweder, J., Rogala, J. T., Johnson, B. L., Anderson, D., Clark, S., Chamberlin, F., Potter, D., and Runyon, K., 2012, Application of Wind Fetch and Wave Models for Habitat Rehabilitation and Enhancement Projects – 2012 Update. Contract report prepared for U.S. Army Corps of Engineers' Upper Mississippi River Restoration – Environmental Management Program. 52 p.

This study was funded and prepared for the U.S. Army Corps of Engineers' Upper Mississippi River Restoration - Environmental Management Program

Application of Wind Fetch and Wave Models for Habitat Rehabilitation and Enhancement Projects – 2012 Update

By

Jason Rohweder
James Rogala
Barry Johnson

U.S. Geological Survey
Upper Midwest Environmental Sciences Center
2630 Fanta Reed Road
La Crosse, Wisconsin 54603

And

Dennis Anderson
Steve Clark
Ferris Chamberlin
David Potter

U.S. Army Corps of Engineers
St. Paul District
190 5th Street East, Suite 401
St. Paul, Minnesota 55101-1638

And

Kip Runyon

U.S. Army Corps of Engineers
St. Louis District
1222 Spruce Street
St. Louis, Missouri 63103-2833

December 2012

Cover image is a depiction of management scenario 4, weighted wind fetch results for the Harper's Slough Habitat Rehabilitation and Enhancement Project in Navigation Pool 9, Upper Mississippi River System. The background image is a grayscale version of a 2009 National Agriculture Imagery Program aerial photograph.

Contents

Tables

Figures

Abstract

Models based upon coastal engineering equations have been developed to quantify wind fetch length and several physical wave characteristics including significant height, length, peak period, maximum orbital velocity, and shear stress. These models, developed using Environmental Systems Research Institute's ArcGIS 10.0/10.1 Geographic Information System platform, were used to quantify differences in proposed island construction designs for the Harper's Slough Habitat Rehabilitation and Enhancement Project in the U.S. Army Corps of Engineers St. Paul District. Weighted wind fetch was calculated using land cover data supplied by the Upper Mississippi River Restoration – Environmental Management Program's (UMRR-EMP) Long Term Resource Monitoring Program (LTRMP) for each island design scenario. Figures and graphs were created to depict the results of this analysis. The difference in weighted wind fetch from existing conditions to each potential future island design was calculated. A simplistic method for calculating sediment suspension probability was also applied. This analysis involved determining the percentage of days that maximum orbital wave velocity calculated over the growing seasons of 2008-2012 exceeded a threshold value taken from the literature where fine unconsolidated sediments may become suspended. This analysis also evaluated the difference in sediment suspension probability from existing conditions to the potential island designs. Bathymetric data used in the analysis were collected from the UMRR-EMP LTRMP and wind direction and magnitude data were collected from the National Oceanic and Atmospheric Administration, National Climatic Data Center.

Key words

Upper Mississippi River Restoration, Environmental Management Program, Long Term Resource Monitoring Program, Habitat Rehabilitation and Enhancement Project, Wind Fetch, Sediment Suspension Probability, Significant Wave Height, Wave Length, Spectral Peak Wave Period, Maximum Orbital Wave Velocity, Shear Stress, Harper's Slough, Geographic Information System

Introduction

The U.S. Army Corps of Engineers (USACE) tasked the Upper Midwest Environmental Sciences Center (UMESC) of the U.S. Geological Survey (USGS) with upgrading geospatial models developed to quantify wind fetch length and calculate several physical wave characteristics that can be altered by Habitat Rehabilitation and Enhancement Projects (HREP). The models originally developed in ESRI ArcGIS software version 9.3 were upgraded to be able to operate using the most current version (10.0/10.1). Within the wind fetch model a feature was added to allow the automated calculation of weighted wind fetch results. Features were also added to the wave model to allow the automated calculation of sediment suspension probability and also a revised water density parameter which accepts a raster surface as input. A new model was also developed to allow the user to delineate the area of potential effects based on the magnitude of difference between alternative project design results.

Using the upgraded models, UMESC was then asked to perform specific analyses to model weighted wind fetch and also calculate the probability that fine unconsolidated particles would be suspended due to wind-generated waves for Harper's Slough HREP within the St. Paul

District of the USACE. Wave output data were created with algorithms that used wind fetch, wind direction, wind speed, and water depth as primary input parameters. The results of these analyses depict how wind fetch and fine unconsolidated particle suspension are affected by alternative HREP management scenarios, allowing managers to quantify gains or losses between these proposed management scenarios.

Toolbox Installation

To use the wind fetch and wave models, there are some preliminary steps that need to be followed for them to function correctly on the computer. First are a few software requirements that need to be met:

1. ArcGIS 10.0/10.1
2. A Spatial Analyst License
3. Python 2.4 or more recent (Automatically installed with ArcGIS)
4. Pywin32 (Python for Windows extension)

Pywin32 allows Python to communicate with COM servers such as ArcGIS, Microsoft Excel, Microsoft Word, etc. Python scripting in ArcGIS cannot work without this extension. This extension can be downloaded at:

http://sourceforge.net/projects/pywin32/files/pywin32/

Once these software requirements are met, the user needs to:

1. Extract the .zip file "Waves2012.zip" to a project directory on your hard drive (Figure 1)
2. Open ArcMap 10.0/10.1 and activate ArcToolbox if not already activated (Geoprocessing -> ArcToolbox)
3. Right-click inside the ArcToolbox panel and select Add Toolbox… (Figure 2)
4. Open the extracted folder *Waves2012* and click on the Waves2012 toolbox icon.

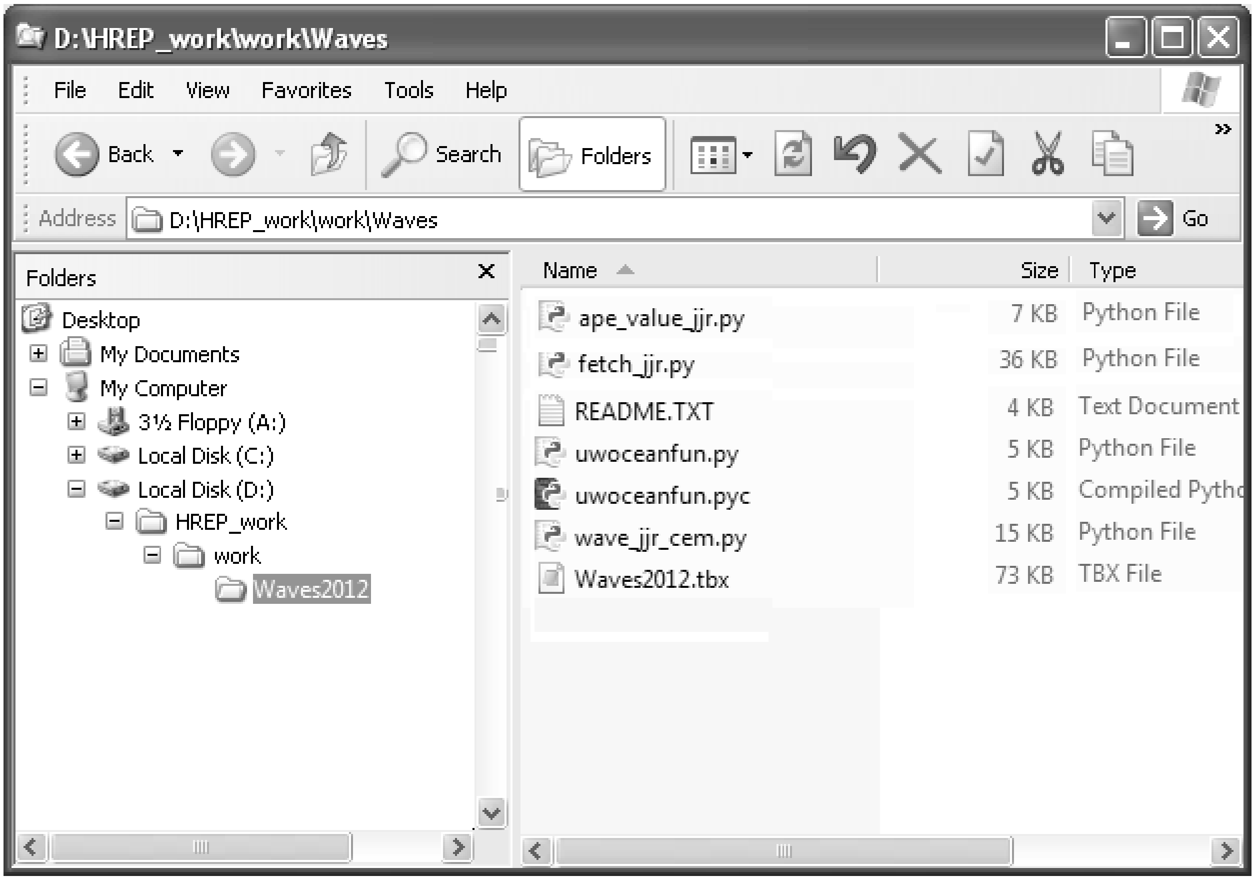


Figure 1. Windows Explorer view of extracted files

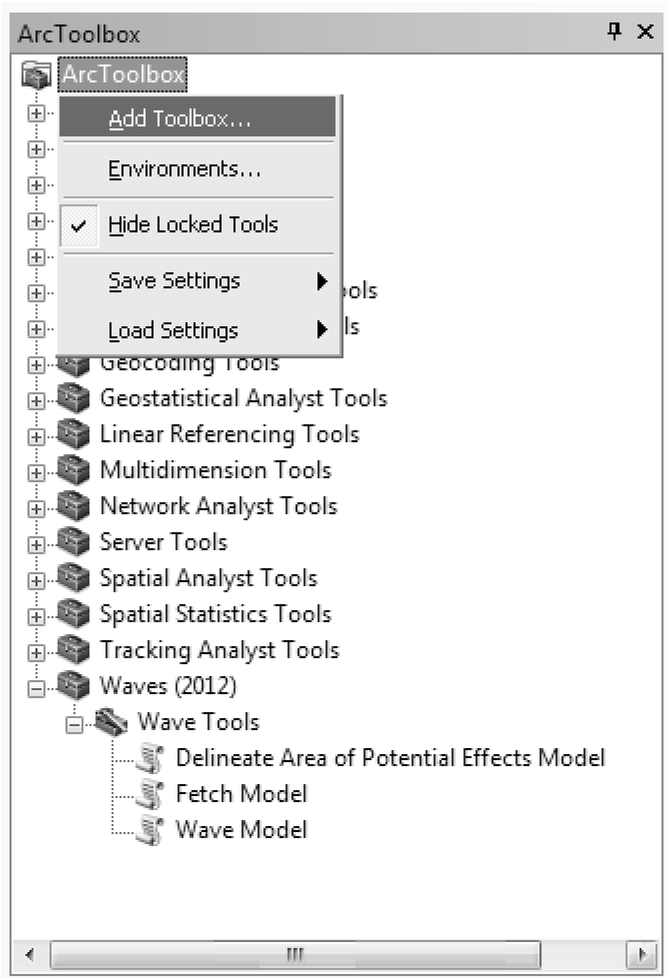


Figure 2. ArcToolbox view of wave tools

You should now be ready to run the wind fetch and wave models within the Waves toolbox (Figure 3).

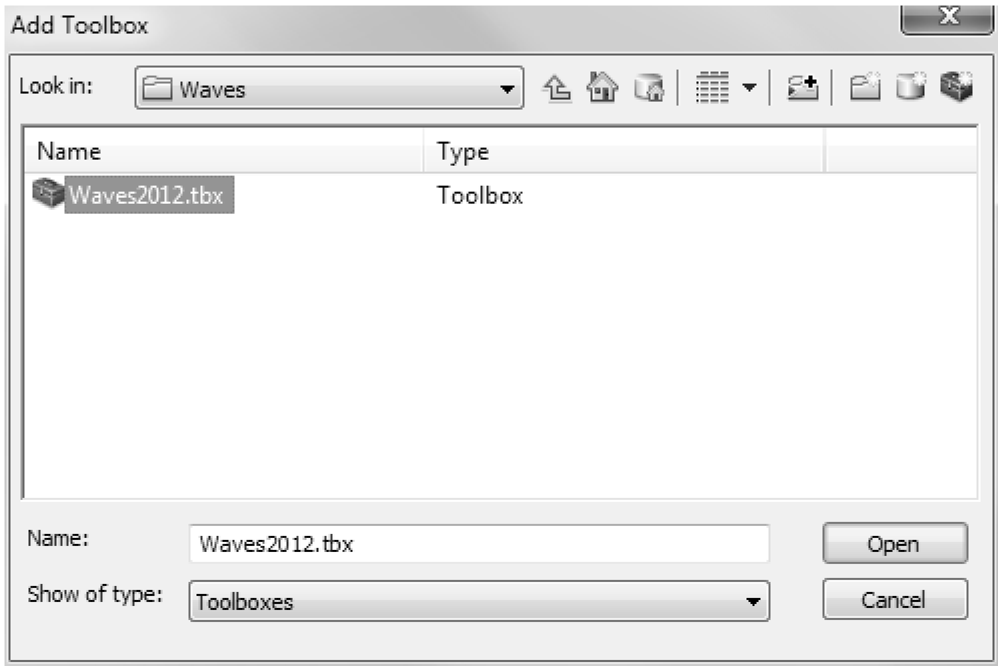


Figure 3. Windows dialog for selecting Waves2012 toolbox

Wind Fetch Model

Introduction

Wind fetch is defined as the unobstructed distance that wind can travel over water in a constant direction. Fetch is an important characteristic of open water because longer fetch can result in larger wind-generated waves. The larger waves, in turn, can increase shoreline erosion and sediment resuspension. Wind fetches in this model were calculated using scripts designed by David Finlayson, U. S. Geological Survey, Pacific Science Center, while he was a Ph.D. student at the University of Washington (Finlayson 2005). This method calculates effective fetch using the recommended procedure of the Shore Protection Manual (USACE 1984). In Inland waters (bays, rivers, lakes, and reservoirs), fetches are limited by land forms surrounding the body of water. Fetches that are long in comparison to width are frequently found, and the fetch width may become quite important, resulting in wave generation significantly lower than that expected from the same generating conditions over more open waters (USACE 1977).

Methodology

The wind fetch scripts that the model operates from were developed by Finlayson using the Python scripting language and were originally designed to run on the ArcGIS 9.0 (Environmental Systems Research Institute ([ESRI] Redlands, California) Geographic Information System (GIS) platform. However, in 2008, these scripts were updated in order to operate using the most current ArcGIS revision at that time, 9.2 and now are being updated again in order to operate using the most current ArcGIS version, 10.0/10.1. The model was also modified to more efficiently meet the needs of USACE planning personnel. These modifications give the model the ability to calculate wind fetch for multiple wind directions based upon a text file listing individual compass directions (first number column) and also to calculate a weighted wind fetch output if individual wind direction weightings are supplied (second number column). Figure 4 displays a portion of an example text file of wind directions and direction weighting percentages used for this example model. In the first number combination of Figure 4, the sequence "360, 2.8" denotes that 2.8% of wind is predicted to come from the direction of 360 degrees (North).

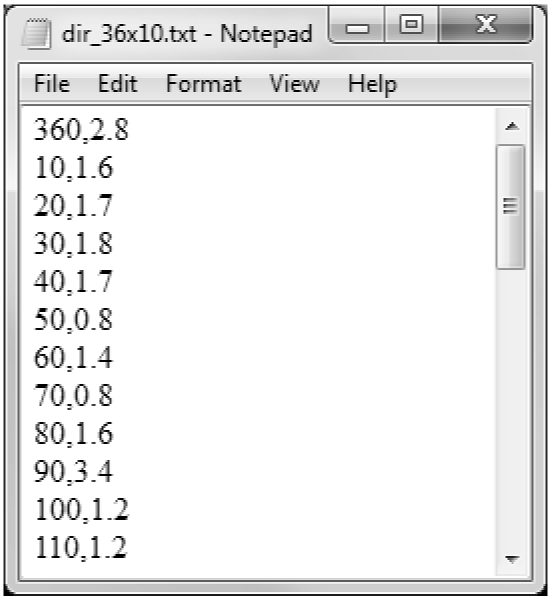


Figure 4. Sample text file with fetch direction and direction weighting input data

Figure 5 shows an example of the wind fetch model's input dialog within ArcGIS 10.0. The "Land Raster" input parameter is the full path to an ArcGIS raster dataset where each cell in the raster is evaluated as being "land" if the value > 0.0 and "water" if the value of that cell is = 0.0. When using the fetch model, it is important for the land raster to have all areas designated as "water" be enclosed by cells designated as "land." "Unbounded fetches are an artifact of calculating fetch lengths on a raster that does not completely enclose the body of water. The length calculation extends only to the edge of the raster. Such cells represent a minimum fetch length only, and the fetch could be much larger depending on how much of the water body is missing. To easily identify these cells, Fetch returns a negative fetch length for unbounded fetches (Finlayson 2005)."

Scale plays an important role with respect to the land raster. If the cell size of the land raster becomes too large you risk the possibility that thin (approximating the width of the cell) islands will be lost. However, if the cell size of the land raster is too fine, the user may experience slow processing times and dramatically enlarged file sizes. There may be trial-and-error involved by the user to identify a land raster spatial resolution that balances the desire for detail with the dilemma of minimizing computer operating time and hard disk space.

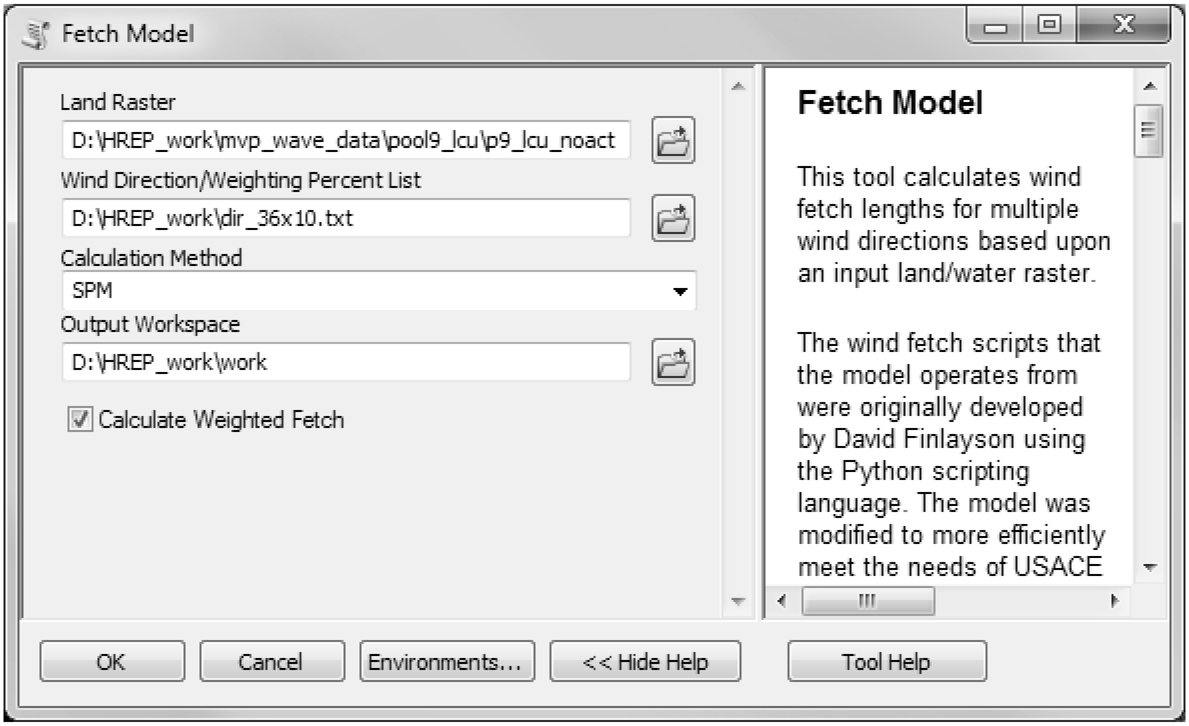


Figure 5. Fetch model dialog window prompting user input

When the model is initiated, the “Calculation Method” defaults to “SPM”. The SPM acronym designates that this process uses the preferred methodology for calculating effective fetch as described in the Shore Protection Manual. This method spreads nine radials around the desired wind direction at three-degree increments. The resultant wind fetch is the arithmetic mean of these nine radial measurements. There have been two other calculation method options added, “Single” calculates wind fetch on a single radial and “SPM-restricted” calculates wind fetch using the average of five radials, spread three degrees apart. This more restricted method for calculating effective fetch may be more appropriate when the habitat project of interest has long and narrow fetches (Smith 1991). Figure 6 shows an example of how fetch is calculated for one reference raster cell based upon a reference bearing of zero degrees using the three methods within the wind fetch model.

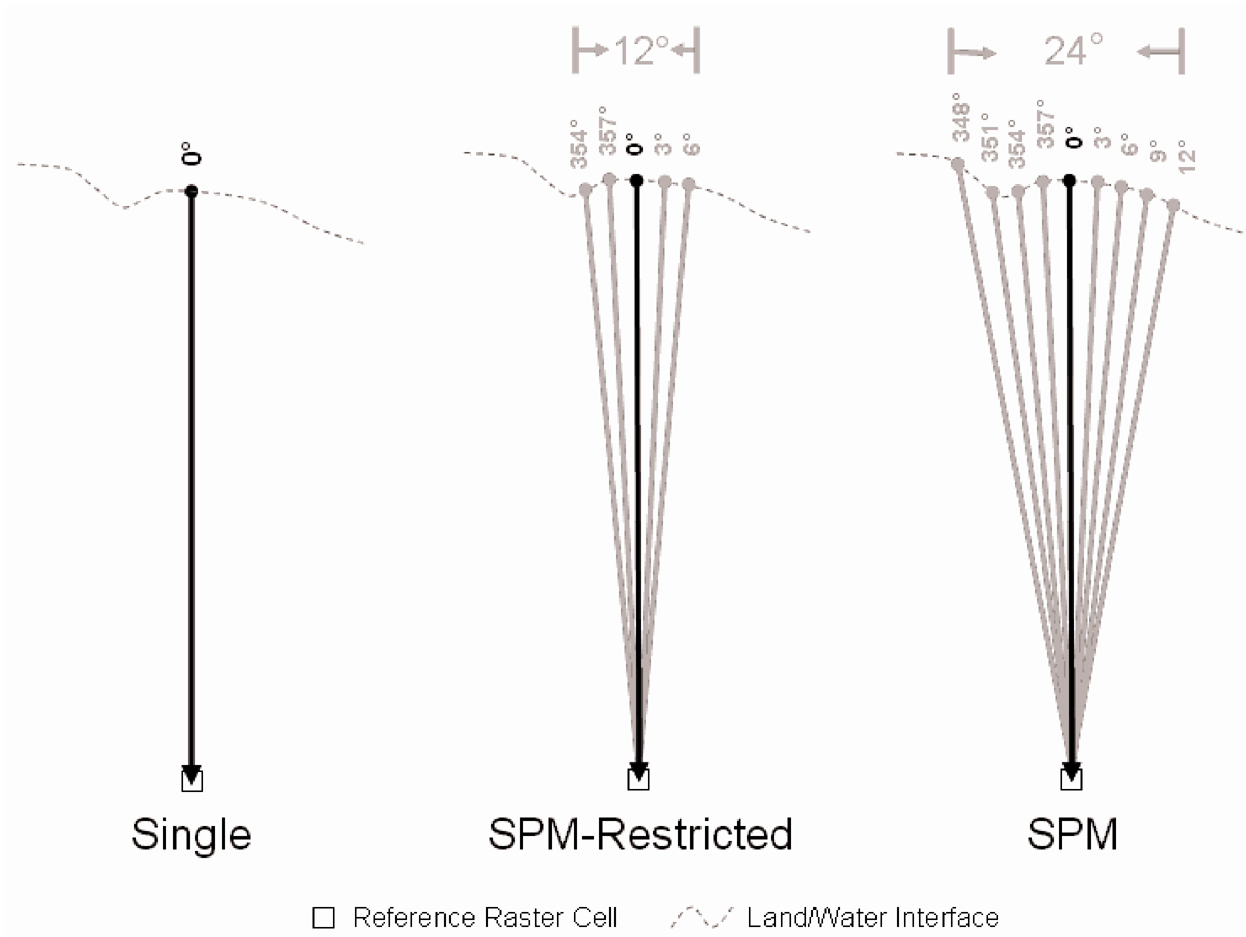


Figure 6. Example depictions of wind fetch calculated using the different methods

For the wind fetch analyses used within this report the SPM Method is used. The larger arc (24 degrees) probably represents a more real-world condition for the areas evaluated. Available wind data are frequently reported to the nearest ten degree. Wind direction is not consistent and varies even over the maximum two-minute average wind speed. It should be noted that the wind-fetch model ignores near-shore processes such as shoaling, breaking, reflection, refraction, and diffraction. The magnitude and importance of these processes in shallow backwaters has not been determined.

Each of the individual directional wind fetch outputs are saved to a specified “Output Workspace” and named according to their respective wind direction (prefixed with the letters “fet_” and ending with the three-digit wind direction (e.g., “180”)). These fetch outputs are saved as ArcGIS Grid raster data sets and thus are easily incorporated into other models including those used to predict biological response.

A checkbox was also added to allow the user to specify if a weighted wind fetch product should be created. To calculate weighted wind fetch, the individual fetch raster outputs are multiplied by the weightings specified in the wind direction/weightings percent list and then summed. The total of the weightings within the second column of the text file must equal 100. An error will be generated if the user checks this box and wind direction weightings are missing from the input text file.

Before the model can be executed, a scratch workspace must be designated using the "Environments…" button. It is suggested that the user select a workspace (folder) for this parameter and not use a geodatabase (.gdb) as is sometimes suggested in the ArcGIS literature. There have been issues with the model not operating when a geodatabase or an invalid workspace was selected. The user should also use input files on their local hard drive and set the output workspace as a folder on the local hard drive.

Figure 7 gives an example depiction of wind fetch calculated using the Single, SPM-Restricted, and SPM calculation method for the Swan Lake HREP area using winds from 0 degrees and 140 degrees using the U. S. Fish and Wildlife Service (USFWS) sample management scenario.

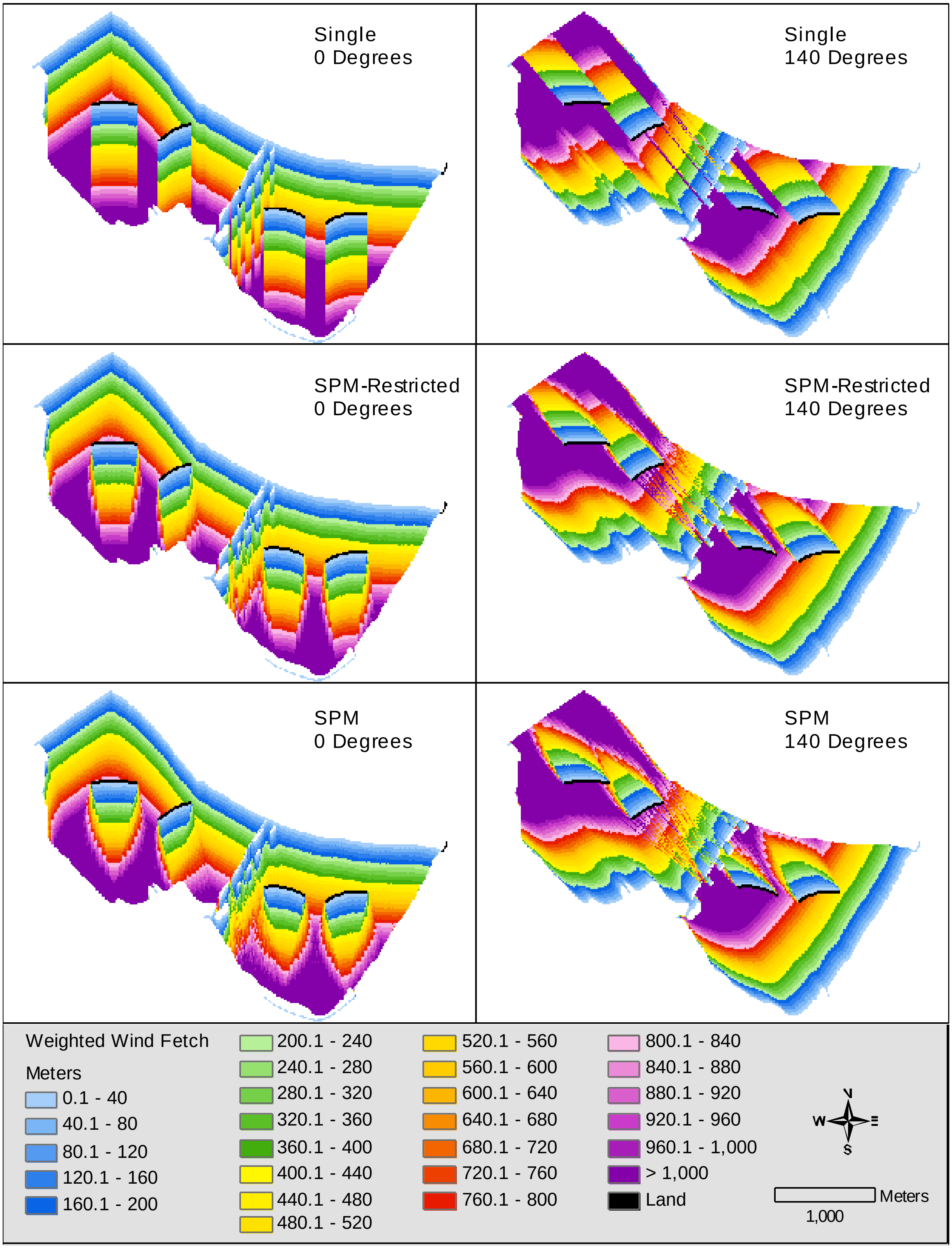


Figure 7. Sample wind fetch model results for Swan Lake Habitat Rehabilitation and Enchantment Project

Wind Fetch Model Validation

A validation was performed in 2008 to compare the results created using the wind fetch model described previously with another method of calculating wind fetch, which will be termed the measured-line method. The measured-line method of calculating fetch involved using trigonometric calculations to create vector lines within ArcGIS from a specific point within the area of interest. These lines were created using nine radials spread around the prevailing wind direction at three degree increments (SPM method of fetch calculation). The point from which the fetch was calculated was selected randomly within the area of interest, in this example Swan Lake HREP using the USFWS proposed island design. Next, the prevailing wind direction was then randomly selected for each fetch reference point. Lines were then generated using trigonometry and their length was calculated using ArcGIS. Figure 8 displays the location of each fetch reference point and the resulting lines that were generated showing the relative length and compass direction of the lines that are used to quantify the fetch using the measured-line fetch method.

The wind fetch was then calculated for the same area of interest using the same prevailing wind directions using the wind fetch model. The calculated wind fetch was then ascertained by identifying the cell within the area of interest that coincided with the reference point as determined earlier. Table 1 shows a breakdown of the measurements calculated using the measured-line method of fetch calculation versus the values obtained using the wind fetch model. We see a difference of less than 10 meters in the average fetch distance using the measured-line method and the results obtained using the wind fetch model. This is relevant since we are basing the wind fetch model calculations off of a 10-meter cell size input dataset.

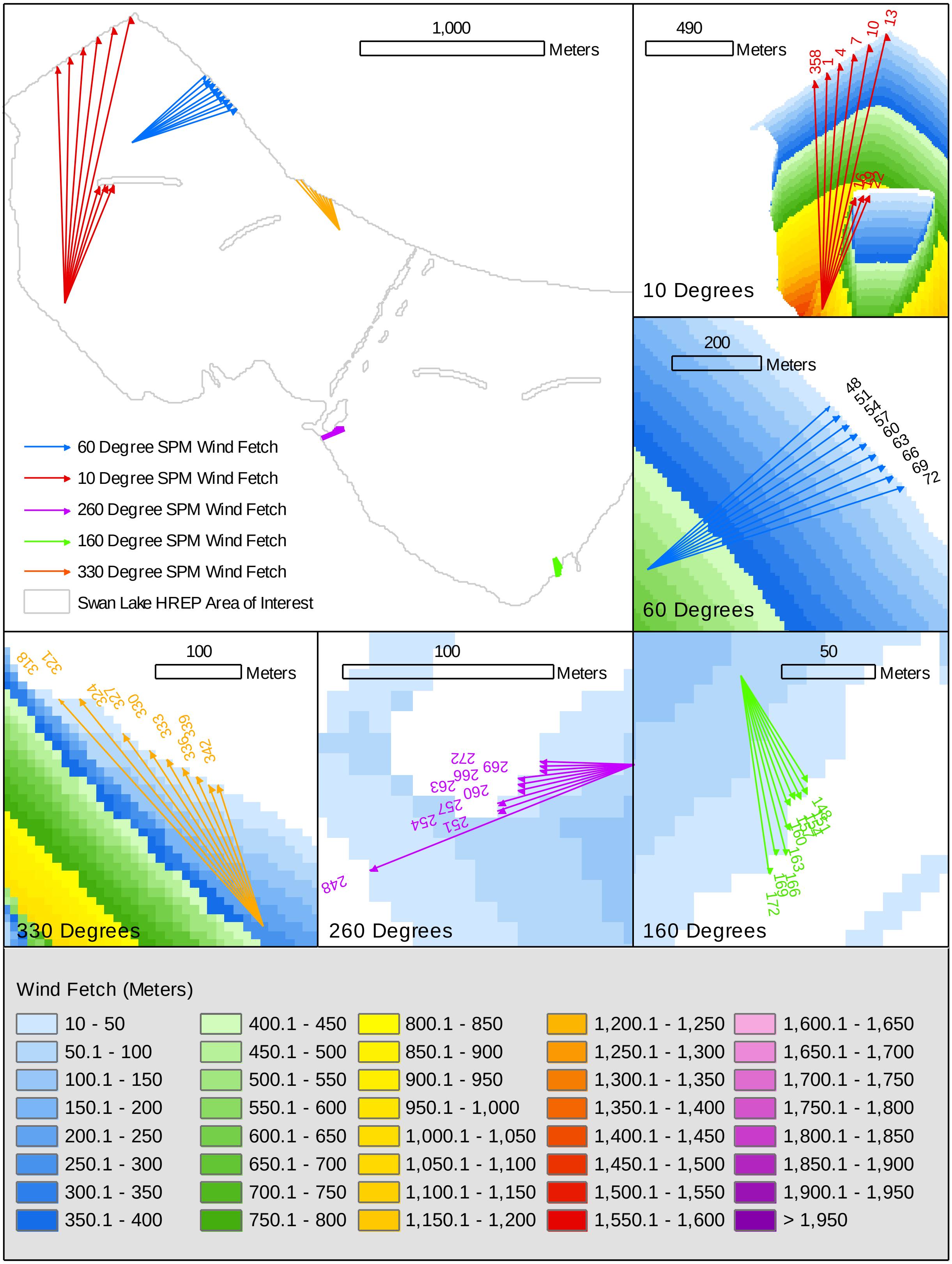


Figure 8. Wind fetch cell locations and prevailing wind directions used for model validation

Table 1. Tabular summarization of wind fetch measurements calculated using the two different methods

	Fetch Reference Angle				
	10°	**60°**	**160°**	**260°**	**330°**
Measured-Line Fetch (Reference Angle - 12°)	1289.42	545.48	66.05	134.82	356.59
Measured-Line Fetch (Reference Angle - 9°)	1335.20	548.21	72.19	68.75	340.99
Measured-Line Fetch (Reference Angle - 6°)	1388.38	550.05	72.32	67.62	278.12
Measured-Line Fetch (Reference Angle - 3°)	1455.85	554.45	70.61	56.45	244.43
Measured-Line Fetch (Reference Angle)	1518.06	560.03	73.10	55.85	225.17
Measured-Line Fetch (Reference Angle + 3°)	1595.90	566.77	85.51	55.41	207.63
Measured-Line Fetch (Reference Angle + 6°)	660.59	574.68	97.91	45.11	191.56
Measured-Line Fetch (Reference Angle + 9°)	682.17	583.77	96.78	45.01	176.74
Measured-Line Fetch (Reference Angle + 12°)	695.65	598.67	106.03	45.03	173.49
Measured-Line Fetch (Average for 9 radials)	**1180.14**	**564.68**	**82.28**	**63.78**	**243.86**
Wind Fetch Model Results (Average for 9 radials)	**1188.00**	**572.00**	**88.00**	**69.00**	**253.00**
Difference (Meters)	7.86	7.32	5.72	5.22	9.14
Percent Difference	0.67%	1.30%	6.96%	8.18%	3.75%

Two-sample permutation test for locations

A permutation test was performed to determine whether the observed pattern (the wind fetch model results) happened by chance. Because sample sizes for the wind fetch model validation results were small ($n = 5$), A non-parametric two-sample permutation test for locations was conducted (Manly 1997). This randomization test works simply by enumerating all possible outcomes under the null hypothesis, i.e., that no differences exist between the wind fetch model results and the measured lines of wind fetch, and then compares the observed wind fetch model results against this permuted distribution (based upon 5,000 permutations of the data). Results indicated no difference between the wind fetch model results and the measured-line fetch ($L = 7.053$, $p = 0.9744$).

In Figure 9 below, the thick black line denotes the mean difference between the wind fetch model results and the measured lines of wind fetch relative to the distribution of all possible differences.

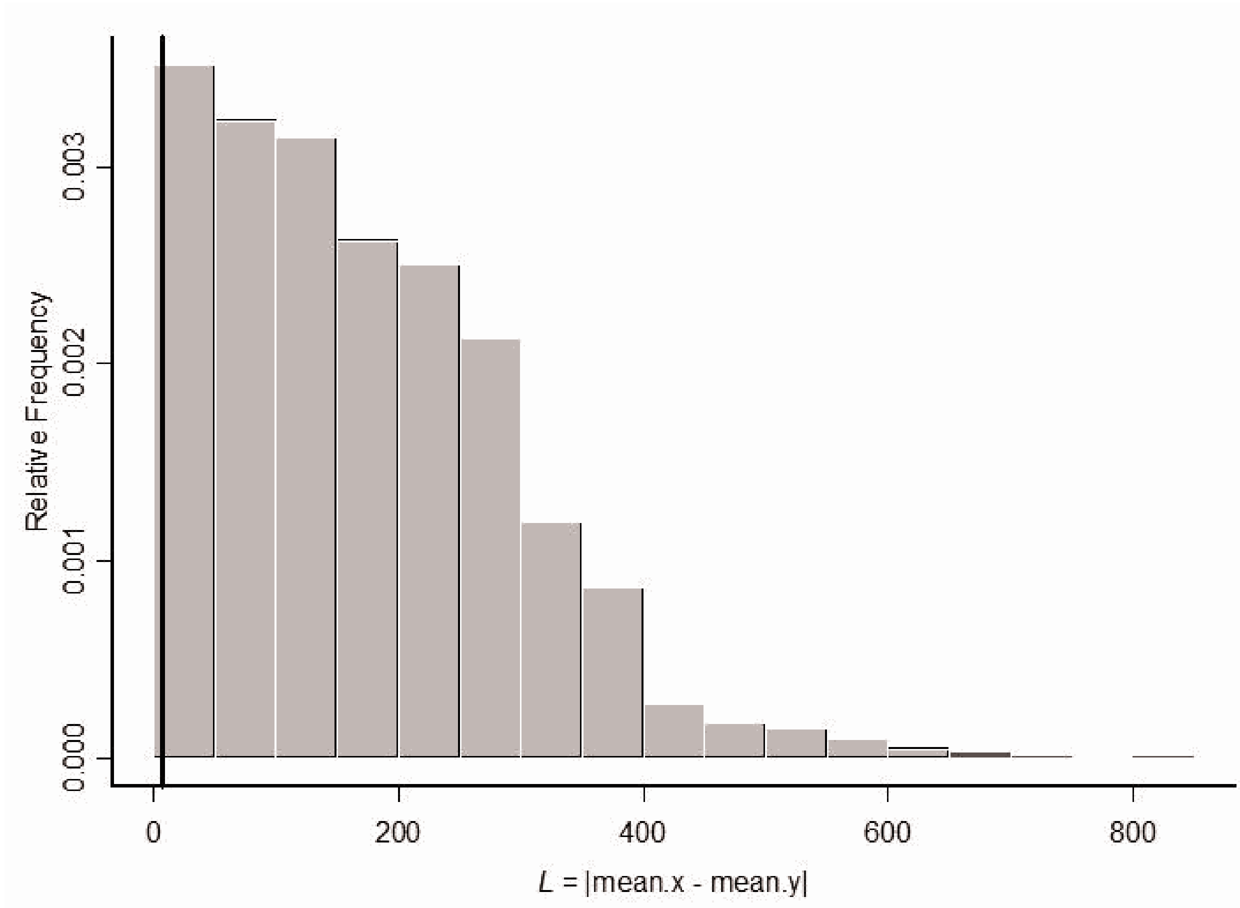


Figure 9. Results for Two-sample permutation test for locations

Wave Model

Introduction

A model was constructed within ArcGIS to create several useful wave outputs. Significant wave height, wave length, spectral peak wave period, shear stress, and maximum orbital wave velocity are all calculated using this model. Figure 10 shows what the wave model dialog looks like for the user. Required inputs to the model include a directory of pre-created wind fetch outputs for the area of interest, a text file (.txt) of wind data (Figure 11), the height aboveground in meters of the anemometer used to collect wind data, a checkbox to denote whether wind measurements were calculated overland, the density of water, a raster with bathymetric values for the area of interest, the threshold for maximum orbital wave velocity to use when calculating sediment suspension probability, a workspace to store derived outputs and a checkbox to denote whether a raster should be developed indicating the percentage of days that sediment is predicted to be suspended based upon the maximum orbital wave velocity selected. The text file of collected wind data is contained as comma-delimited numeric values consisting of the wind direction, followed by the wind speed, and finally the date of data collection expressed as a two-digit year, followed by a two-digit month, and finally the two-digit day (e.g. 020421 = April 21, 2002).

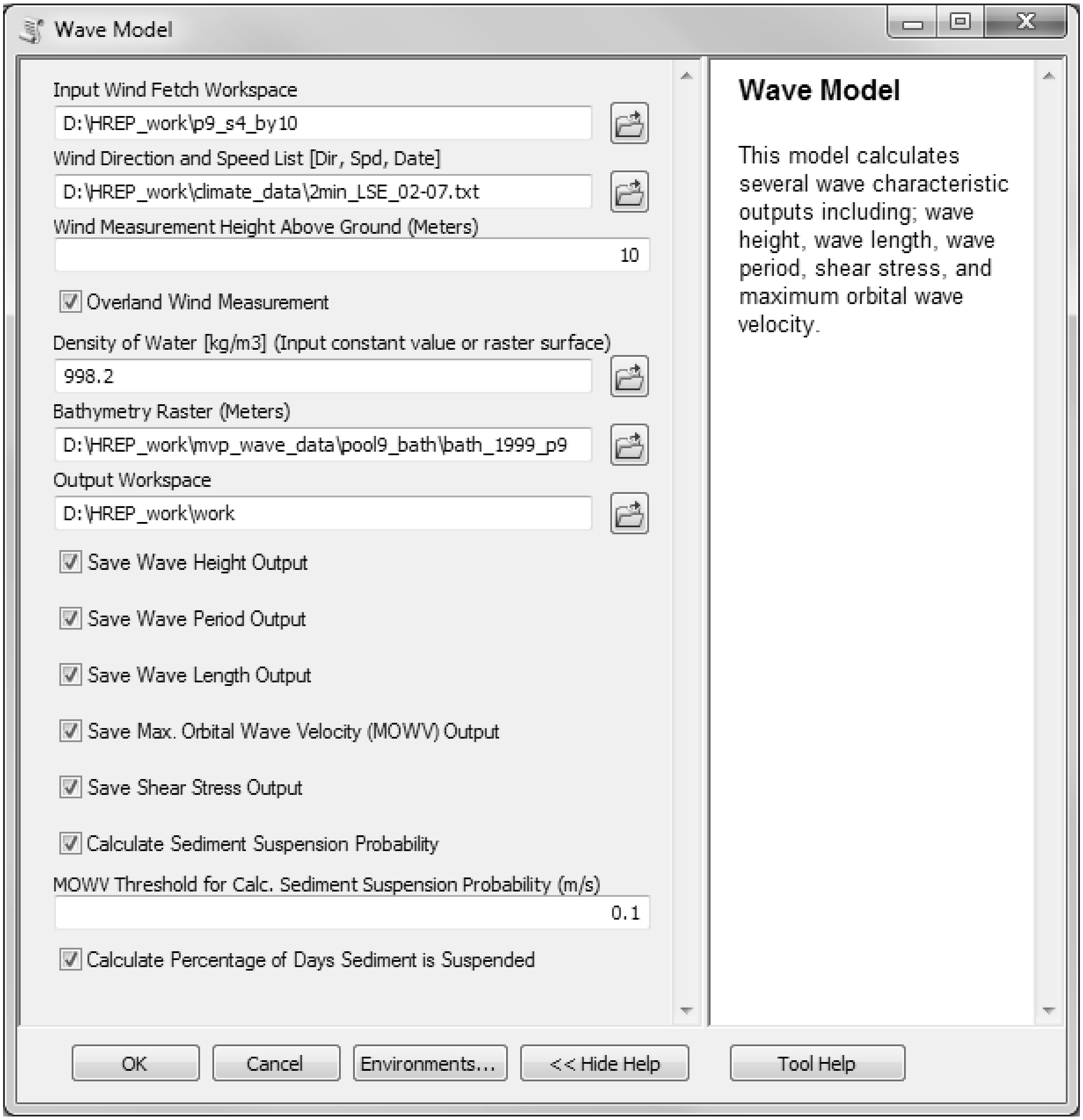


Figure 10. Wave model dialog window prompting user input

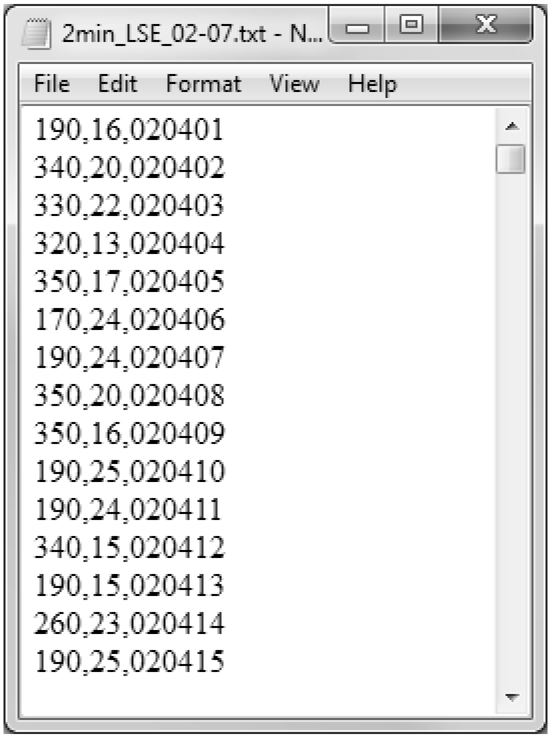


Figure 11. Sample text file depicting valid input values for wind data in wave model

It is important the date values be organized like this for the model to work correctly.

The assembled wind speed data were adjusted to approximate a 1-hour wind duration, a 10-meter anemometer height above the ground surface, an overwater measurement, and also adjusted for coefficient of drag. These adjustments directly affect the input parameters of wave height, period, and length. Bathymetric (water depth) data used within the model were collected from the UMRR-EMP LTRMP (see "spatial datasets used in analyses" section for detailed background information).

The checkbox entitled "Overland Wind Measurement" should be checked if the wind data used within the model were collected on land and not over water which is the preferred alternative.

In the previous iteration of the wave model, the user was able to designate a single value to represent the density of water used in model calculations. Per request of the USACE, the functionality was added to allow the user to specify a raster surface depicting varying water density values in addition to being able to specify a singular value. This functionality was added to give scientists the opportunity to simulate the dampening effects of existing submersed aquatic vegetation. Aquatic vegetation can have an effect on wave growth by dissipating waves and thus reducing wave energy (Anderson and others 2011). It is important for the user to have a solid understanding as to what degree the presence of aquatic vegetation may affect the density of water before adjusting this parameter and also understand the seasonality of when certain vegetation types are present in the water column.

The decimal number required for the input parameter "MOWV Threshold for Calc. Sediment Suspension Probability (m/s)" is used in the calculation of sediment suspension probability (see section describing Sediment Suspension Probability Analysis for more information). Any maximum orbital wave velocity value derived that has a speed greater than or equal to the value specified will be attributed as having sufficient maximum orbital wave velocity to suspend sediment.

The user is given the opportunity to save the derived outputs permanently to their hard drive. This was done to give the user the opportunity to save space, as creating several of these floating-point raster datasets can quickly fill large amounts of disk space on the user's computer.

Checking the checkbox labeled "Calculate Percentage of Days Sediment is Suspended" allows the tool to automatically calculate the probability that aquatic areas within the area of interest will have maximum orbital wave velocities sufficient to suspend sediments based upon the wind direction and speed data used (see section describing Sediment Suspension Probability Analysis for more information).

Before the model can be executed, a scratch workspace must be designated using the "Environments…" button. It is suggested that the user select a workspace (folder) for this parameter and not use a geodatabase as is sometimes suggested in the ArcGIS literature. There have been issues with the model not operating when a geodatabase or an invalid workspace was selected.

Wave model outputs are named according to a three digit code as a prefix and then the date the wind data used was collected as a suffix. Sample output grid names are given below for all potential parameters:

- Wave Height = hgt_020421
- Wave Period = per_020421
- Wave Length = len_020421
- Maximum Orbital Wave Velocity = vel_020421
- Shear Stress = str_020421
- Sediment Suspension Probability = vec_020421
- Percentage of Days Sediment is Suspended = susp_prob

Assumptions and Model Limitations

The wave model described in this report provides a simplistic method for calculating multiple wave parameters. However, it should be noted that in many cases these simple methods have been replaced with more realistic, and much more complex, numerical wave models. This model provides a first-order approximation of the wave field and it should be noted that the methodology employed neglects the effect of bathymetry on wave growth. Also, since the method does not account for refraction or diffraction due to topography, reflection due to barriers (including the shoreline itself), wave-wave interactions, or wave-current interactions, the results are unrealistic and should be considered accurate only on a regional level and not on a cell-by-cell basis (D. Finlayson, personal communication 2008.)

Wave height, period, and length inputs were derived based upon a deep-water model. There is no single theoretical development for determining the actual growth of waves generated by winds blowing over relatively shallow water (USACE 1984). Shallow water curves presented in the Shore Protection Manual (USACE 1984) are based on a successive approximation in which wave energy is added due to wind stress and subtracted due to bottom friction and percolation (Chamberlin 1994). While it is realized that that the deep-water assumption will slightly over predict wave-height, a shallow water assumption would not only make computations more difficult, but it would also under predict wave height.

These models do not include the effect of terrestrial elevation on wave propagation. There is no accounting for island height or the height of trees on these terrestrial land forms. As wind is deflected up and over an island and its trees, a sheltered zone is created on the downwind side of the island (USACE 2006). This zone is roughly 10 times the height of the island and its trees (Ford and Stefan 1980). The value for this sheltered zone hasn't been stated in a quantitative fashion; however providing thermal refuge for migrating waterfowl is a desirable outcome of island projects (USACE 2006).

The proximity of the meteorological station that the wind data is obtained from to the project area could introduce errors due to variations in wind speed and direction caused by river valley orientation (ie. river bluff effects). Although it is usually not practical to collect wind data onsite, the project teams using these results should be aware of this effect.

Wave height was not tested for depth-limited breaking. If shallow bars or shoals or island remnants exist along the fetch, they may also dissipate energy and limit the wave height.

Also, neglecting diffraction of larger waves into the protected areas within the islands will underestimate wave energy in the protected area.

Methodology

Calculating the multiple wave characteristic raster outputs is accomplished using algorithms published in the Coastal Engineering Manual (USACE 2002) and the Shore Protection Manual (USACE 1984). The following is a listing of variables used within these algorithms and a short description of what they represent:

U = observed wind speed (miles/hour)
U_A = adjusted wind speed (meters/second)
z = observed elevation of wind speed measurements (meters)
t = number of seconds to travel one mile
U_t = ratio of wind speed of any duration
C_d = coefficient of drag
U_* = friction velocity
$\lambda_1 = 0.0413$
$\lambda_2 = 0.751$
$m_1 = 1/2$
$m_2 = 1/3$
$\hat{H}_{m0}$ = non-dimensional significant wave height
H_{m0} = significant wave height (meters)
$\hat{x}$ = non-dimensional wind fetch
x = wind fetch (meters)
g = acceleration of gravity (9.82 meters/second^2)
$\hat{T}_p$ = non-dimensional spectral peak wave period
T_p = spectral peak wave period (seconds)
L = wave length (meters)
u_m = maximum orbital wave velocity at the bottom (meters/second)
d_f = water depth in the floodplain (meters)
τ = shear stress at the bottom (Newtons/square meter)
ρ = density of water (Kg/m3)
f = friction factor (assumed to be .032)

Adjusting Wind Speed Data

The first step within the wave model is to make adjustments to the wind speed data to better approximate real-world conditions above water. Wind data used for the example analyses were collected from the National Oceanic and Atmospheric Administration, National Climatic Data Center (http://www7.ncdc.noaa.gov/IPS/lcd/lcd.html). Wind data used in this analysis was collected only during the growing seasons (April – July) from 2008 to 2012. Specific wind parameter used was the maximum 2-minute average wind speed and direction (in miles per hour and degrees, respectively). The wind speed collected is adjusted to approximate a 10-meter anemometer height above the ground surface using the input within the model dialog entitled "Wind Measurement Height Above Ground (Meters)". Since the wind speed data were collected by the NCDC at the 10-meter elevation for these particular example locations, no adjustment is made to the wind speed data collected. The 10-meter elevation measurement guideline is established within the Automated Surface Observing System (ASOS) specifications. If however, the data collected were from an anemometer at an elevation other than 10 meters the following algorithm would have been applied:

$$U_A = U\,(10/z)^{1/7}$$

This approximation can be used if z is less than 20 meters (USACE 1984).

Next, the wind speed is then corrected to better approximate a 1-hour wind duration. Most fastest mile wind speeds are collected using short time intervals, for the St. Paul and St. Louis District examples the maximum 2-minute average wind speed is used. It is most probable that on a national basis many of the fastest mile wind speeds have resulted from short duration storms such as those associated with squall lines or thunderstorms. Therefore, the fastest mile measurement, because of its short duration, should not be used alone to determine the wind speed for wave generation. On the other hand, lacking other wind data, the measurement can be modified to a time-dependent average wind speed (USACE 1984). Therefore, the 1-hour average wind speed is recommended when using a steady-state model for determining wave characteristics (Chamberlin 1994). It is important to document, however, with shorter fetches the 1-hour averaged wind speed may be longer than needed and may result in an underestimate of wave heights and periods. The following algorithms make this modification within the wave model:

$$t = 3600 / U_A$$
$$U_t = 1.277 + 0.296 * \tanh(0.9 * \log_{10}(45/t))$$
$$U_A = U_A / U_t$$

Next, if the checkbox labeled "Overland Wind Measurement" is checked, the wind speed is adjusted to better approximate what the wind speed would be if it were collected over water (Chamberlin 1994).

$$U_A = 1.2 (U_A)$$

Finally, the adjusted wind speed is converted from miles per hour to meters per second:

$$U_A \text{ (meters per second)} = U_A \text{ (miles per hour)} * 0.44704$$

This wind speed value (U_A) is used in all subsequent wave model equations. It is important to note that the wind data used in these analyses were not corrected for stability or location.

Deep Water Test

A test was performed to ascertain whether deep-water or shallow-water wave models would be more appropriate for the analyses. In this test, if the ratio of water depth (h) to wave length (L) is greater than 0.5 we are in an area more typically classified as deep water and the calculated wave characteristics are virtually independent of depth, whereas if the ratio h/L is less than 0.05 we are in an area more typically thought of as shallow water (USACE 1977). For this test the typical water depth was calculated to be 1.6092 meters. To determine this, the UMRS Pool 9 UMRR-EMP LTRMP bathymetric data were clipped using subareas defined as part of reach planning conducted in 2011 (USACE 2011). The subareas that encompassed Capoli and Harper's Slough HREP were used to calculate the mean water depth (Figure 12).

Next, the typical wave length was calculated. To accomplish this, the wave model was executed using 28 days of wind data from 2006. These 28 days encompassed the first week of each month during the growing season (April 1-7, May 1-7, June 1-7, and July 1-7, 2006). Upon completion of the model, the average wave length for all 28 iterations of the model was 3.4988 meters (Table 2).

The average water depth (1.6092) was then divided by the average wave length (3.4988) to get a ratio of 0.4898 that tends more towards what we classify as deep water (0.5). Thus, in the model and the following analyses, the wave calculations were based upon deep water wave theory.

It is recommended that deep water wave growth formulae be used for all depths, with the constraint that no wave period can grow past a limiting value (USACE 2002). A limiting wave period was then calculated and compared with typical wave periods for the study areas. It was found that the observed wave periods were less than the limiting wave period calculated using CEM Equation II-2-39 (USACE 2002). The limiting wave period was calculated to be 3.9 seconds based upon the average water depth of 1.6092 meters calculated. It is unlikely that in our applications the wave period would exceed this value and become limited.

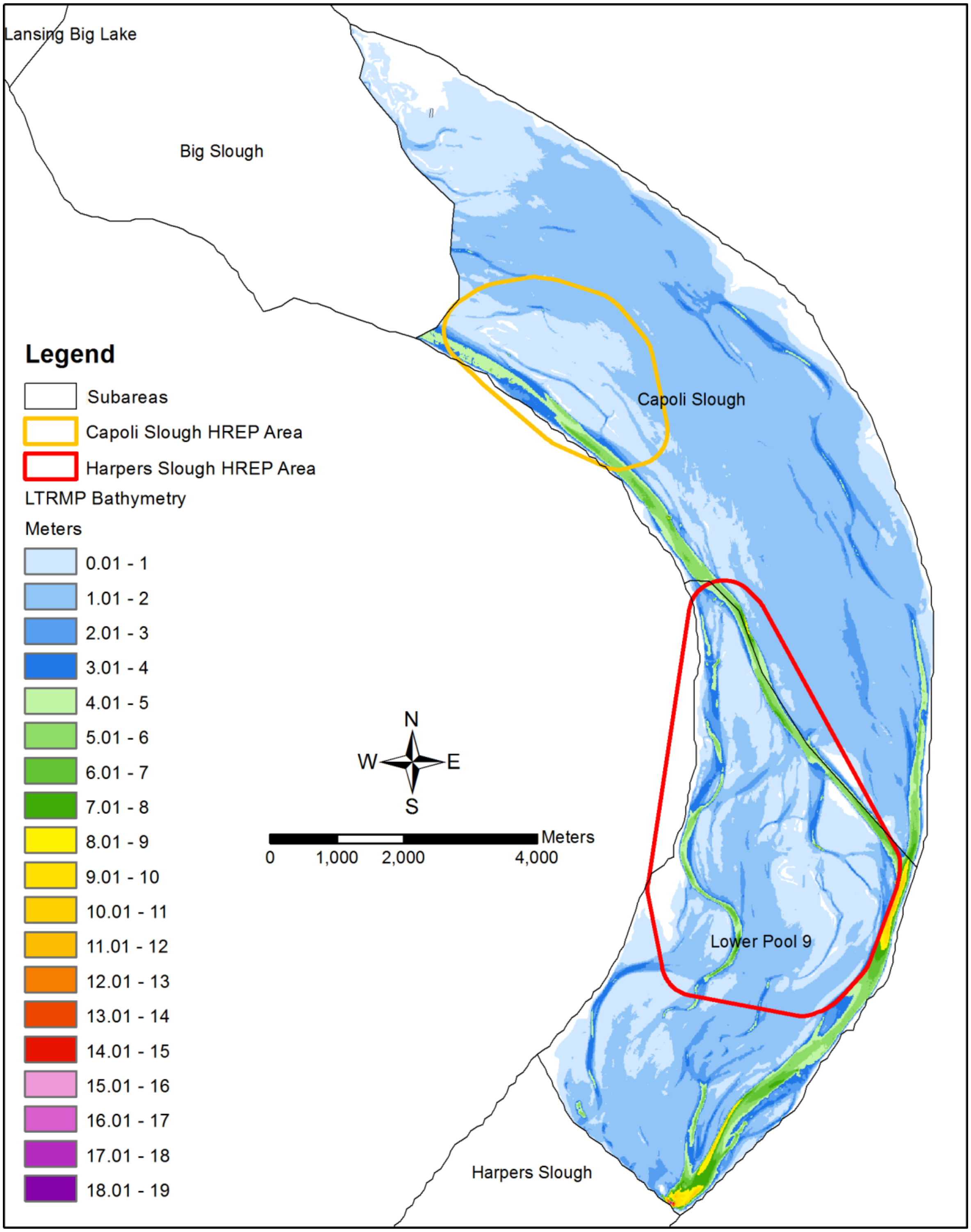


Figure 12. Visual depiction of USACE subareas used to calculate average water depth

Table 2. Summarization of results used to test for deep vs. shallow water

Day	Date	Wind Direction	Unadjusted Wind Speed (U) MPH	Wave Height (H) Meters	Wave Length (L) Meters	h/L
1	4/1/2006	320	21	0.2692	4.4784	0.3593
2	4/2/2006	340	22	0.2784	4.5167	0.3563
3	4/3/2006	330	30	0.3920	5.7217	0.2812
4	4/4/2006	300	18	0.2148	3.7027	0.4346
5	4/5/2006	150	13	0.1588	3.1032	0.5186
6	4/6/2006	140	16	0.1943	3.5205	0.4571
7	4/7/2006	10	21	0.2474	4.0030	0.4020
8	5/1/2006	150	20	0.2494	4.1930	0.3838
9	5/2/2006	260	13	0.1256	2.2573	0.7129
10	5/3/2006	300	22	0.2656	4.2657	0.3772
11	5/4/2006	300	17	0.2023	3.5573	0.4524
12	5/5/2006	320	17	0.2154	3.8597	0.4169
13	5/6/2006	210	18	0.1943	3.2237	0.4992
14	5/7/2006	190	18	0.2114	3.6171	0.4449
15	6/1/2006	320	14	0.1758	3.3710	0.4774
16	6/2/2006	330	12	0.1489	3.0008	0.5363
17	6/3/2006	40	12	0.1177	2.1935	0.7336
18	6/4/2006	150	14	0.1715	3.2668	0.4926
19	6/5/2006	200	18	0.2043	3.4546	0.4658
20	6/6/2006	280	22	0.2361	3.6343	0.4428
21	6/7/2006	330	21	0.2676	4.4357	0.3628
22	7/1/2006	300	20	0.2401	3.9877	0.4035
23	7/2/2006	270	12	0.1193	2.2298	0.7217
24	7/3/2006	30	12	0.1247	2.3767	0.6771
25	7/4/2006	340	15	0.1859	3.4514	0.4662
26	7/5/2006	300	13	0.1528	2.9512	0.5453
27	7/6/2006	220	9	0.0903	1.8721	0.8595
28	7/7/2006	200	20	0.2284	3.7205	0.4325
Averages		**237**	**17**	**0.2029**	**3.4988**	**0.4898**

Significant Wave Height

The highest point of the wave is the crest and the lowest point is the trough. For linear or small-amplitude waves, the height of the crest above the still-water level (SWL) and the distance of the trough below the SWL are each equal to the wave amplitude a. Therefore $a = H/2$, where H = the wave height (USACE 2002). Significant wave height is defined as the average height of the one-third highest waves, and is approximated to be about equal to the average height of the waves as estimated by an experienced observer (Munk 1944). Significant wave height is calculated within the wave model according to the following formulae taken from the Coastal Engineering Manual (USACE 2002):

$$C_d \approx 0.001 * (1.1 + (0.035 * U_A))$$
$$U_* = (C_d)^{1/2} * U_A$$
$$\hat{x} = (g * x) / (U_*)^2$$
$$\hat{H}_{m0} = \lambda_1 * (\hat{x})^{m1}$$
$$H_{m0} = \hat{H}_{m0} * ((U_*)^2 / g)$$

The units for this output are meters. The top-left frame of Figure 13 displays an example output for wave height using wind fetch calculated from 300 degrees and a wind speed of 21 miles per hour for Capoli Slough HREP, management scenario 4. Areas within the HREP area of interest that are black denote land. The presence of "streaks" in this and the following figures are an unfortunate artifact of the stair-step nature of raster datasets. When polygons become thin (approximating the raster's cell size, in this example 10 meters), gaps are created in the island areas during the conversion to a raster dataset. When fetch is then calculated at certain angles, the fetch calculation is unimpeded by land. A possible resolution to this problem would be to further decrease cell-size to 5 or even 2 meters but then analysis time increases significantly.

Wave Length

The wave length is the horizontal distance between two identical points on two successive wave crests or two successive wave troughs (USACE 2002). Wave length measurements within the wave model are based upon linear wave theory. Linear wave theory is easy to apply and gives a reasonable approximation of wave characteristics for a wide range of wave parameters (USACE 2002). The assumptions made in developing the linear wave theory are:

- Surface tension can be neglected.
- Coriolis Effect due to the Earth's rotation can be neglected.
- Pressure at the free surface is uniform and constant.
- The fluid is ideal or inviscid (lacks viscosity).
- The particular wave being considered does not interact with any other water motions. The flow is irrotational so that water particles do not rotate (only normal forces are important and shearing forces are negligible).
- The bed is a horizontal, fixed, impermeable boundary, which implies that the vertical velocity at the bed is zero.
- The wave amplitude is small and the waveform is invariant in time and space.
- Waves are plane or long-crested (two-dimensional).

Wave length is calculated within the wave model according to the following formula:

$$L = g\, T_p^{\,2} / 2\pi$$

The units for this output are meters. The top-right frame of Figure 13 displays an example output for wave length using wind fetch calculated from 300 degrees and a wind speed of 21 miles per hour for Capoli Slough HREP, management scenario 4.

Spectral Peak Wave Period

The time interval between the passage of two successive wave crests or troughs at a given point is the wave period (USACE 2002). Spectral peak wave period is calculated within the wave model according to the following formulae taken from the Coastal Engineering Manual (USACE 2002):

$$\hat{T}_p = \lambda_2 * (\hat{x})^{m2}$$
$$T_p = (\hat{T}_p * U_*) / g$$

The units for this output are seconds.

The middle-left frame of Figure 13 displays an example output for wave period using wind fetch calculated from 300 degrees and a wind speed of 21 miles per hour for Capoli Slough HREP, management scenario 4.

Maximum Orbital Wave Velocity

As waves begin to build, an orbital motion is created in the water column resulting in a bottom velocity and shear stress (USACE 2006). This orbital wave velocity can be sufficient enough to suspend unconsolidated sediments into the water column. In sufficiently deep water, the wave particle orbital velocity at the bottom is effectively zero and sediment particles on the bed do not experience a force due to surface wave motion (Kraus 1991). The maximum orbital wave velocity is calculated within the wave model according to the following formula (Kraus 1991):

$$u_m = \pi H_{m0} / (T_p \sinh(2\pi d_f / L))$$

Maximum orbital wave velocity is based upon linear wave theory (see section describing wave length). The units for this output are meters per second. The middle-right frame of Figure 13 displays an example output for maximum orbital wave velocity using wind fetch calculated from 300 degrees and a wind speed of 21 miles per hour for Capoli Slough HREP, management scenario 4.

Shear Stress

Shear stress is the drag force created on the bed by the fluid motion (Kraus 1991). Shear stress at the bottom of the water column is understood to be an average over a wave period and is calculated within the wave model according to the following formula (Kraus 1991):

$$\tau = \rho f u_m^2 / 2$$

The units for this output are Newtons per square meter. The bottom-left frame in Figure 13 displays an example output for shear stress using wind fetch calculated from 300 degrees and a wind speed of 21 miles per hour for Capoli Slough HREP, management scenario 4.

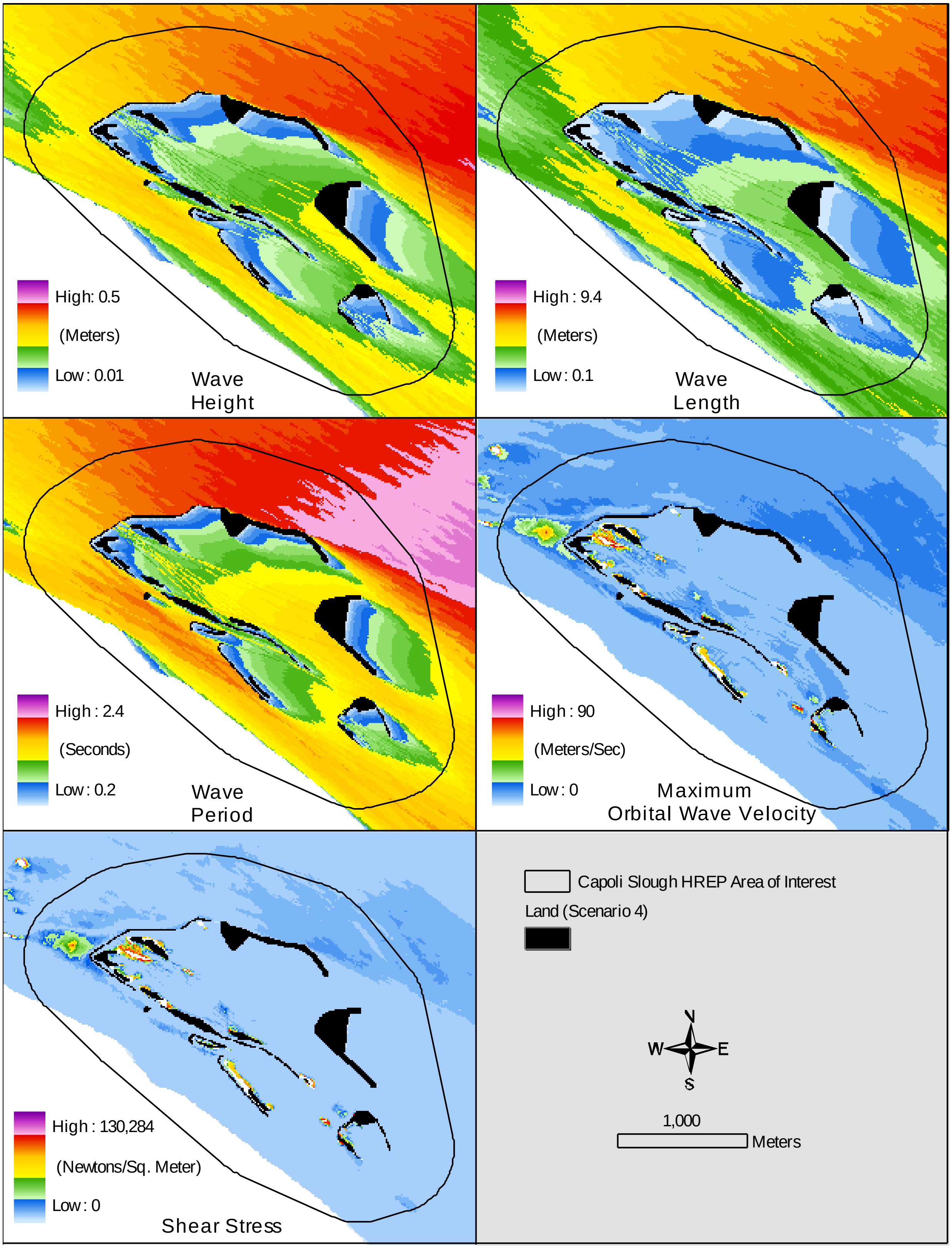


Figure 13. Sample wave model outputs for scenario 4, Capoli Slough Habitat Rehabilitation and Enhancement Project

Figure 14 is a flowchart diagram depicting the relationships of the input and output parameters used to develop the wave model outputs within the tool.

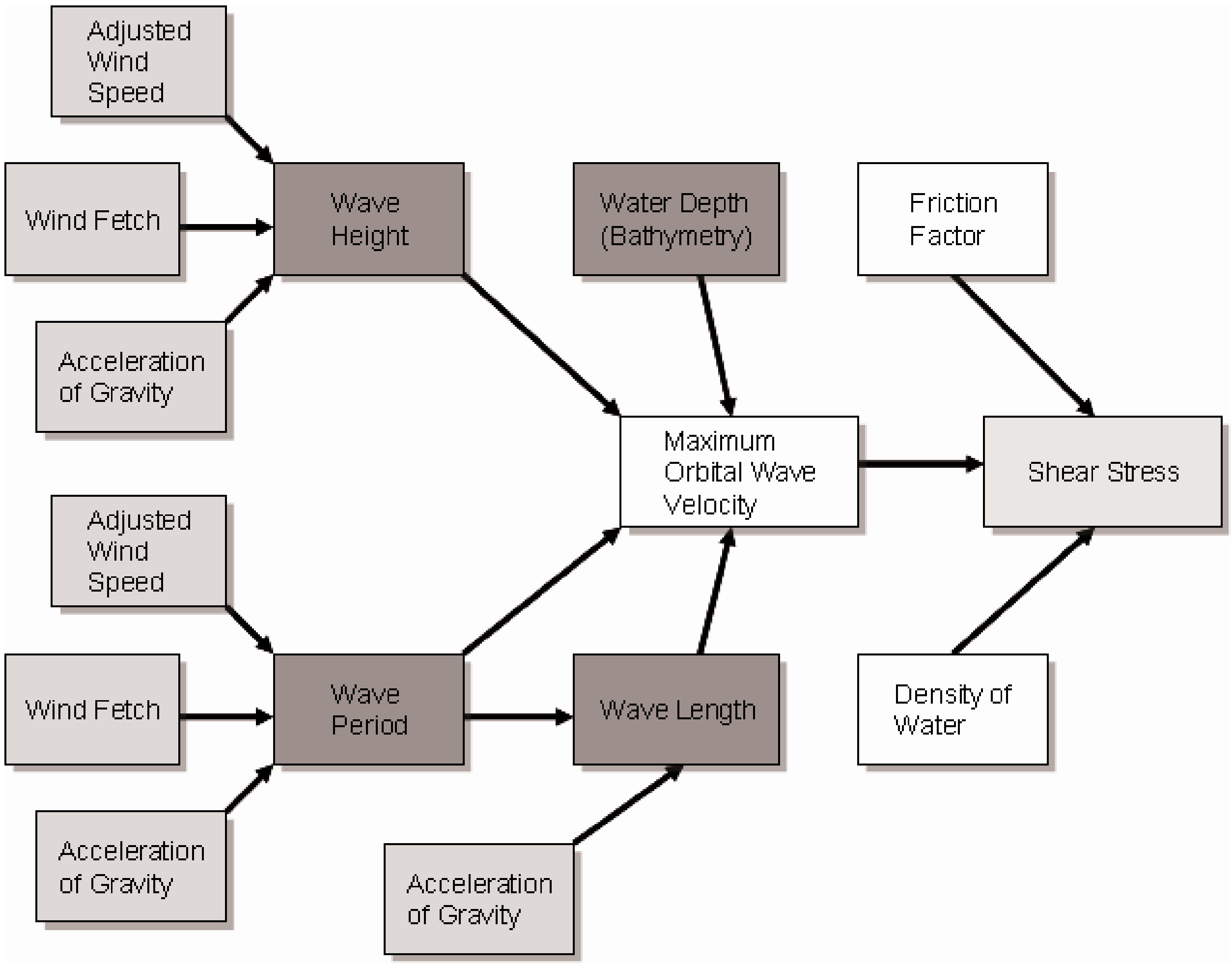


Figure 14. Diagram depicting relationships of input and output parameters used within wave model

Delineate Area of Potential Effects Model

Using this model the user can identify the areas where the differences between the values from two raster datasets are above a certain specified threshold (magnitude). So, for instance, if you want to see where there is at least a 600 meter change in weighted wind fetch when comparing existing conditions to another scenario it will generate a shapefile identifying those areas. Required inputs to the model include two rasters to compare against one another, a number identifying a desired magnitude of difference, and a location to save the output shapefile (Figure 15). An output raster dataset can also be identified if the user would like to save the resultant difference raster to a permanent location on their computer. In the resulting shapefile, use the field GRIDCODE to identify areas meeting the specified magnitude of difference. Polygons with a GRIDCODE of "1" have a greater magnitude of difference than that specified and those polygons with a GRIDCODE of "0" have a smaller or equal magnitude of difference than that specified (Figure 16). The existing conditions (2015) scenario and scenario 4 for Harper's

Slough HREP were used to develop figures 15 and 16 using an identified magnitude of difference of 600 meters.

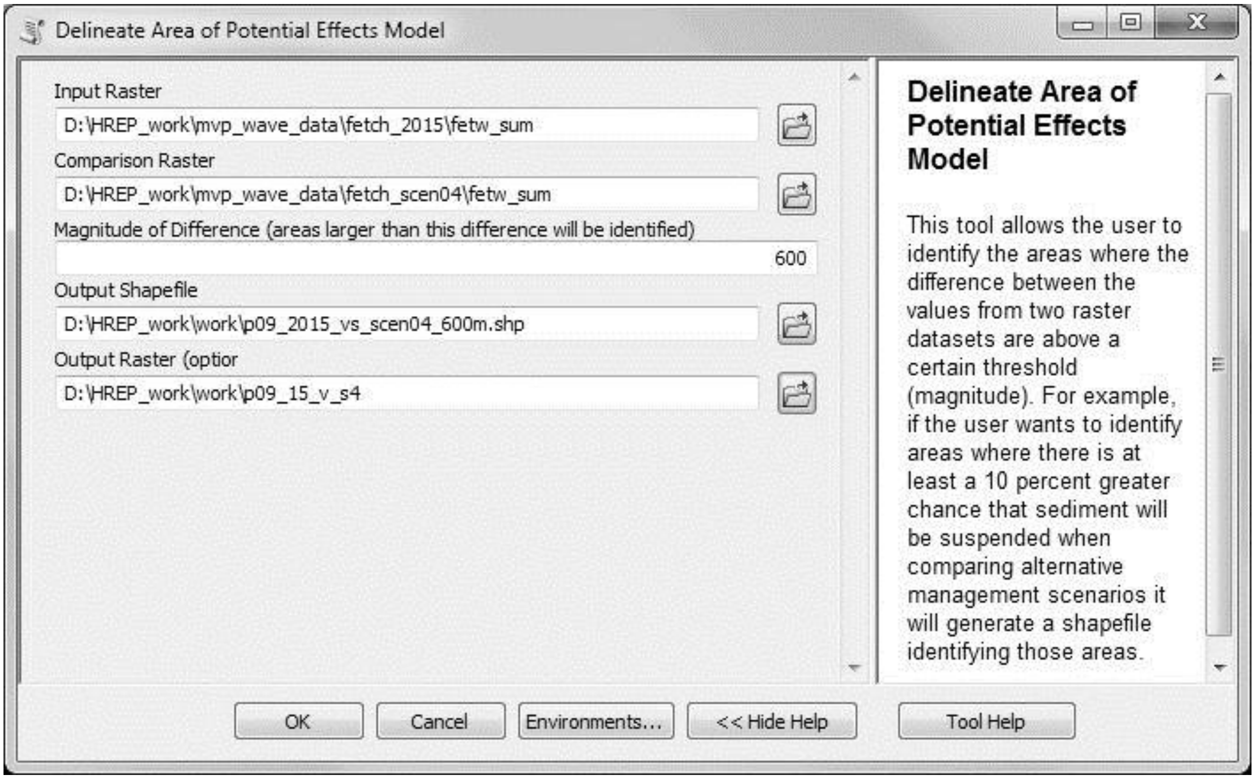


Figure 15. Delineate Area of Potential Effects Model dialog window

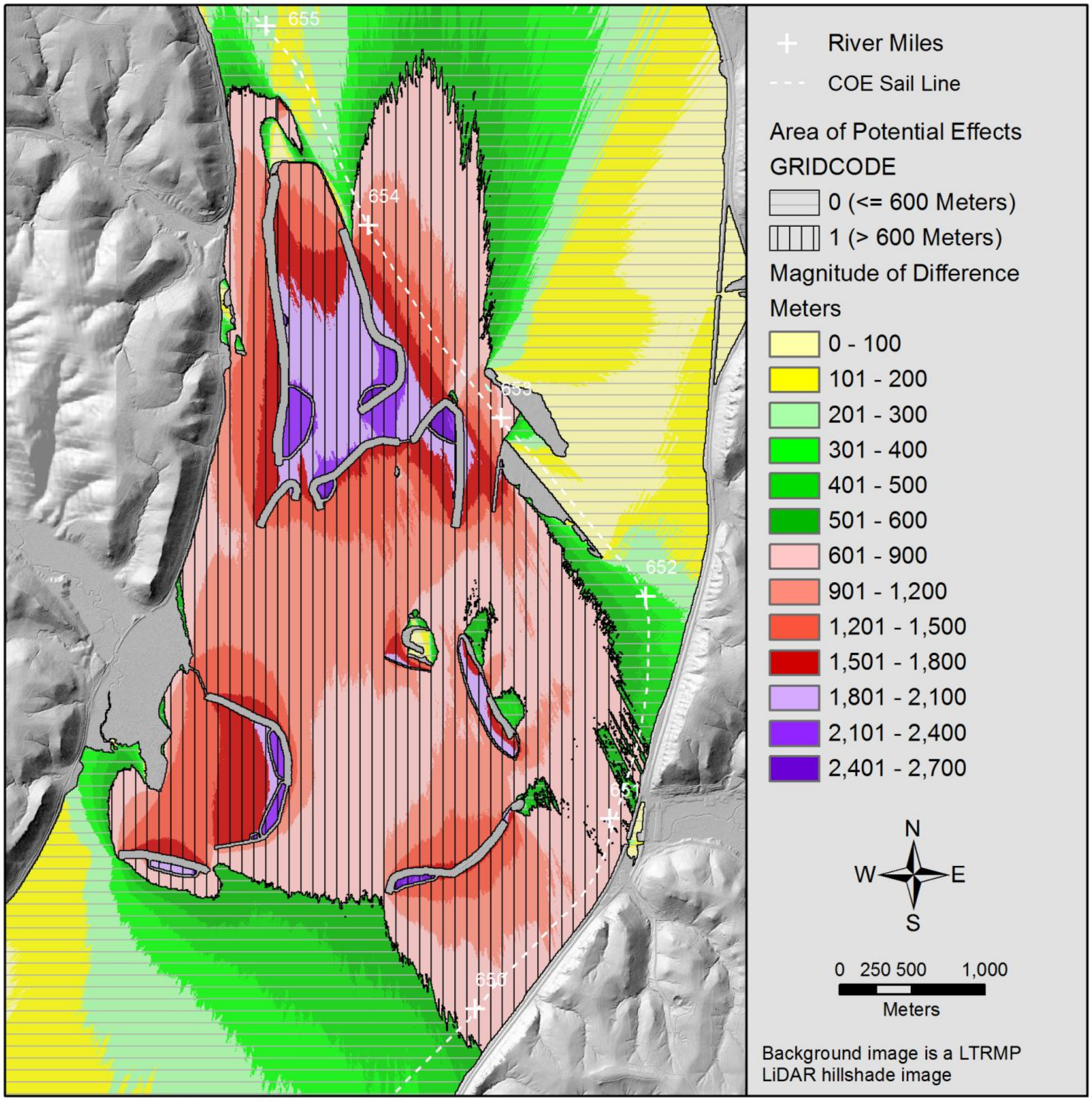


Figure 16. Results from Delineate Area of Potential Effects Model for Harper's Slough HREP using existing conditions (2015) and Scenario 4 weighted wind fetch products as inputs

St. Paul District Analyses

Study Areas

The study area for these analyses was Harper's Slough HREP in Navigation Pool 9 of the Upper Mississippi River System (UMRS; Figure 17). This HREP is being designed to not only achieve goals and objectives related to the improvement of habitat but to also have a physical impact on riverine processes. The intent of the project is to slow the loss of existing islands and to also restore islands that were lost.

“Islands reverse many of the effects of lock and dam construction. A new island essentially becomes the new natural levee, separating channel from floodplain, reducing channel-floodplain connectivity, and increasing channel flow while decreasing the amount of floodplain flow. This increases the velocity in adjacent channels increasing the erosion and transport of sediment. Wind fetch and wave action is reduced in the vicinity of islands, reducing the resuspension of bottom sediments, floodplain erosion, and shoreline erosion. In some cases, islands act primarily as wave barriers and don’t alter the river-wide distribution of flow. Islands reduce the supply of sediment to the floodplain potentially decreasing floodplain sediment deposition” (USACE 2006).

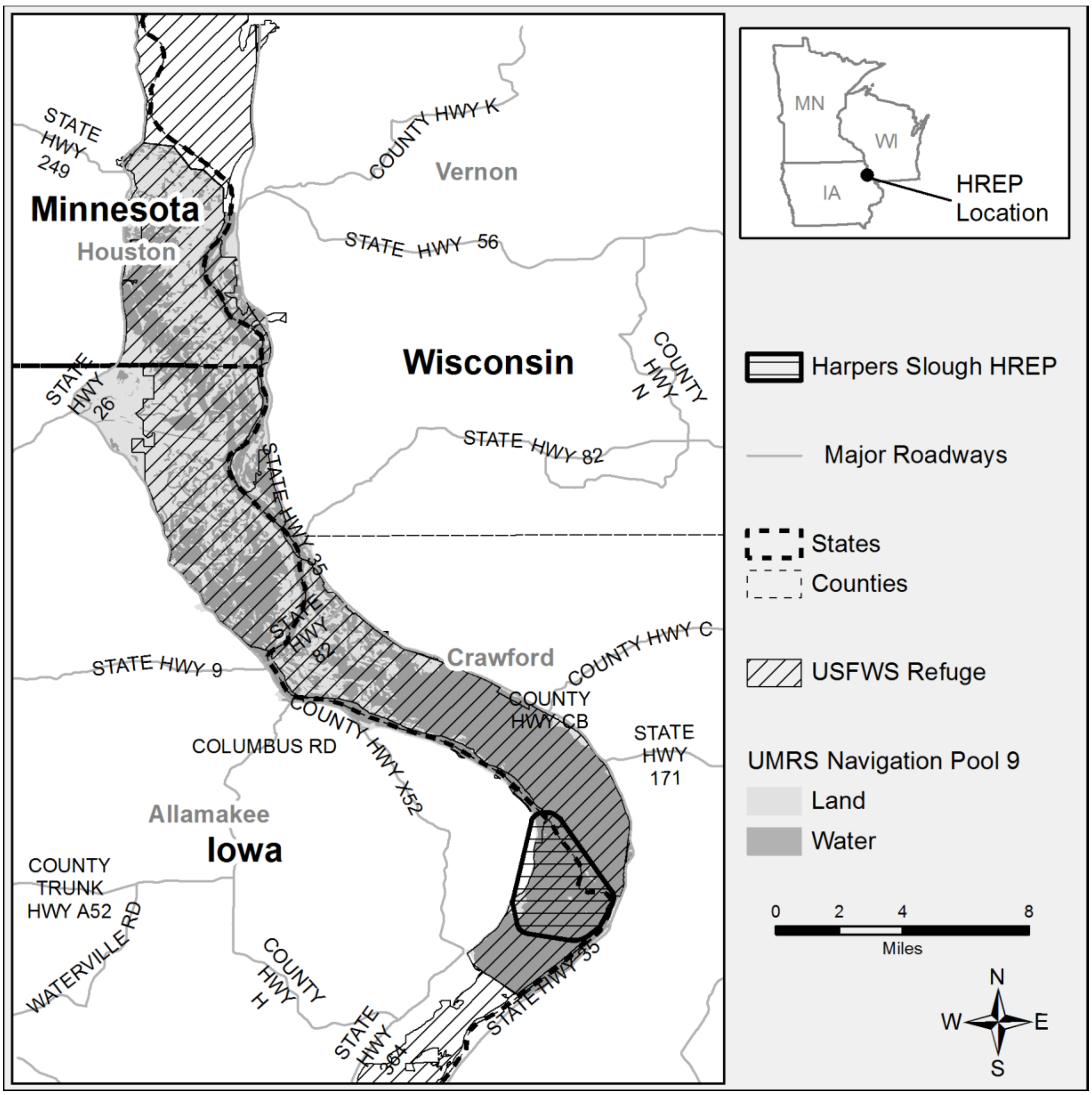


Figure 17. Location of Pool 9 and Harper’s Slough Habitat Rehabilitation and Enhancement Project

Harper’s Slough HREP

The Harpers Slough HREP is described in the USACE fact sheet as a 2,200-acre backwater area located primarily on the Iowa side of the Mississippi River in Pool 9, about 3 miles upstream of

Lock and Dam 9. The site lies within the Upper Mississippi River National Wildlife and Fish Refuge (USACE n.d).

The area is used heavily by tundra swans, Canada geese, puddle and diving ducks, black terns, nesting eagles, bitterns, and cormorants and is also significant as a fish nursery area. Many of the islands in the area have been eroded or lost because of wave action and ice movement. This allows more turbulence in the backwater area, resulting in less productive habitat for fish and wildlife. Harpers Slough is one of the few remaining areas in lower Pool 9 where high quality habitat could be maintained (USACE n.d).

The proposed project would restore about 25,000 feet of islands at the upper portion of the area using material from the backwater and near the main channel. About 8,000 feet of islands in the lower portion of the area would be stabilized. The project would slow the loss of existing islands, reduce the flow of sediment-laden water into the backwaters, and increase the diversity of land and shoreline habitats (USACE n.d).

There are four goals outlined within the Harper's Slough rough draft Definite Project Report (USACE 2005).

1. Maintain and/or enhance habitat in the Harpers Slough backwater area for migratory birds.
2. Create habitat for migratory and resident vertebrates with emphasis on marsh and shorebirds, bald eagles, and turtles.
3. Improve and maintain habitat conditions for backwater fish species.
4. Enhance secondary and main channel border habitat for riverine fish species and mussels.

Figure 18 gives a visual representation of the Harper's Slough HREP area using the 2010 UMRR-EMP LTRMP Land Cover/Land Use spatial data layer as a backdrop. The yellow Harper's Slough HREP area of interest polygon was created by calculating where the difference in weighted wind fetch between the existing conditions (2015) and scenario 4 was greater than 600 meters using the Delineate Area of Potential Effects Model and then buffering this output by 100 meters. Features are labeled according to USACE HREP planning maps.

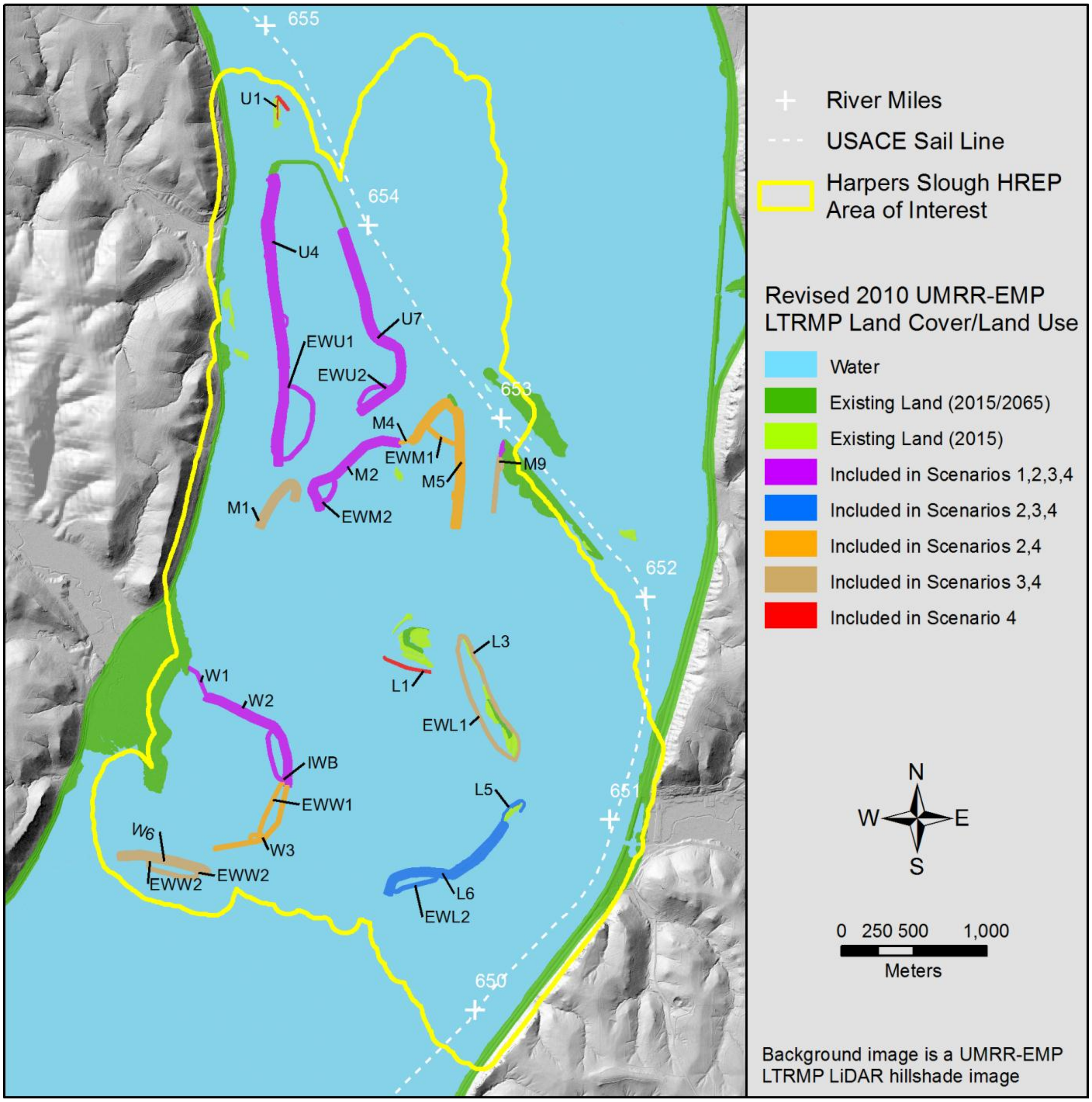


Figure 18. Harper's Slough Habitat Rehabilitation and Enhancement Project map with feature labels

Weighted Wind Fetch Analysis

Land Raster Input Data

2010 land cover data created by the UMRR-EMP LTRMP were used to depict the land/water interface used within the wind fetch model for this particular analysis (see "spatial datasets used in analyses" section for detailed background information). There were existing artificial islands missing from the 2010 land cover data, these were digitized and included into all management scenarios for Harper's Slough HREP (red polygons in Figure 19). These islands are too thin to be included in the land cover data developed by the UMRR-EMP LTRMP but were felt to be wide enough to have an impact on wave development.

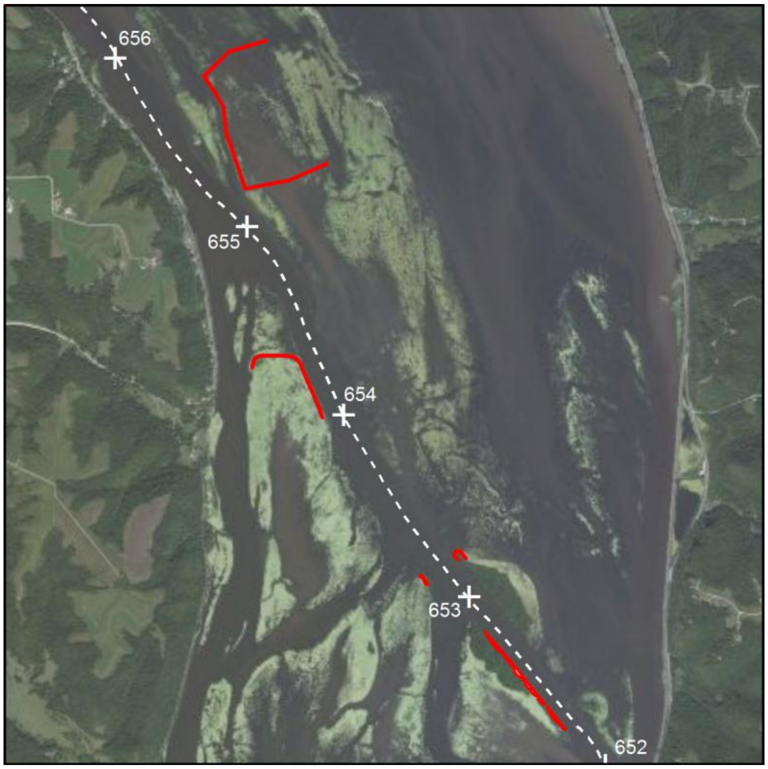


Figure 19. Location of revised island additions to Harper's Slough HREP area

Island design scenarios were provided by the St. Paul District, U.S. Army Corps of Engineers and incorporated into the 2010 UMRR-EMP LTRMP land cover. These land/water datasets provided the base layers used to calculate fetch. To be used within the model, these land/water datasets were given a new field. This field was attributed so all land polygons were "1" and all water polygons were attributed as "0". The polygons were then converted from their native polygonal (shapefile) format into an ESRI raster format (Grid) to be used in the model. The field that was added was then used to assign values to the output raster within the wind fetch model. This was accomplished in ArcGIS 10.0 using the "Feature to Raster" tool. The output rasters have a cell size of 5 meters.

The specific island configuration scenario to be used within the wind fetch model is designated using the "Land Raster" control on the wind fetch model dialog window.

Wind Direction Input Data

Wind direction data used within the wind fetch model were collected from the National Oceanic and Atmospheric Administration, National Climatic Data Center (NCDC) (http://www7.ncdc.noaa.gov/IPS/lcd/lcd.html). The specific wind parameter used was the maximum 2-minute average wind direction. Wind data used in this analysis were collected only during the growing seasons (April – July) from 2008 to 2012. All daily wind data were used regardless of collected wind speed. Wind data for significant events could be selected manually to represent wind speeds and directions of primary concern. Figure 20 gives an example of NCDC local climatological data for May 2006 from the La Crosse Municipal Airport. This was the closest data collection location to the study area of Harper's Slough HREP. Similar to the wave model, the proximity of the meteorological station that the wind data is obtained from for use in the weighted wind fetch model could introduce errors due to variations in wind direction caused by river valley orientation. Although it is usually not practical to collect wind data onsite, the project teams using these results should be aware of this effect.

MAY 2006
LOCAL CLIMATOLOGICAL DATA
NOAA, National Climatic Data Center

LA CROSSE, WI
LA CROSSE MINICIPAL AIRPORT (KLSE)
Lat:43 ° 45'N Long: 91 ° 15'W Elev (Ground) 652 Feet
Time Zone : CENTRAL WBAN: 14920 ISSN#: 0198-571X

Date	Temperature °F MAXIMUM	MINIMUM	AVERAGE	DEP FROM NORMAL	AVERAGE DEW PT	AVERAGE WET BULB	Deg Days BASE 65° HEATING	COOLING	WEATHER	SNOW/ICE ON GND(IN) 0600 LST DEPTH	1200 LST WATER-EQUIV	PRECIPITATION ON GND(IN) 2400 LST SNOW-FALL	2400 LST WATER EQUIV	PRESSURE (INCHES OF HG) AVERAGE STATION	AVERAGE SEA LEVEL	WIND (SPEED = MPH, DIR = TENS OF DEGREES) RESULTANT SPEED	RES DIR	AVERAGE SPEED	MAXIMUM 5-SEC SPEED	DIR	2-MIN SPEED	DIR	Date
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
01	57	54	56	0	52	53	9	0	RA BR	0		0.0	0.14	29.18	29.88	10.0	17	10.4	24	13	20	15	01
02	73	49	61	5	51	56	4	0	BR	0		0.0	0.00	29.18	29.89	3.9	19	5.9	15	25	13	26	02
03	71	53	62	6	44	53	3	0		0		0.0	0.00	29.21	29.91	8.4	29	10.8	26	28	22	30	03
04	62	48	55	-2	41	48	10	0		0		0.0	0.00	29.31	30.00	11.7	31	12.3	22	30	17	30	04
05	51	38	45	-12	36	42	20	0	RA	0		0.0	T	29.34	30.05	9.3	32	10.7	21	33	17	32	05
06	67	34*	51	-6	34	44	14	0	BR	0		0.0	0.00	29.29	30.01	7.9	20	8.7	24	21	18	21	06
07	72	46	59	1	38	49	6	0		0		0.0	0.00	29.19	29.91	8.3	18	8.7	21	19	18	19	07
08	67	51	59	1	52	55	6	0	TSRA RA BR VCTS	0		0.0	1.70	29.07	29.78	6.5	16	10.0	28	12	24	12	08
09	66	56	61	3	57	59	4	0	RA BR VCTS	0		0.0	0.31	28.95	29.65	7.7	18	8.3	20	18	16	18	09
10	70	49	60	1	47	53	5	0	FG+ FG BR	0		0.0	0.00	29.01	29.69	7.2	30	10.1	23	28	21	29	10
11	54	40	47	-12	39	43	18	0	RA	0		0.0	0.22	28.95	29.67	19.7	34	19.8	40*	33	31	33	11
12	44	39	42*	-17	38	40	23	0	RA BR	0		0.0	0.44	28.87	29.59	15.9	33	16.0	29	33	23	32	12
13	50	40	45	-15	41	42	20	0	RA BR	0		0.0	0.14	29.07	29.76	7.5	33	7.7	15	33	13	33	13
14	57	45	51	-9	48	50	14	0	RA BR	0		0.0	0.20	29.28	29.97	8.7	35	8.9	18	01	14	01	14
15	66	51	59	-1	50	53	6	0	RA BR	0		0.0	0.03	29.31	30.03	9.4	34	9.7	23	35	18	33	15
16	72	50	61	1	50	54	4	0	RA VCTS	0		0.0	T	29.15	29.88	6.5	33	7.5	30	05	23	05	16
17	74	47	61	1	43	51	4	0	RA BR	0		0.0	T	28.98	29.69	7.1	34	8.4	30	33	25	34	17
18	67	47	57	-4	37	47	8	0		0		0.0	0.00	29.04	29.73	9.9	34	10.7	30	33	25	33	18
19	66	44	55	-7	41	48	10	0	RA	0		0.0	0.01	29.10	29.79	0.8	11	3.2	13	04	10	04	19
20	76	44	60	-2	45	52	5	0	RA	0		0.0	T	29.16	29.84	4.2	31	8.4	23	29	20	29	20
21	60	39	50	-13	31	43	15	0		0		0.0	0.00	29.38	30.06	4.5	34	5.6	16	31	13	35	21
22	71	37	54	-9	34	46	11	0		0		0.0	0.00	29.44	30.15	1.8	16	3.9	13	29	9	12	22
23	81	45	63	0	43	53	2	0		0		0.0	0.00	29.32	30.04	9.5	17	10.2	23	17	18	20	23
24	88	62	75	12	58	63	0	10	TS TSRA RA VCTS	0		0.0	0.03	28.94	29.66	12.2	20	13.7	38	26	33*	27	24
25	77	63	70	7	62	64	0	5	TSRA RA BR VCTS	0		0.0	0.33	28.83	29.51	3.0	30	6.3	26	34	21	34	25
26	81	62	72	9	63	66	0	7	BR HZ	0		0.0	0.00	29.02	29.67	2.5	33	4.7	15	33	12	33	26
27	85	62	74	10	66	68	0	9	RA FG+ FG BR HZ VCTS	0		0.0	0.01	29.05	29.71	7.8	15	8.4	24	18	21	19	27
28	93	73	83	18	65	71	0	18		0		0.0	0.00	29.13	29.78	12.3	18	12.5	31	19	25	19	28
29	95*	75	85*	20	68	73	0	20	TS RA VCTS	0		0.0	T	29.22	29.87	9.5	18	10.0	24	19	21	20	29
30	82	63	73	8	66	68	0	8	TS TSRA RA FG+ BR VCTS	0		0.0	0.56	29.33	30.00	2.3	01	5.3	21	19	17	18	30
31	85	57	71	6	54	62	0	6		0		0.0	0.00	29.43	30.11	3.6	01	5.8	15	02	13	36	31
	70.3	50.4	60.4	¤	48.2	53.8	7.1	2.7	< MONTHLY AVERAGES | TOTALS >			0.0	4.12	29.15	29.85	2.2	29	9.1	< MONTHLY AVERAGES				
	-2.2	1.7	-0.2		<---- DEPARTURE FROM NORMAL ---->								0.74	SUNSHINE, CLOUD, & VISIBILITY TABLES ON PAGE 3									

DEGREE DAYS

	MONTHLY TOTAL	MONTHLY DEPARTURE	SEASON TO DATE TOTAL	SEASON TO DATE DEPARTURE
HEATING :	221	19	6364	-938
COOLING :	83	34	83	26

GREATEST 24-HR PRECIPITATION : 2.00 DATE : 08-09
GREATEST 24-HR SNOWFALL : 0.0 DATE :
GREATEST SNOW DEPTH : 0 DATE :

SEA LEVEL PRESSURE		DATE	TIME
MAXIMUM :	30.23	22	0953
MIMIMUM :	29.47	25	1553

NUMBER OF DAYS WITH ->

MAXIMUM TEMP >= 90 :	0	MINIMUM TEMP <= 32 :	0	PRECIPITATION >= 0.01 INCH:	13
MAXIMUM TEMP <= 32 :	0	MINIMUM TEMP <= 0 :	0	PRECIPITATION >= 0.10 INCH:	9
THUNDERSTORMS :	5	HEAVY FOG :	3	SNOWFALL >= 1.0 INCH :	0

Figure 20. Sample National Climatic Data Center, Local Climatological Data summary sheet

Weighted Wind Fetch

Wind fetch was calculated at 10 degree increments around entire compass for each management scenario using the wind fetch model. Figure 21 depicts the graphical breakdown of wind direction frequencies. Of note are peaks in wind frequency from the south and the northwest. Using the wind fetch model, these weighted individual wind fetch outputs were summed to create a final weighted wind fetch model for each particular management scenario.
Another possible method for weighting the collected wind data instead of by the percentage of observations from each respective direction would be to weight according to the average intensity of the wind from each direction or some combination of the two methods. Alternatively, you could weight only for intensities greater than a certain threshold.

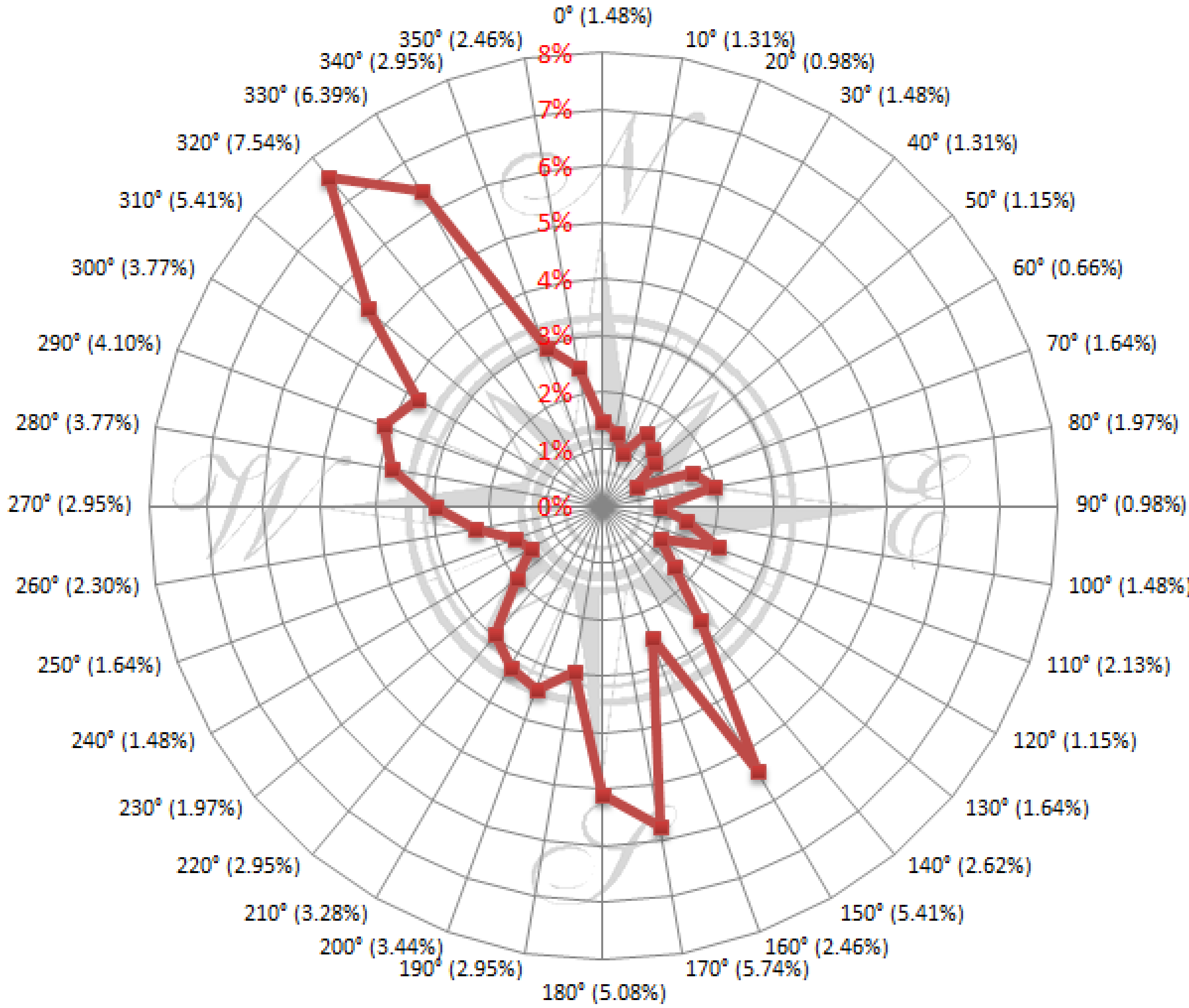


Figure 21. Breakdown of wind directions collected for La Crosse Municipal Airport site

Analysis Results

Weighted wind fetch was calculated for UMRS Pool 9 for each potential management scenario; No-Action (2065), Existing Conditions (2015), Scenario 1, Scenario 2, Scenario 3, and Scenario 4.

Figure 22 displays the results of the weighted wind fetch analysis for each management scenario for the Harper's Slough HREP.

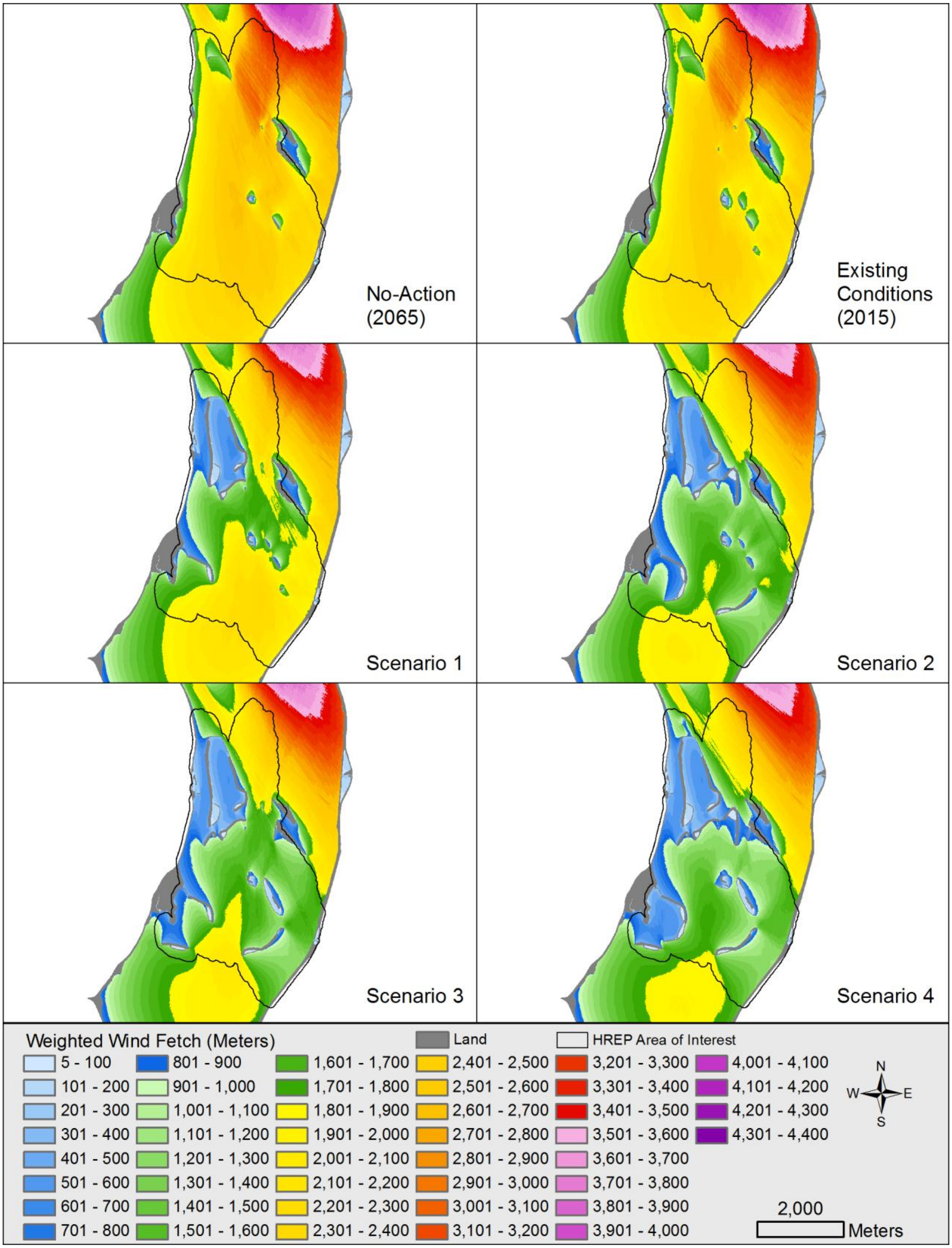


Figure 22. Weighted wind fetch results for the Harper's Slough Habitat Rehabilitation and Enhancement Project

Figure 23 depicts the difference in weighted wind fetch in meters from the no-action (2065) conditions management scenario to the existing conditions (2015) scenario and scenarios 1, 2, 3, and 4 for Harper's Slough HREP.

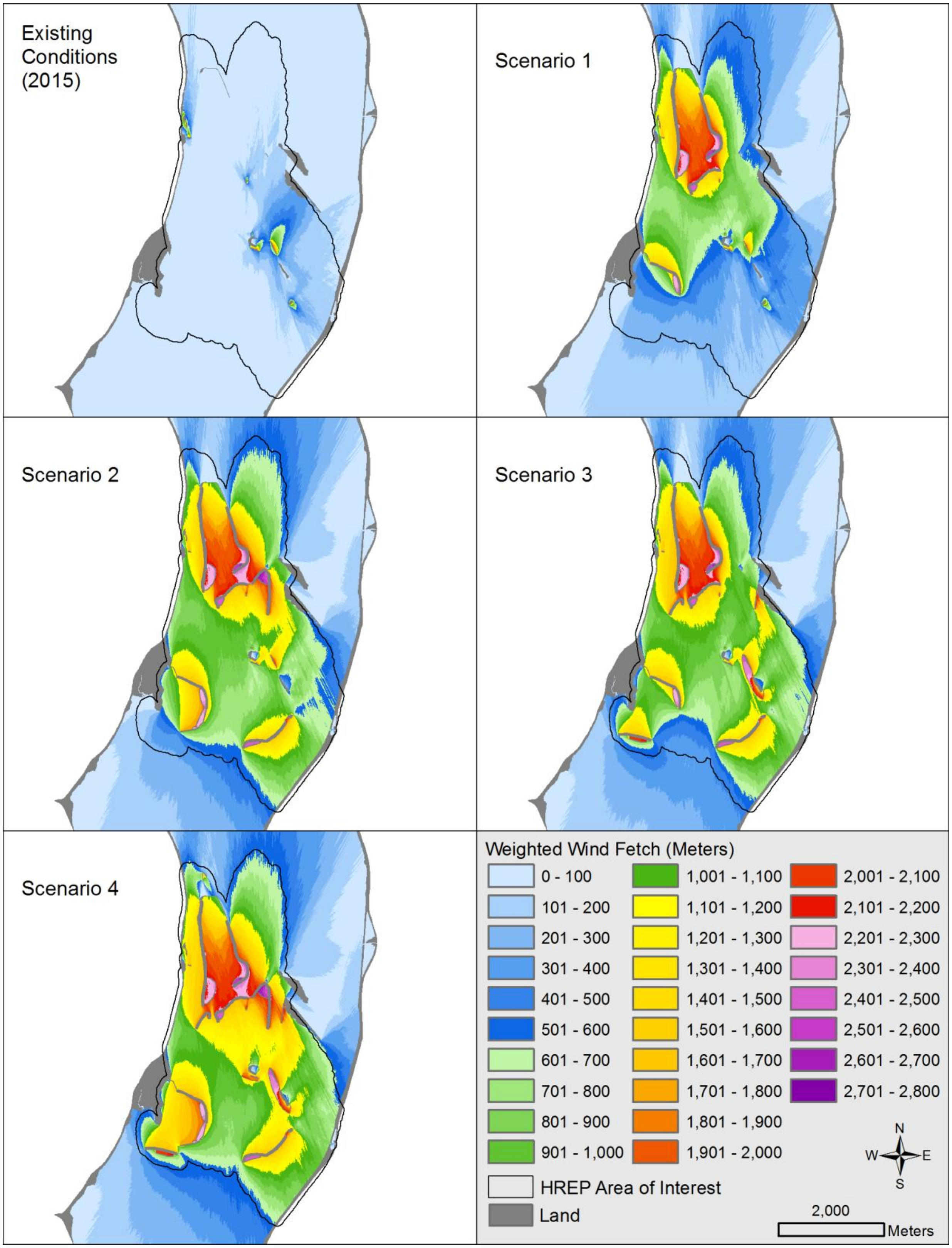


Figure 23. Difference in weighted wind fetch from the no-action (2065) conditions management scenario to the existing conditions (2015) scenario and scenarios 1, 2, 3, and 4 for the Harper's Slough HREP

Figure 24 shows the percent decrease in weighted wind fetch from the No-Action (2065) management scenario to the existing conditions (2015) scenario and scenarios 1, 2, 3, and 4 for the Harper's Slough HREP area of interest which was defined using the Delineate Area of Potential Effects Model. Parameters used to generate the area of interest were based upon identifying pixels where there was at least a 600 meter difference in weighted wind fetch between the existing conditions (2015) management scenario and management scenario 4. The area that these selected pixels encompassed was then buffered 100 meters to create a continuous bounding polygon.

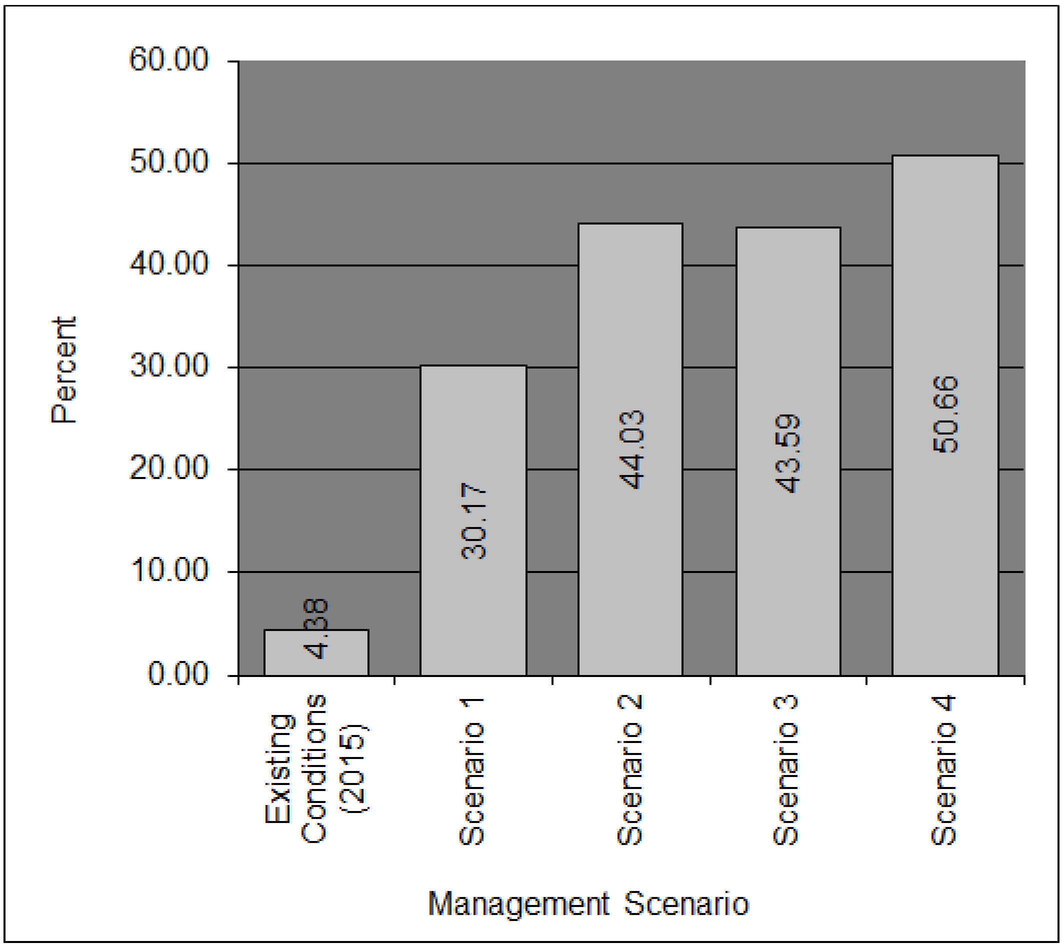


Figure 24 Graph depicting the percent decrease in weighted wind fetch from the No-Action (2065) management scenario to the existing conditions (2015) scenario and scenarios 1, 2, 3, and 4 for the Harper's Slough Habitat Rehabilitation and Enhancement Project area of interest

Discussion

Using this weighted fetch analysis approach it is possible to quantify the amount of wind fetch for each of the separate island design management scenarios and compare how the addition of potential island structures may affect wind fetch. This approach took into account historical wind data. Site-specific wind data would have been preferred but this was unavailable. The ability to decrease wind fetch within the HREP locations would benefit these sites by lessening the forces applied due to wave energy and thereby decreasing turbidity. With the addition of features for each management scenario progressing from 1 to 4 we see decreases in the amount of weighted wind fetch within both study areas.

Sediment Suspension Probability Analysis

Many factors affect aquatic plant growth. These may include site-characteristic changes in climate, water temperature, water transparency, pH, and oxygen effects on CO_2 assimilation rate at light saturation, wintering strategies, grazing and mechanical control (removal of shoot biomass), and of latitude (Best and Boyd 1999). According to Kreiling and others 2007, "light, rather than nutrients, was the main abiotic factor associated with the peak *Vallisneria* shoot biomass in Pool 8." Wave action has a direct effect on water transparency. When sediments are suspended by wave action, it causes an increase in water turbidity. High turbidity can reduce aquatic plant growth by decreasing water transparency, thus limiting light penetration.

The sediment suspension probability analysis developed for the Harper's Slough HREP involved executing the wave models to calculate maximum orbital wave velocity (MOWV) outputs for each potential management scenario and applying these MOWV values to predict sediment suspension probabilities. According to Coops and others 1991, "maximal wave heights and orbital velocities were concluded to be key factors in the decreased growth rates of plants at exposed sites."

The MOWV was calculated once daily over the growing season (April through July) encompassing the 5-year period between 2008 and 2012 (n = 610 days). The MOWV of 0.10 meters per second was then selected to represent velocities required to suspend fine unconsolidated sediments (Håkanson and Jansson 1983). This empirical derivation may need to be improved upon and tested across a wider range of environments but for our purposes provides a baseline to compare the alternative management scenarios.

Bathymetric data used in the wave model equations were obtained from the UMRR-EMP LTRMP (see "spatial datasets used in analyses" section for detailed background information). The bathymetric data had to be modified when calculating the MOWV for the "No Action" management scenario. All island areas that were predicted to be lost in that scenario were given the lowest water depth for those areas, in this example 0.01 meters (1 centimeter). A case can be made to exclude these areas from analysis (treat as land/no data) as water depths this shallow would most likely cause waves to break.

The next step in the analysis involved reclassifying areas within the output MOWV raster that had MOWV values >= 0.10 meters per second with a "1" value and reclassifying areas within the output MOWV raster that had MOWV < 0.10 meters per second with a "0" value. This was done for all 610 raster outputs automatically by the wave model by selecting the check box to

“Calculate Percentage of Days Sediment is Suspended”. The tool accomplished this by summing the individual sediment suspension probability rasters together into one raster dataset and dividing the values by the total number of days (610) to get a percentage of days that MOWV was at least 0.10 meters per second for each individual raster cell. This value then represents the probability to suspend fine unconsolidated particles. Figure 25 gives a graphical illustration of the process used to create the percentage of days sediment is suspended output using four hypothetical raster datasets as an example.

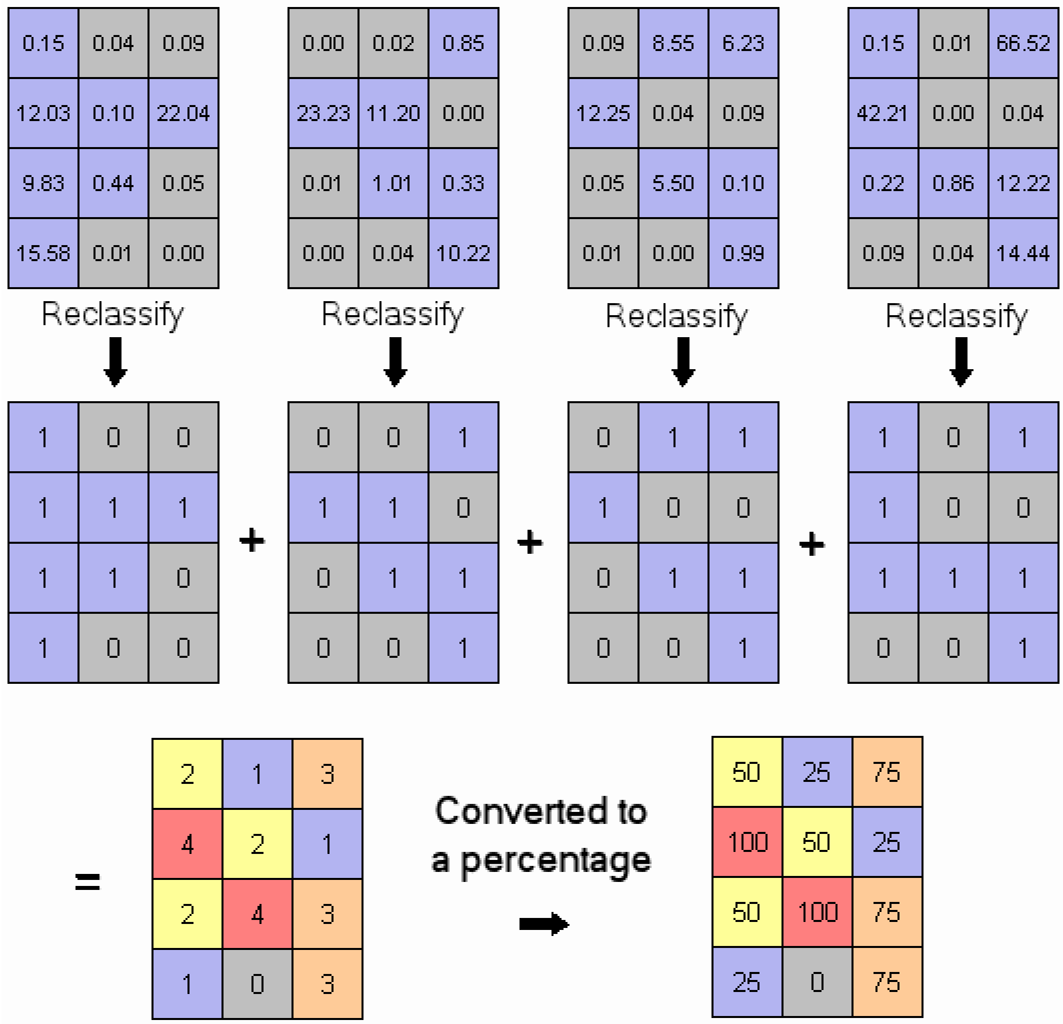


Figure 25. Diagram explaining process for calculating percent of days capable of suspending sediments

Analysis Results

Sediment suspension probability was calculated for UMRS Pool 9 for each potential management scenario: No-Action (2065), Existing Conditions (2015), Scenario 1, Scenario 2, Scenario 3, and Scenario 4.

Figure 26 displays the results of the sediment suspension probability analysis for each management scenario for the Harper’s Slough HREP.

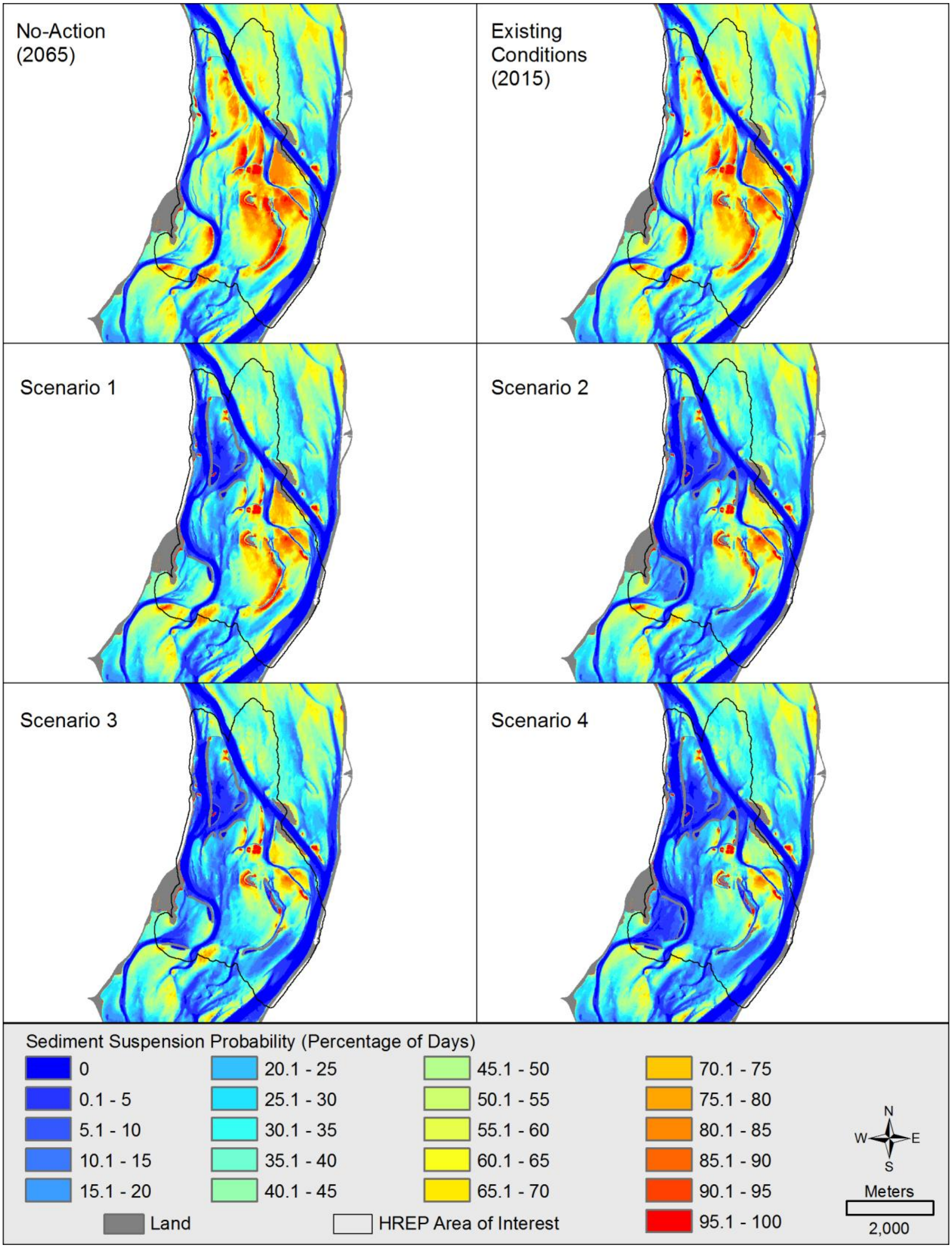


Figure 26. Sediment suspension probability results for the Harper's Slough HREP

Figure 27 depicts the difference in sediment suspension probability from the no-action (2065) management scenario to the existing conditions (2015) scenario and scenarios 1, 2, 3, and 4 for Harper's Slough HREP.

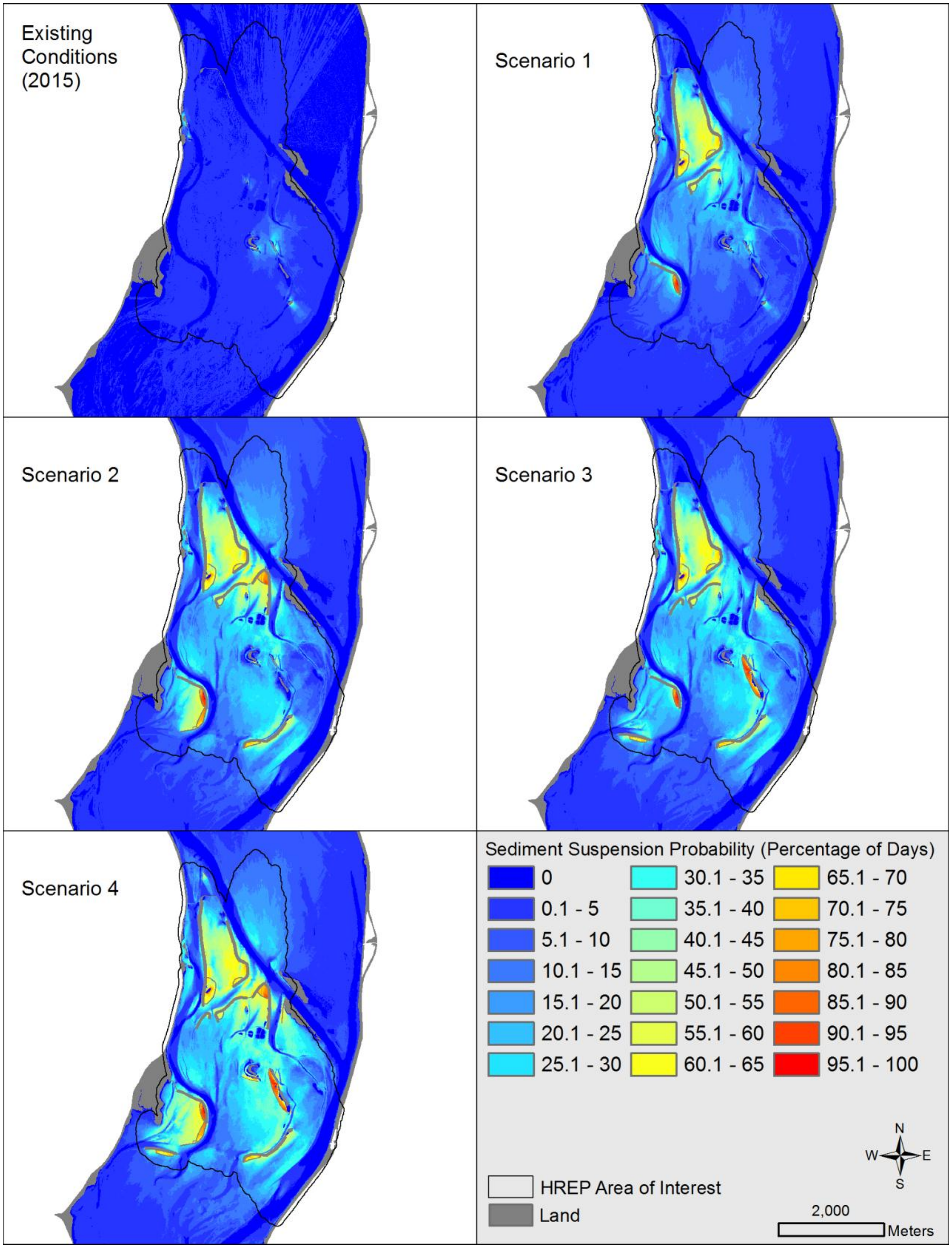


Figure 27. Difference in sediment suspension probability from the no-action (2065) conditions management scenario to the existing conditions (2015) scenario and scenarios 1, 2, 3, and 4 for the Harper's Slough HREP

Figure 28 shows the percent decrease in sediment suspension probability from the No-Action (2065) management scenario to the existing conditions (2015) scenario and scenarios 1, 2, 3, and 4 for Harper's Slough HREP.

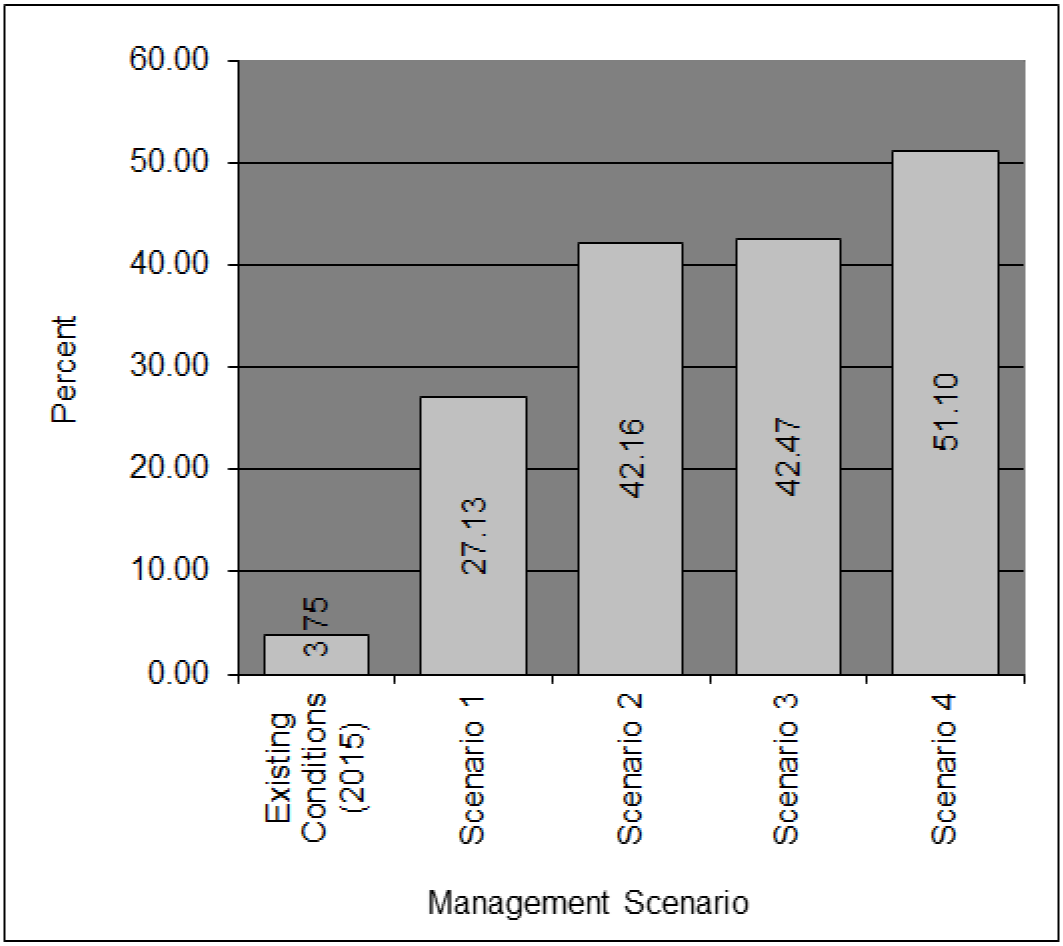


Figure 28 Graph depicting the percent decrease in sediment suspension probability from the No-Action (2065) management scenario to the existing conditions (2015) scenario and scenarios 1, 2, 3, and 4 for the Harper's Slough Habitat Rehabilitation and Enhancement Project

Discussion

This analysis provides a simplistic approach to forecasting wave effects on the suspension of fine unconsolidated sediment particles. Based upon this approach, it is possible to depict changes in sediment suspension probability for several potential island construction scenarios at the identified HREP areas both with maps and summary charts. By decreasing the potential for sediments to be suspended, there would be a decrease in turbidity. Decreasing turbidity would increase light penetration and, therefore, create conditions more conducive to aquatic plant growth. This approach took into account historical wind data. Site-specific wind data would have been preferred but this was unavailable. With the addition of features for each management scenario progressing from 1 to 4, we see decreases in the percentage of days with MOWV capable of suspending fine unconsolidated particles within both study areas. A next step in the process would most likely be to perform a sensitivity analysis on the MOWV identified that causes suspension of fine unconsolidated sediments.

Spatial Datasets Used in Analyses

UMRR-EMP LTRMP 2010 Land Cover/Land Use Data for the Upper Mississippi River System

Originator

Upper Mississippi River Restoration – Environmental Management Program's Long Term Resource Monitoring Program element, as distributed by the U.S. Geological Survey, Upper Midwest Environmental Sciences Center, La Crosse, Wisconsin

Abstract

Aerial photographs for Pools 1-13 Upper Mississippi River System and Pools, Alton-Marseilles, Illinois River were collected in color infrared (CIR) in August of 2010 at 8"/pixel and 16"/pixel respectively using a mapping-grade Applanix DSS 439 digital aerial camera All CIR aerial photos were orthorectified, mosaicked, compressed, and served via the UMESC Internet site. The CIR aerial photos were interpreted and automated using a 31-class UMRR-EMP LTRMP vegetation classification. The 2010/11 LCU databases were prepared by or under the supervision of competent and trained professional staff using documented standard operated procedures and are subject to rigorous quality control (QC) assurances (NBS, 1995). Online Linkage http://www.umesc.usgs.gov/data_library/land_cover_use/2010_lcu_umesc.html

UMRR-EMP LTRMP Bathymetric Data for the Upper Mississippi and Illinois Rivers

Originator

Upper Mississippi River Restoration – Environmental Management Program's Long Term Resource Monitoring Program element, as distributed by the U.S. Geological Survey, Upper Midwest Environmental Sciences Center, La Crosse, Wisconsin

Abstract

Water depth is an important feature of aquatic systems. On the UMRS, water depth data are important for describing the physical template of the system and monitoring changes in the template caused by sedimentation. Although limited point or transect sampling of water depth can provide valuable information on habitat character in the UMRS as a whole, the generation of bathymetric surfaces are critical for conducting spatial inventories of the aquatic habitat. The maps are also useful for detecting bed elevation changes in a spatial manner as opposed to the more common method of measuring changes along transects. The UMESC has been collecting bathymetric data within the UMRS since 1989 in conjunction with the UMRR-EMP LTRMP.

Online Linkage

http://www.umesc.usgs.gov/data_library/aqa_feat_bath_str/bathymetry.html

Acknowledgements

We thank Keith LeClaire and Jon Hendrickson, U.S. Army Corps of Engineers, St. Paul District for their assistance with this project. We thank Dr. Wayne Thogmartin for his assistance in the statistical validation of the wind fetch model. This contract report was also made measurably better by the comments of reviewers.

References Cited

Anderson, M.E., J.M. Smith,, and S.K. McKay. 2011. Wave Dissipation by Vegetation. Coastal and Hydraulics Engineering Technical Note ERDC/CHL CHETN-I-82. Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://chl.erdc.usace.army.mil.chetn.

Best, E.P.H. and W.A. Boyd, 1999, A simulation model for growth of the submersed aquatic macrophyte *Myriophyllum spicatum L*. Technical Report A-99-3, US Army Engineer Research and Development Center, Vicksburg, Mississippi.

Chamberlin, F. 1994. Wind-generated waves in navigation pools. Report by the U.S. Army Corps of Engineers, St. Paul, Minnesota, for the National Biological Service, Environmental Management Technical Center, Onalaska, Wisconsin, December 1994. LTRMP 94-S001. 16 pp. (NTIS #PB95-209532)

Coops, H., R. Boeters and H. Smit. 1991, Direct and indirect effects of wave attack on helophytes. Aquat. Bot. 41:333-352.

Finlayson, D. 2005, david.p.finlayson - Puget Sound Fetch. School of Oceanography, University of Washington, Seattle, WA. Accessed October 16, 2007, from http://david.p.finlayson.googlepages.com/pugetsoundfetch

Ford, D.E., and H.G. Stefan 1980, Thermal predictions using integral energy model. Journal of the Hydraulics Division, Vol. 106, No HY1.

Håkanson, L., and Jansson, M., 1983, Principles of lake sedimentology, Second edition. The Blackburn Press, New Jersey, 316 p.

Kraus, N. Class notes for coastal sediment processes, OCEN 682, Texas A&M University and Waterways Experiment Station Graduate Institute, 5 June to 9 August 1991.

Kreiling, R. M., Yin, Y., and Gerber, D. T., 2007, Abiotic influences on the biomass of *Vallisneria americana Michx*. in the Upper Mississippi River: River Research and Applications, v. 23, no. 3, p. 343-349.

Manly, B.F.J., 1997, Randomization, bootstrap and Monte Carlo methods in biology. Second Edition, Chapman & Hall, New York, pp.96-97.

Munk, W.H., 1944, Proposed uniform procedures for observing waves and interpreting instrument records. Wave Project, Scripps Institute of Oceanography, LaJolla, California.

Smith, J.M., 1991, Wind-wave generation on restricted fetches. U.S. Army Engineer Waterways Experiment Station, Misc. Paper CERC-91-2, 25pp.

U.S. Army Corps of Engineers (USACE), 1977, Shore Protection Manual, Third Edition. Coastal Engineering Research Center, Fort Belvoir, Virginia.

USACE, 1984. Shore Protection Manual, Coastal Engineering Research Center, Fort Belvoir, Virginia.

USACE, 2002, Coastal Engineering Manual, Engineer Manual 1110-2-1100, U.S. Army Corps of Engineers, Washington, D.C. (in 6 volumes).

USACE, 2005, Harper's Slough habitat rehabilitation and enhancement project: rough draft definite project report and integrated environmental assessment, St. Paul District.

USACE, 2006, Environmental Design Handbook, Upper Mississippi River System, Environmental Management Program.

USACE 2011. Upper Mississippi River System Ecosystem Restoration Objectives 2009. U.S. Army Corps of Engineers, Rock Island, Illinois. 87 pp.

USACE, (n.d), Harpers Slough Habitat Project, Pool 9, Iowa, St. Paul District. Accessed September 27, 2007, from http://www.mvp.usace.army.mil/environment/default.asp?pageid=129