FlightPath v1.1

BETA Version

Terrain-based Raptor Migration Model

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1. Overview

FlightPath is a theoretical model for simulating raptor migration pathways in mountainous terrain. It uses a spatially explicit, individual-based modeling approach (see DeAngelis and Mooij, 2005; Grimm and Railsback, 2005) based on the premise that raptors will preferentially migrate where updrafts are present to reduce their energy expenditure. By combining the results of many simulations of individual raptors (more properly termed "model raptors" since the model cannot reproduce the complexity inherent in raptor migratory behavior), the model predicts the frequency or probability of migration on a pixel-by-pixel basis throughout a user-specified region for given wind conditions. In aggregate, the high probability locations form the expected migration pathways through the region.

In its current form, the model uses a fixed wind speed and direction, but can also be run for multiple fixed wind conditions. A dynamic mode using hourly meteorological data which will better apply over long migration distances is under development and should be available in the near future.

The model is being developed in part as a tool to assist regulatory agencies (particularly the Pennsylvania Game Commission), wind energy developers, and other interested parties in assessing the potential collision risk of proposed wind turbine sites to migrating raptors. This version of the software is applicable to Pennsylvania, particularly mountainous regions of the Commonwealth. The model uses ~148 km X ~168 km overlapping simulation regions based on the DeLorme *Pennsylvania Atlas & Gazetteer*.

The model applies to species such as golden eagles, bald eagles, and red-tailed hawks that make extensive use of ridge lift for slope-soaring and gliding flight during migration in late autumn or early spring (Maransky et al, 1997). The model should not be used to predict migration pathways of raptor species that often use powered flight or thermals for lift during migration (see Section 7 for further discussion of model limitations).

The model is best used as a tool or guide in assessing the likelihood of concentrated migration pathways and in designing field studies, especially where little raptor migration data are currently available. It is necessary to verify the model simulations with field data, e.g. pre-construction monitoring data from proposed wind energy sites.

2. Model Inputs and Outputs

A limited set of inputs is needed to run the model (see Figure 2.1). The model inputs are listed briefly below and are described more fully in Sections 4 -6:

- digital elevation model (DEM) data for the region of interest – the model includes the 3 arc sec (~90-m) DEM files corresponding to the DeLorme *Pennsylvania Atlas & Gazetteer* pages 28-96 (see Figure 2.2)
- model raptor starting locations (latitude, longitude coordinates) and number of tracks to simulate from each point
- wind speed and wind direction
- principal axis of migration (PAM), i.e., the direction of migration within a model region
- the threshold updraft velocity, i.e. the velocity below which updrafts are too weak for raptors to use during migration
- the look-ahead distance, i.e. the distance that raptors will travel to find updrafts, such as when crossing a gap in a ridge
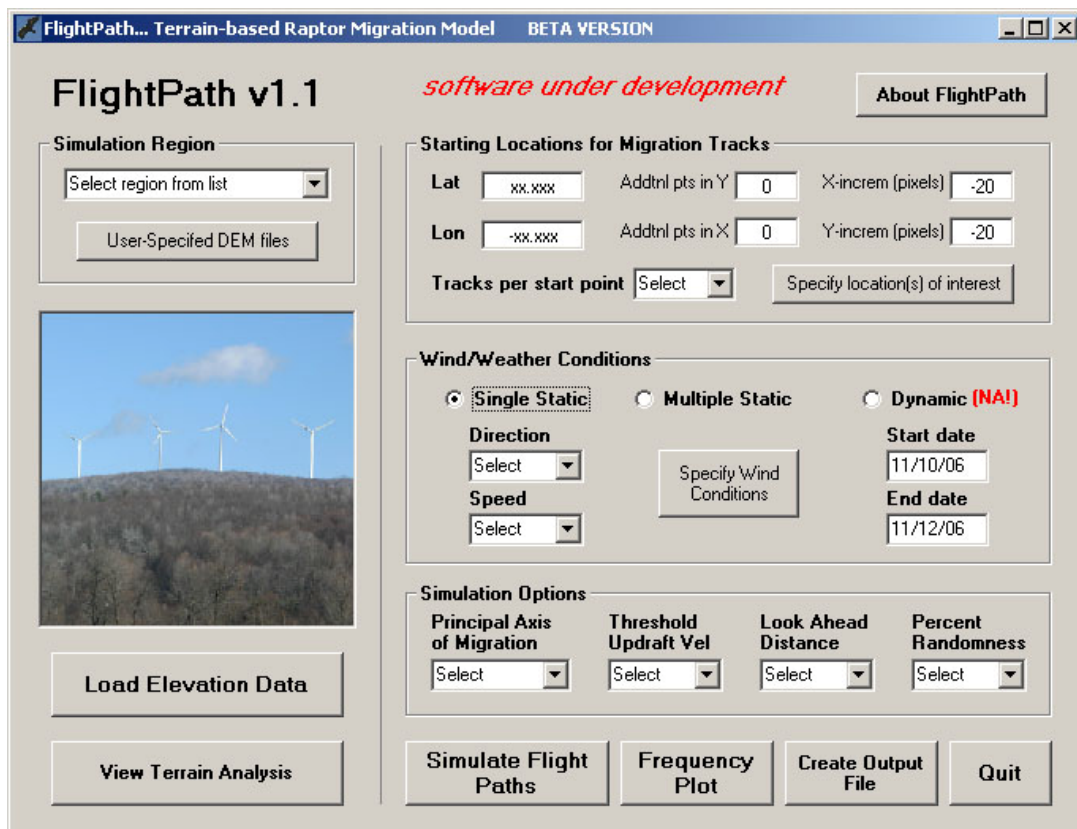- percent randomness, i.e. how frequently migrating raptors deviate from an energy-minimizing route

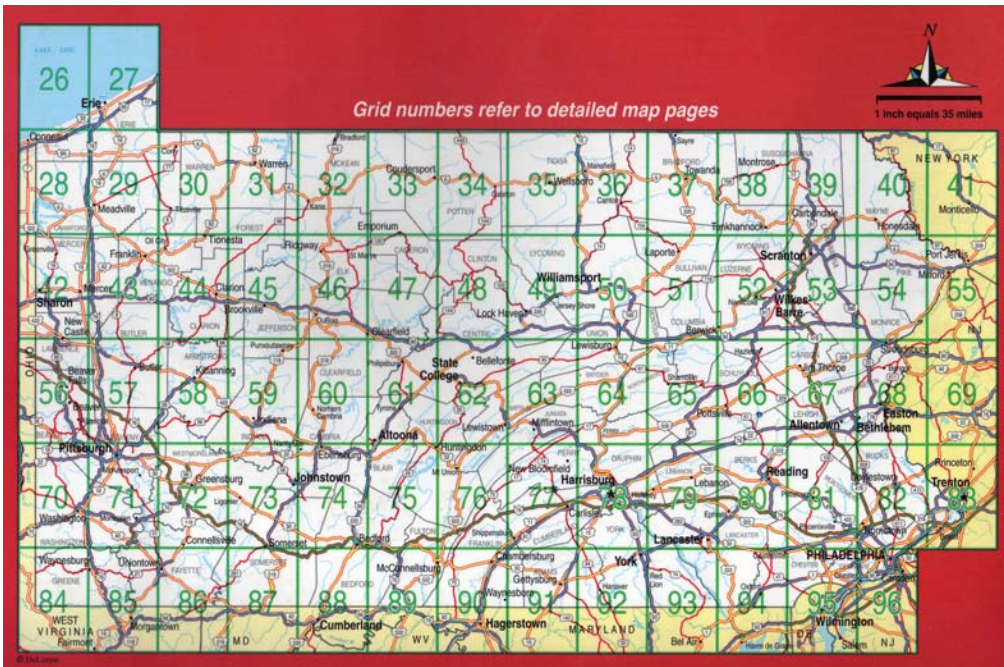Figure 2.1 FlightPath software interface

Figure 2.2 DeLorme *Pennsylvania Atlas & Gazetteer* page numbers

For a given set of input parameters (region, wind conditions, raptor starting locations, direction of migration, etc.) the model produces a graphic showing the model raptor migration tracks through the region specified, and a graphic showing the simulated frequency of migration at each pixel of the region, as shown below in Figure 2.3. Note that the expected migration pathways emerge in the simulated frequency of migration plot.
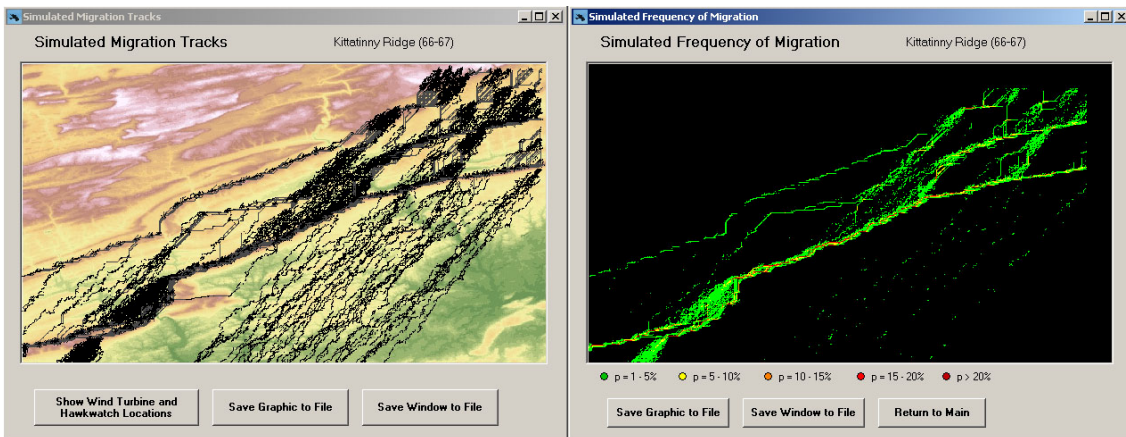

Figure 2.3 Example of graphical output from FlightPath (Kittatinny Ridge (66-67) region)

The user has the option of creating a text output file that summarizes the input parameters, gives the estimated migration frequencies at user-specified latitude-longitude (lat-lon) locations, and gives a listing of lat-lon coordinates for all locations with high estimated migration frequencies. This file can be imported easily into ArcGIS, or display software such as Google Map or Google Earth.

3. Theoretical Basis of the Model

3.1 Model Principles

The model is based on the following principles:

(1) updrafts produced by horizontal wind striking sloping terrain provide the dominant source of lift;
(2) raptors within a model region migrate in a preferred direction termed the "principal axis of migration (PAM)" (see Kerlinger, 1989);
(3) raptors reduce their energy expenses by preferentially migrating where updrafts are present;
(4) when updrafts are not available locally, raptors can identify where updrafts are present (either by recognizing landforms conducive to the formation of updrafts, or by observing other raptors using updrafts) and will seek out these areas;
(5) a variety of behavioral patterns (e.g., foraging, interaction with other birds) occur during migration that are unrelated to updrafts and energy minimization – the model incorporates a random component to represent such behavior.

3.2 Model "Rules of Motion"

To implement the above principles, the model employs four hierarchical rules of motion for each model raptor:

(1) based on the user-specified percent randomness, make a random move in any direction for a random distance
(2) check updrafts in adjacent pixels in the PAM-ward quadrant (the PAM-ward quadrant extends 45 deg on either side of PAM) – move to the pixel within the PAM-ward quadrant that has the greatest updraft and elevation, so long as the updraft exceeds the user-specified threshold
(3) if Rule 2 cannot be satisfied, look ahead in the PAM-ward quadrant for stronger updrafts, searching as far as the user-specified look-ahead distance. Move to the location of maximum updraft in this region, so long as the updraft exceeds the user-specified threshold
(4) if Rule 3 cannot be satisfied (i.e., no updrafts exceed threshold), randomly move to one of the three adjacent pixels in the PAM-ward quadrant

These rules are applied iteratively from each start point until the model raptor reaches the boundary of the simulation region. After all model raptors have been simulated, the frequency or probability of migration at each pixel is determined by dividing the number of times a model raptor passed the pixel by the total number of model raptors simulated.

4. Step-by-Step Tutorial

To run the model you must have the FlightPath.exe file and the "FlightPathdatafiles" folder in the same directory. These files are available on the web at xxxxxxx. The model will run on any PC; however 2 GB of RAM or more and a fast processor are recommended.

4.1 Double-click the FlightPath icon

The model definition screen will appear as shown above in Figure 2.1

4.2 Load the data for the region of interest

Select the region from the pull-down menu (see Fig 4.1) and then click on the "Load Elevation Data" button. If you want to apply the model to a location not listed, you must provide the DEM input files (see Appendix A-1). Click on the "User-Specified DEM files" button and then enter the file information (see Fig 5.2).
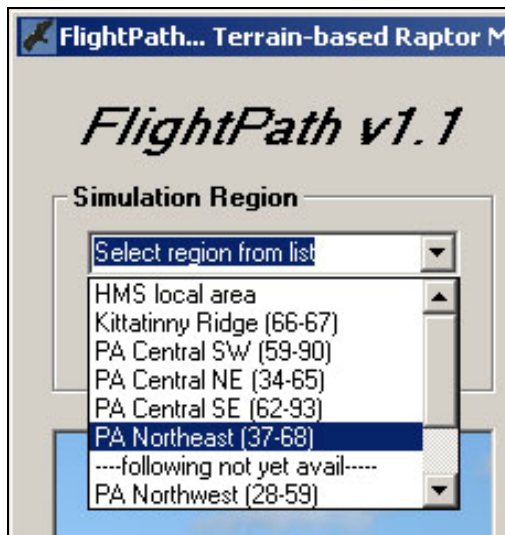

Figure 4.1 Pull-down menu used to select model region
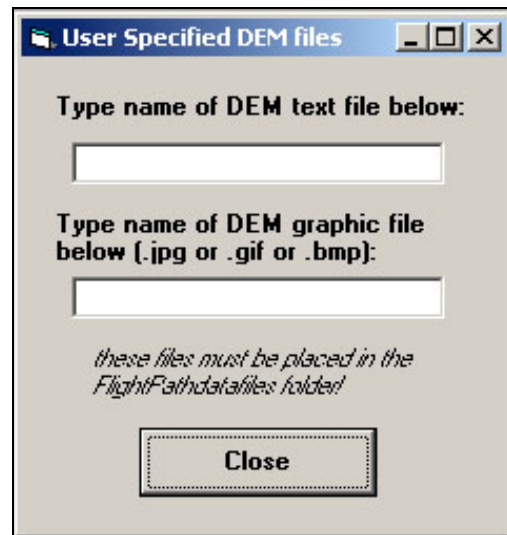
Figure 4.2 Window for user-specified model region

Warning: the Model Principles and Rules of Motion discussed in Section 3 apply to Pennsylvania. Additional model rules are necessary to simulate raptor migration pathways in regions with differing terrain, geography, and land cover. For example the current model has limited input parameter options and has no built-in mechanisms for the effects of high elevation terrain, water barriers, or land cover such as snow, desert, or urban regions.

Once the data are loaded, the latitude-longitude coordinates for the corners of the region will be displayed (see Figure 4.3). If desired, click on the "View Terrain Analysis" button to see an analysis of terrain aspect, terrain slope, and updrafts for different wind directions in the region selected – note this may take a while if the region is large (the cursor will take the shape of an hourglass whenever the program is processing data). You will get output on terrain slope, aspect (orientation from north), and updrafts under different wind conditions (see Figure 4.4).
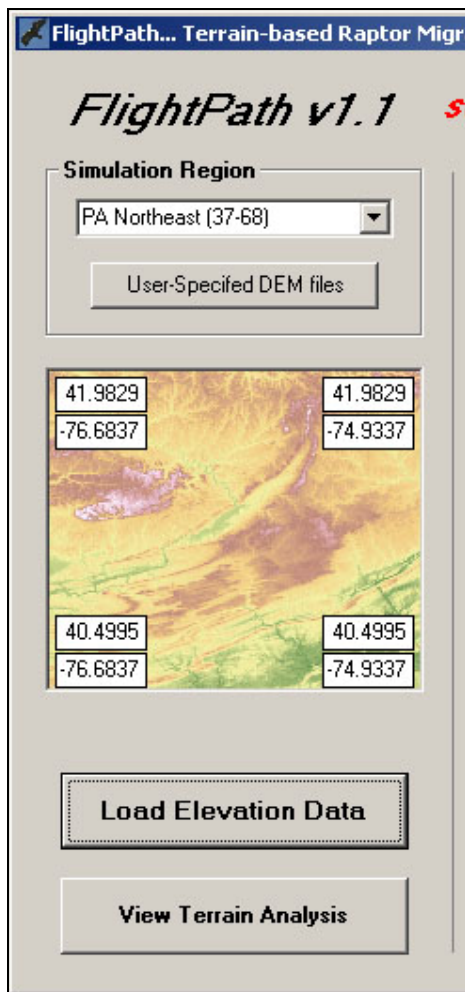

Figure 4.3 Loaded DEM showing lat-lon coordinates of each corner of the region
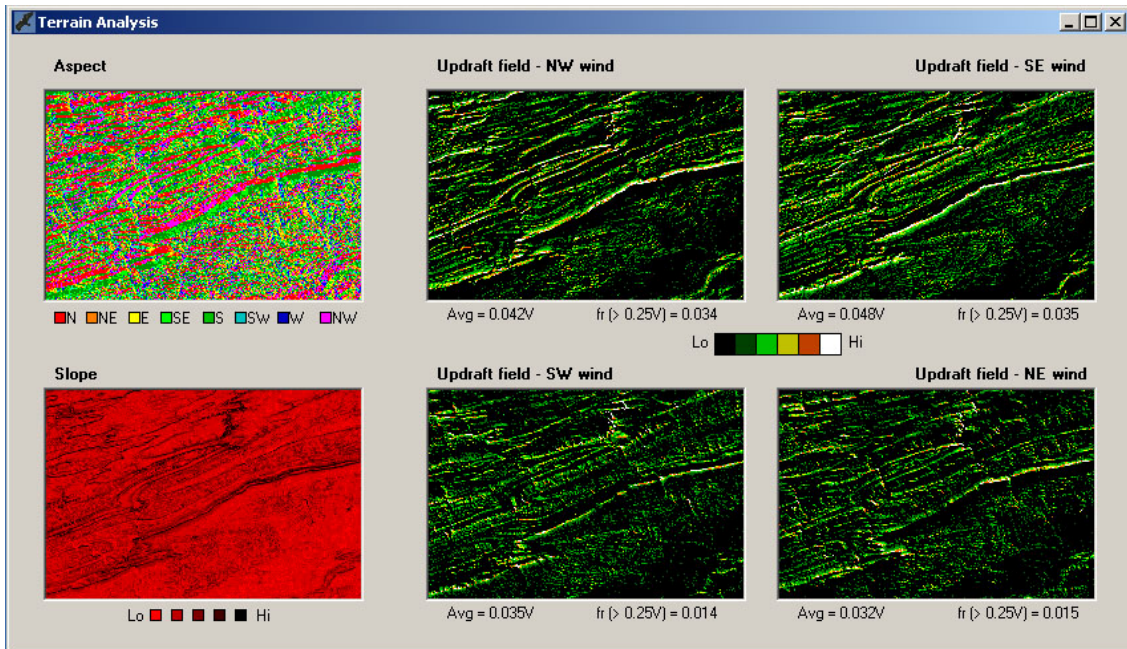
Terrain Analysis

Aspect

■N ■NE □E ■SE ■S ■SW ■W ■NW

Slope

Lo ■ ■ ■ ■ ■ Hi

Updraft field - NW wind

Avg = 0.042V   fr (> 0.25V) = 0.034

Lo ■■■■■ Hi

Updraft field - SE wind

Avg = 0.048V   fr (> 0.25V) = 0.035

Updraft field - SW wind

Avg = 0.035V   fr (> 0.25V) = 0.014

Updraft field - NE wind

Avg = 0.032V   fr (> 0.25V) = 0.015

Figure 4.4 FlightPath terrain analysis (Kittatinny Ridge (66-67) region)

4.3 Specify the starting locations for migration

These are the locations for which a migration track will be simulated. Place start points where you expect migrating raptors to be distributed as they enter the region of interest (e.g., in autumn, along the northern and possibly eastern boundary of the region simulated). It is helpful in choosing these locations to examine the latitude-longitude coordinates for the corners of the region (see Figure 4.3 above).

Begin by specifying the latitude and longitude coordinates of one start point, and then use the boxes labeled "Addtnl pts in X" and "Addtnl pts in Y" to add more start points to the east/west and north/south of the first location. Note that the coordinate system is set up such that north and east are the positive directions. If additional start points are desired in the south and west directions, enter *negative* values for X-increment and Y-increment. Each pixel = 3 arc sec of latitude or longitude (~90 m), so 20 pixels is equivalent to one minute of latitude or longitude, or about 2 km . This is an appropriate spacing for most applications.

Finally, select how many tracks you want to simulate per starting point – it is critical to simulate multiple tracks per start point because the random component of the model ensures that each track will look somewhat different. More tracks take more time for a simulation to run but result in more reliable estimates of model raptor migration probability. You may want to start with 1 track per start point and run the model a few

times until you get the start points located exactly where you want them, then increase the number of tracks per start point.

The model does not allow the user to vary the number of tracks per start location from one start point to another. In testing the model we found that when appropriate starting locations are used relative to the location of the site of interest (see note below), the resulting simulated migration patterns were essentially invariant to differences in number of tracks at different start points.

Important note: the placement of the starting locations will influence the model results (these are often called "boundary effects" in modeling terminology). See Section 6 for further discussion.

4.4 Specify locations for which you want to output results

If output for specific locations in the region is desired, click on the button "Specify location(s) of interest" and a window will appear as shown in Figure 4.5. Enter the latitude and longitude of up to four locations. These locations will show up as purple dots on your output graphics.

Figure 4.5 Window for specifying locations of interest for additional model output

4.5 Specify the wind and weather conditions

There are three options for wind and weather conditions: static single, static multiple and dynamic (not yet available). For the static single option, use the pull down menus to specify one of the eight cardinal wind directions and a wind speed. Wind speeds (2.5, 5, 7.5, and 10) are given in meters per second, corresponding to 5.6, 11.2, 16.8, and 22.4 mph. The 2.5 mps option is only included to illustrate the fact that migration

patterns are essentially independent of terrain at such low wind speeds. Cut-in speeds (the minimum wind speed at which the rotor turns) for wind turbines are typically around 5 mps, so the rotor would not be turning at 2.5 mps.

Use the Multiple Static option to run several different wind directions and wind speeds and aggregate the results (see Figure 4.6). The 2.5 mps wind speed is not simulated for the multiple winds option for the reasons discussed above.
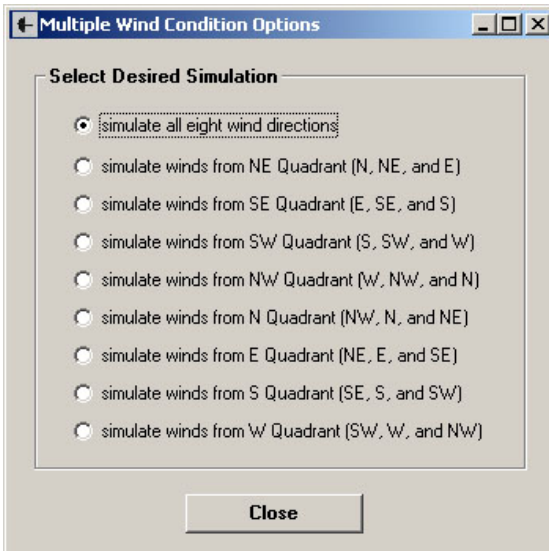

Figure 4.6 Window for specifying multiple wind conditions

4.6 Specify the simulation options

4.6.1 PAM
This will depend primarily on the season (spring vs. autumn) and the migration direction in the region of interest. See discussion in Section 6.

4.6.2 Threshold Updraft Velocity
This is the updraft velocity below which terrain updrafts are too weak to be utilized for migration. A default value of 1.5 mps is recommended.

4.6.3 Look Ahead Distance
When the raptor moving at high elevation encounters an area of minimal or no updrafts (e.g., a gap in a ridge), this is the distance it will search ahead in the PAM-ward quadrant to find updrafts. Typically a value of 2-3 km gives reasonable results.

4.6.4 Percent Randomness
This is the percentage of movement that is uninfluenced by PAM, by wind conditions, or by local terrain. Random movement may occur in any direction, from a minimum

distance of ~200 m to a maximum of ~500 m (these distances are based on jumps of 2 to 5 pixels in the 3 arcsec DEM data).

4.7 Simulate Flight Paths

Once all input parameters are entered, press the Simulate Flight Paths button and be prepared to allow your computer to work for a while. If there are or missing inputs, you will be prompted with a message box. A window will open showing the simulated model raptor migration tracks (see Figure 2.3). There is an option for showing existing wind turbine sites (blue dots) and hawkwatch locations (red dots for autumn sites, green dots for spring sites). The Save Graphic to File option allows the user to save the plot as a .bmp file, and The Save Window to File option allows the user to save the entire window as a .bmp file.

4.8 View Frequency Plot

After the simulated migration tracks graphic appears, press the View Frequency Plot button to view the simulated frequency of migration plot showing the expected migration pathways through the region. This plot can also be saved as a .bmp file.

4.9 Save the Simulation Results

Press the Create Output File button and type in the file name to save the simulation results in a text file. The file summarizes the input parameters, results for each location of interest, and then gives a listing of latitude-longitude coordinates and model migration frequencies for all locations with migration frequencies (probability) > 0.05.

To view the lat-lon locations in ArcGIS, the text output file can be opened (and edited) in MS Excel, and then saved as a .dbf file. The .dbf file can then be used to create a "points" layer in ArcGIS.

To view the lat-lon locations in Google Earth or Google Map, you'll need to create a .KML file from the lat-lon coordinates. See the website http://code.google.com/apis/kml/documentation/ for more information. Another option is to use to the GPS Visualizer site (www.gpsvisualizer.com) to do the conversion for you and create the Google Earth or Google Map file. If you use GPS Visualizer, select the box for forcing text files to be input as waypoints, not trackpoints. This will avoid drawing segments between the points.

5. Sample Applications

This section contains two sample applications that illustrate how the model is intended to be used.

5.1 Assessing likely raptor migration pathways in a region with no monitoring data

Penobscot and Nescopeck Mountains are prominent parallel ridges just west of the Pocono Plateau region (within FlightPath model region PA Northeast (37-68), see Fig 5.1). No hawk migration monitoring data are available for these two ridges. In this example, the model is run to estimate the probability of autumn raptor migration along these ridges at several points along each ridge.
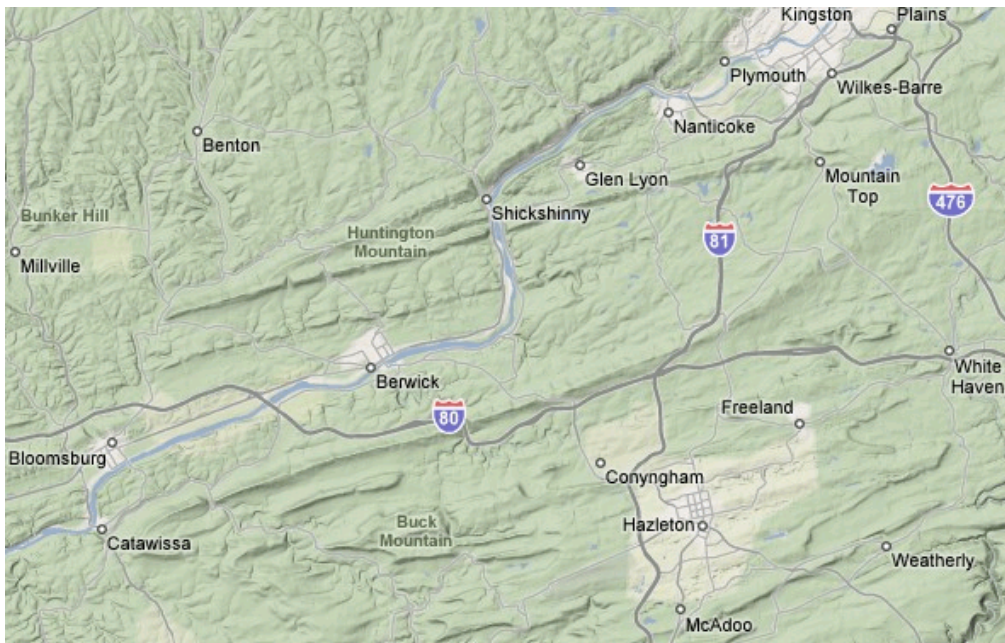
Figure 5.1 Shaded relief map showing the parallel ridges of Penobscot (to the north) and Nescopeck (to the south) Mountains (image from Google Maps).

Two sites along each ridge were chosen for analysis, one near I-81 and one closer to the Susquehanna River. Due to the orientation of the ridges, it is expected that winds from the NW and SE quadrants will generate the best conditions for raptor migration (i.e. the highest simulated migration frequencies). The model was run using the multiple winds option for winds from the NW and SE quadrants (5, 7.5, and 10 mps). Simulations were run with PAM values of 225 (SW) and 202.5 (SSW).

Additional model parameters used are listed below:

```
"threshold updraft strength = 1.5 mps"
"PAM = 225 (SW)"
"look ahead distance = 3 km"
"randomness = 20%"
"main start lat = 41.98"
"main start lon  = -74.94"
"total start points = 51"
"additional pts in y dir = 20"
"additional pts in x dir = 30"
"increment for add pts in y = -20"
"increment for add pts in x = -20"
"number of tracks per pt = 10"

"PAM = 202.5 (SSW)"
"look ahead distance = 3 km"
"randomness = 20%"
"main start lat = 41.98"
"main start lon  = -75.18"
"total start points = 41"
"additional pts in Y dir = 0"
"additional pts in X dir = 40"
"increment for add pts in Y = -20"
"increment for add pts in X = -20"
"number of tracks per pt = 10"
```

Note that the start points depend on the choice of PAM, but in both cases these were confined to the northeast corner of the domain where it is likely that model raptor tracks might intercept the four locations of interest. The number of tracks per point was set to 10 to reduce the time to run the simulations (a model run with winds from a particular quadrant is 9 simulations (3 wind directions X 3 wind speeds for each track).

Figure 5.2 shows migration frequency maps for winds from the NW quadrant. Note the simulated flightline along the ridges bordering Wyoming Valley on the west.
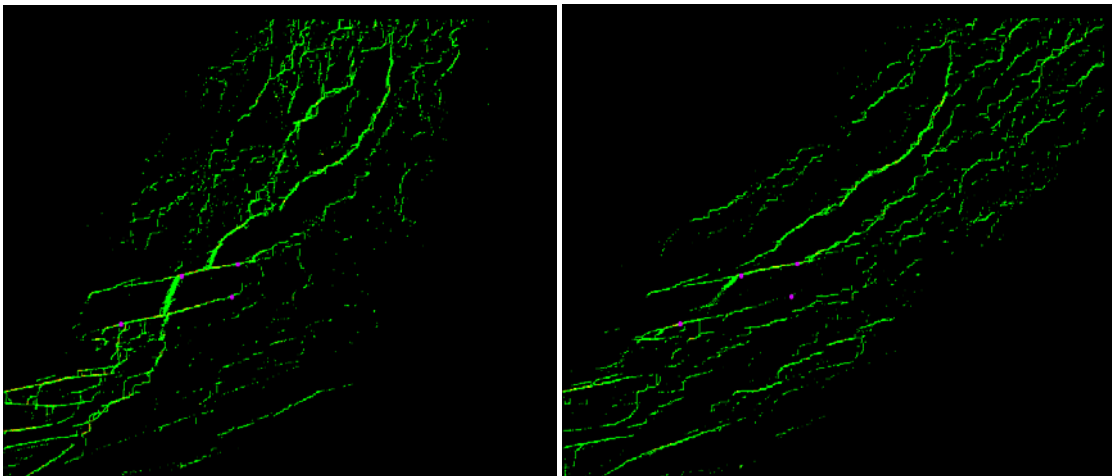

Figure 5.2 Autumn migration frequency maps for winds from NW quadrant (left: PAM=202.5, right: PAM=225)

Results of the simulations are summarized in the table below:

PAM	Wind Condition	Simulated quantity	Penobscot I-81 (41.174, -75.942)	Penobscot west (41.139, -76.12)	Nescopeck I-81 (41.074, -75.962)	Nescopeck west (40.986, -76.313)
225 (SW)	NW quadrant	Avg p within ~0.2 km =	0.0202	0.0391	0.0004	0.0305
	at 5, 7.5, 10 mps	Max p within ~0.2 km =	0.1222	0.1283	0.0011	0.1022
		Avg p within ~0.5 km =	0.0174	0.0278	0.0008	0.0160
		Max p within ~0.5 km =	0.1222	0.1405	0.0059	0.1222
225 (SW)	SE quadrant	Avg p within ~0.2 km =	0.0035	0.0020	0.0014	0.0007
	at 5, 7.5, 10 mps	Max p within ~0.2 km =	0.0098	0.0063	0.0052	0.0024
		Avg p within ~0.5 km =	0.0072	0.0043	0.0016	0.0013
		Max p within ~0.5 km =	0.0660	0.0266	0.0092	0.0050
202.5 (SSW)	NW quadrant	Avg p within ~0.2 km =	0.0164	0.0550	0.0017	0.0222
	at 5, 7.5, 10 mps	Max p within ~0.2 km =	0.1103	0.1957	0.0054	0.0805
		Avg p within ~0.5 km =	0.0158	0.0380	0.0050	0.0130
		Max p within ~0.5 km =	0.1103	0.2707	0.0390	0.1173
202.5 (SSW)	SE quadrant	Avg p within ~0.2 km =	0.0030	0.0019	0.0078	0.0002
	at 5, 7.5, 10 mps	Max p within ~0.2 km =	0.0111	0.0049	0.0886	0.0005
		Avg p within ~0.5 km =	0.0127	0.0028	0.0074	0.0004
		Max p within ~0.5 km =	0.1268	0.0306	0.0886	0.0043

Note: red cells indicate values > 0.1, gold cells indicate values > 0.05

The model results suggest the following (which require field verification):

- raptor migration occurs along both ridges, but probabilities are much higher on NW winds than on SE winds;
- Penobscot Mountain has higher migration probabilities than Nescopeck Mountain;
- the Nescopeck I-81 location has the lowest migration probabilities of the four sites;
- the western end of Nescopeck Mountain (west of I-80) likely has a larger flight than the eastern end, due apparently to raptors leaving Penobscot Mountain near the Susquehanna River gap and crossing to Nescopeck.

Another useful approach (not shown here) for an example like this is to compare the migration probabilities of the site of interest with that of a site in the same simulation region (PA Northeast (37-68)) where monitoring data are available - for example, Hawk Mountain. This would require additional start points to the south along the eastern boundary of the region because those used above are too far north for simulated tracks to intercept Hawk Mountain (see Fig 5.2).

5.2 Micro-siting wind turbines to avoid a raptor migration pathway

The region of Pennsylvania with the highest wind energy potential (i.e., highest average wind speeds) is the Allegheny Plateau of southwestern Pennsylvania, including the Plateau's eastern edge that forms a dramatic escarpment known as the Allegheny Front (see Figure 5.3). The Allegheny Front is a raptor migration pathway - the Allegheny Front Hawkwatch (see Figure 5.3) has recorded the highest single-day golden eagle counts in Pennsylvania.

Figure 5.3 Shaded relief map showing the Allegheny Front and the Hawkwatch location (image from Google Maps).

In this example, simulations of spring migration are used to assess if placing turbines at a "setback distance" from the edge Allegheny Front is likely to reduce the numbers of raptors moving in close proximity to the turbines. A transect of three locations perpendicular to the Allegheny Front were chosen for analysis: (1) the edge of the

escarpment near Ogletown, (2) 0.25 km to the west-northwest of location 1, and (3) 0.5 km to the west-northwest location 1. These sites are approximately 15 km north of the Allegheny Front hawkwatch. As a comparison point, data were also generated for the Somerset Turnpike wind energy site.

Based on monitoring data from the hawkwatch it is known that winds from the E and SE generate good conditions for raptor migration along the Allegheny Front (as might be expected based on the terrain). The model was run for SE and NW winds at 7.5 mps, and then for winds from the SE and NW quadrants. Due to the SSW-to-NNE orientation of the Allegheny Front as well as recent satellite tracking data of golden eagles through the region (see maps at www.aviary.org), a PAM of 22.5 (NNE) was used for the simulations. Start points were placed near the southeast corner of the region. Additional model parameters are listed below:

```
"threshold updraft strength = 2 mps"
"PAM = 22.5 (NNE)"
"look ahead distance = 3 km"
"randomness = 20%"
"main start lat = 39.51"
"main start lon  = -79.31"
"total start points = 51"
"additional pts in Y dir = 20"
"additional pts in X dir = 30"
"increment for add pts in Y = 20"
"increment for add pts in X = 20"
"number of tracks per pt = 10"
```

Figure 5.4 shows migration frequency maps for winds from the NW and SE quadrants. Note the concentrated flightline along the Allegheny Front on SE winds.
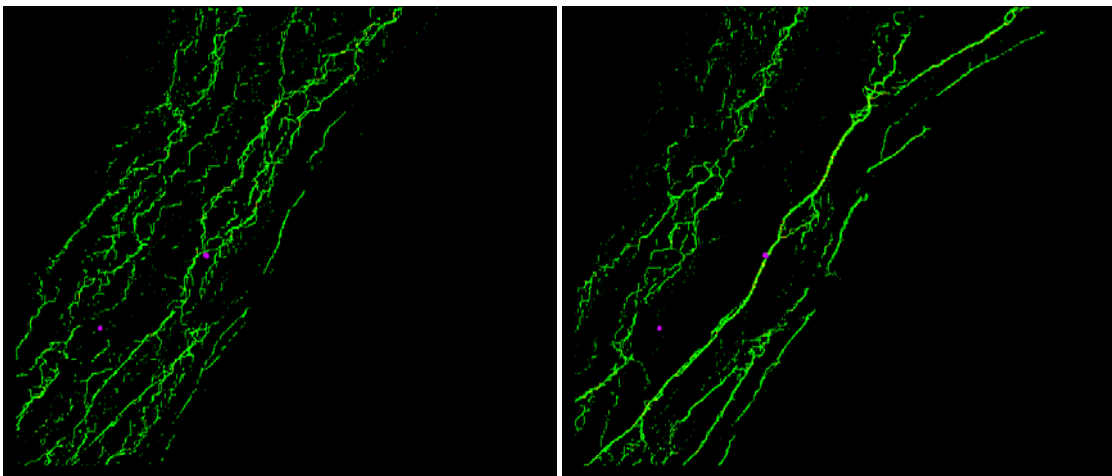

Figure 5.4 Spring migration frequency maps for winds from NW quadrant (left) and SE quadrant (right)

Results of the simulations are summarized in the table below:

Season	Wind Condition	Simulated quantity	Edge of the Alleg Front (40.2099, -78.674)	0.25 km offset from Alleg Front (40.2108, -78.6767)	0.5 km offset from Alleg Front (40.2118, -78.6794)	Somerset Turnpike Site (39.98, -79.012)
Spring	NW @ 7.5 mps	Avg p within ~0.2 km =	0.0000	0.0000	0.0000	0.0002
		Max p within ~0.2 km =	0.0000	0.0000	0.0000	0.0010
		Avg p within ~0.5 km =	0.0000	0.0000	0.0001	0.0001
		Max p within ~0.5 km =	0.0000	0.0010	0.0059	0.0010
Spring	SE @ 7.5 mps	Avg p within ~0.2 km =	0.0920	0.0051	0.0005	0.0005
		Max p within ~0.2 km =	0.6314	0.0294	0.0029	0.0020
		Avg p within ~0.5 km =	0.0385	0.0276	0.0027	0.0004
		Max p within ~0.5 km =	0.6314	0.6314	0.0471	0.0020
Spring	NW quadrant at 5, 7.5, 10 mps	Avg p within ~0.2 km =	0.0002	0.0002	0.0003	0.0002
		Max p within ~0.2 km =	0.0004	0.0004	0.0004	0.0009
		Avg p within ~0.5 km =	0.0002	0.0002	0.0003	0.0006
		Max p within ~0.5 km =	0.0008	0.0012	0.0015	0.0049
Spring	SE quadrant at 5, 7.5, 10 mps	Avg p within ~0.2 km =	0.0466	0.0040	0.0004	0.0003
		Max p within ~0.2 km =	0.2139	0.0135	0.0015	0.0007
		Avg p within ~0.5 km =	0.0238	0.0149	0.0023	0.0003
		Max p within ~0.5 km =	0.2139	0.2139	0.0625	0.0009

Note: entries of 0.0000 indicate probability less than 0.0001

The model results suggest the following:

- migration probabilities are orders of magnitude higher along the Allegheny front with winds from the SE or SE quadrant, than with winds from the NW or NW quadrant (this agrees with count data from the Allegheny Front hawkwatch)

- with winds from the SE or SE quadrant (conditions known to result in high counts at the Allegheny Front hawkwatch), migration probabilities are significantly lower at the setback locations than on the edge of the Allegheny Front

- migration probabilities are much lower at the Somerset Turnpike wind turbine site than along the Allegheny Front

Note that these results are for simulated spring migration; however, similar results were also obtained for autumn migration.

6. Model Testing

6.1 Approach

A large suite of simulations was performed to test the sensitivity of the model to the input parameters and develop guidelines for parameter values. Two of the eight Pennsylvania model regions were used for this testing, PA Northeast (DeLorme pages 37-68) and PA Central Southwest (DeLorme pages 59-90). The findings are summarized below.

6.2 Findings

6.2.1 Location of start points and point spacing

The locations of starting points are critical because estimated migration probabilities are determined by normalizing by the total number of simulated model raptor tracks. If start points are positioned at locations where there is no chance of the tracks passing the locations of interest within the domain, then the migration probabilities will be unreasonably diluted. Decisions about start point locations should be based on (1) the direction of PAM, (2) the general orientation of the terrain, and (3) the location(s) of the point(s) of interest. For example, if the location of interest is at the center of the model region, and the PAM is 225 (migration to the SW), then you would specify a start point at the northeast corner of the domain and add start points along the northern and eastern boundaries of the region, perhaps halfway along each boundary. To save time, it is recommended that several test runs be conducted with 1 track per start point before finalizing the starting locations and increasing the number of tracks per point.

Although the locations of the starting points are important, their spacing is not. Spacings of 5-10 km are recommended because more densely space points have little effect on the estimated migration probabilities, but result in longer model run times.

6.2.2 Number of tracks per start point

The number of tracks per start point is not critical although it is important to run multiple tracks due to the random component of the model. Values of 20 or 30 for number of tracks per start point are typically adequate. Note that run times can be several hours if the Multiple Static winds option is used, so you may want to reduce this to 10 tracks per start point.

6.2.3 Specification of locations of interest

The user can specify lat-lon coordinates for which data are outputted by the model. However, the estimated probabilities at these user-specified locations can be misleading because: (1) the location may not correspond to a model grid point, and (2)

model raptor tracks may pass very near to but not exactly over that particular location. Therefore the model also outputs data for the *region* surrounding the point of interest (e.g., avg and max probabilities within 0.2 km, 0.5 km, and 1 km). These results should be used rather than the data for the specific lat-lon coordinates entered.

One additional important point regarding specifying locations of interest: migration probabilities will not be reliable for locations that are close to the upstream boundary (i.e., close to the start points). This is because it takes a certain distance for the effects of convergence/divergence of migration tracks to develop into a migration pattern. This is evident in several of the plots shown in the previous section (for example, see Figure 5.2) where there is less structure in the migration pattern close to the upstream boundary.

6.2.4 Regional principal axis of migration (PAM)

The model results not surprisingly are sensitive to the value chosen for PAM. There is a large body of raptor migration literature demonstrating that PAM varies during migration, particularly for long-distance migrants that navigate areas of widely varying geography. For mountainous regions where leading lines are oriented in a direction that is close to the PAM (like much of Pennsylvania), raptors temporary adjust their heading to take advantage of the terrain orientation. PAM also varies among raptor species; however, tracking radar data (Kerlinger, 1989) from a site in central New York indicates that this interspecies variation is relatively small.

Over short distances (within each ~148 km X ~168 km simulation region) the model assumes that PAM is a fixed direction. It is recommended that model runs be made for several different PAM values (e.g., both 225 (SW) and 202.5 (SSW) in autumn) before drawing conclusions about migration probabilities at specific locations**.**

A concept related to PAM is that of wind drift. When gliding between ridges under high wind conditions, some raptors may be drifted downwind from the desired PAM (thus the term "wind drift"), or they may compensate by adjusting their heading into the wind so that their migration tracks still follow the PAM (see discussion in Kerlinger (1989) Chapter 7). The model assumes that raptors compensate for wind drift, although there is much evidence from satellite data that compensation is a learned behavior (Thorup et al, 2003).

6.2.5 Threshold updraft velocity

This is the updraft velocity below which terrain updrafts are too weak to be used for migration. Kerlinger (1989) provides data for raptor flight performance indicating that sink rates of gliding raptors are on the order of 1 mps – thus this can be interpreted as a minimum value for threshold updraft velocity. A higher threshold should be used under high wind conditions when strong updrafts are available or to simulate less willingness for raptors to follow terrain, as seems to occur during spring for most

species. Note that the largest updraft values generated by wind striking sloping terrain are typically about 50% of the wind speed, so a wind speed as low as 2.5 mps will produce very weak updrafts (less than the threshold) and thus migration tracks that have essentially no relationship to terrain. Overall, model results are not particularly sensitive to threshold updraft velocity.

6.2.6 Look-ahead distance

Model results can be sensitive to look-ahead distance because many terrain features are discontinuous at the local scale. An option for a 1-km look-ahead was removed from the model because it resulted in migration patterns that often deviated from terrain at minor terrain discontinuities, inconsistent with observations at many sites that raptors readily cross over gaps and dips in terrain (e.g. Klem et al., 1985). A look-ahead distance of at least 2-3 km is recommended.

6.2.7 Randomness

Overall model results are not particularly sensitive to degree of randomness, an interesting finding. As expected, increasing randomness does reduce the simulated migration probabilities at specific locations; however it does not impact the overall spatial pattern of the higher migration probabilities. A randomness value of 20% or 33% is recommended. The option "None" should not be used as it does not represent the flexibility of raptor behavior during migration. Figure 6.1 shows the effect of increasing randomness on 10 migration tracks along the Kittatinny Ridge. Note that with higher randomness, more tracks leave the ridge and the average distance of migration along the ridge decreases.
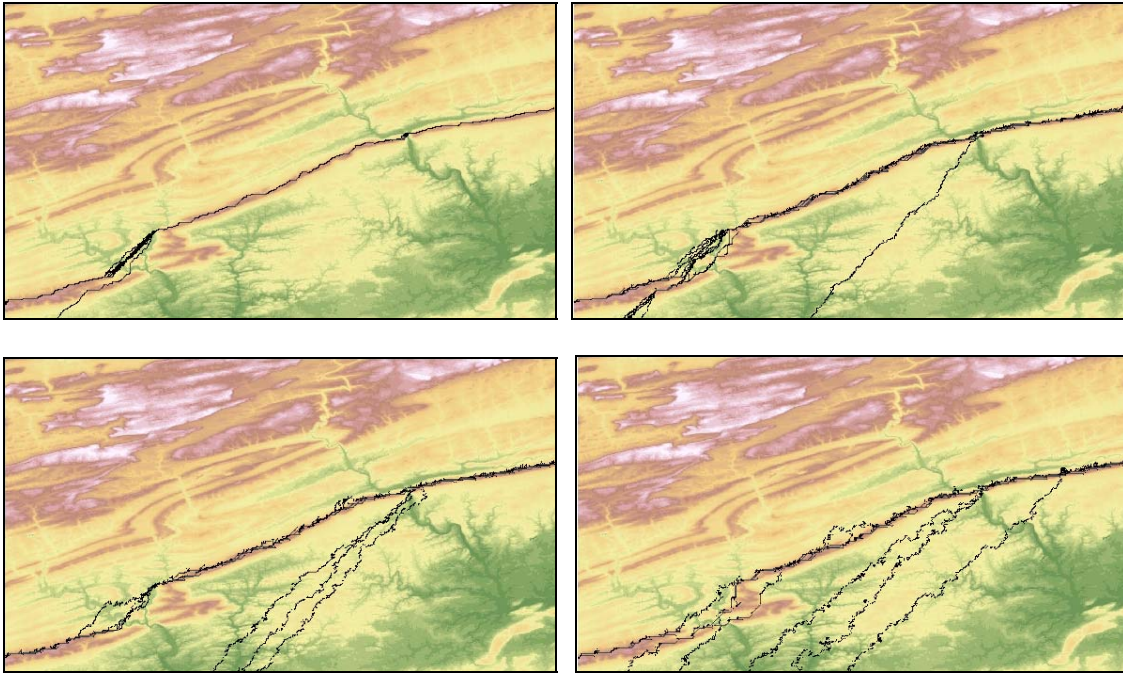
Figure 6.1. Effect of randomness on 10 simulated tracks along the Kittatinny Ridge. The first frame is with no randomness, the second with 10%, the third with 20%, and the fourth with 33% randomness. (wind NW @ 7.5 mps, PAM=225(SW), threshold=1.5 mps, look ahead=3 km)

6.2.8 Reproducibility

Because of the random component, model results for user-specified locations are not strictly reproducible. For example, the same input parameters were run five times for the PA Northeast region (DeLorme pages 37-68), and resulted in the following values for maximum migration probability within 0.5 km of Hawk Mountain's North Lookout: 0.152, 0.141, 0.195, 0.170, 0.138. The values clearly vary, but in all cases are among the highest for the entire region. In summary, the spatial pattern of migration probability is reproducible, but the results at individual locations are not.

7. Limitations

Use of the model assumes a high degree of familiarity with raptor-migration science. The user must understand that the model is based on the mechanism of migration by lift resulting from the upward deflection of horizontal surface winds ("ridge lift"). Thus, it does not account for the effect of convective thermals, which are an important source of lift during the early autumn and later spring migration periods for many species.

However, the absence of thermal lift in the model does not compromise its utility as a tool in assessing the risk potential of proposed turbine installations. This is due to three reasons. First, published studies in the peer-reviewed literature (Barrios & Rodriguez, 2004; Hoover & Morrison, 2005) have concluded that collision risks are highest when raptors are using terrain updrafts rather than thermals for lift. Second, many observers have noted that migrating raptors fly much higher during fair, warm conditions when thermals are strong than when using updrafts, which extend only several hundred meters above terrain height. Kerlinger (1989, p. 99) states "migrants flying in updrafts generated by wind along ridges and hills are normally constrained to fly at lower altitudes than migrants using thermals." Finally, in the Appalachian region, wind speeds are typically low when thermal strength is high, in fact high winds disrupt the formation of thermals. Thus, wind turbine rotor speed (and therefore collision risk) is generally low when thermals are strong.

An ideal application of the model would be to predict where concentrations of migrating raptors are likely to occur in mountainous terrain under various wind conditions in late autumn (e.g., November-December) or early spring (e.g., February-March). However, it would be inappropriate to attempt to determine locations of raptor concentration under fair conditions in mid-September or mid-April, or to simulate migration along the flat Atlantic coastal plain.

I emphasize that although the model provides useful insights as to where and under what conditions concentrations of migrating raptors are expected to occur, it is necessary to verify the model simulations with field data, e.g. pre-construction monitoring data from proposed wind energy sites. The model is best used as a tool or guide in assessing the likelihood of concentrated migration pathways and in designing field studies, especially where little raptor migration data are currently available.

8. References

Barrios, L. and A. Rodriguez, 2004. Behavioural and environmental correlates of soaring-bird mortality at on-shore turbines. *Journal of Applied Ecology* 41: 72-81.

DeAngelis, D.L and W.M. Mooij, 2005. Individual-based modeling of ecological and evolutionary processes. *Annu. Rev. Evol. Syst.* 36:147-168.

Grim, V. and S.F. Railsback, 2005. *Individual-based Modeling and Ecology.* Princeton Univ Press. 428 pp.

Hoover, S.L. and M.L. Morrison, 2005. Behavior of red-tailed hawks in a wind turbine development. *J. Wildl. Manage.* 69(1):150-159.

Kerlinger, P. 1989. *Flight strategies of migrating hawks.* The University of Chicago Press, Chicago, IL U.S.A.

Klem, D., Jr., B. S. Hillegass, D. A. Peters, and J. A. Villa, 1985. Analysis of individual flight patterns of migrating raptors at a break in the Kittatinny Ridge: Lehigh Gap, Pennsylvania. In Harwood, M. Editor. Proceedings of Hawk Migration Conference IV, pp 1-11.

Maransky, B., L. Goodrich, and K. Bildstein, 1997. Seasonal shifts in the effects of weather on the visible migration of red-tailed hawks at Hawk Mountain, Pennsylvania. Wilson Bull. 109(2):246-252.

Thorup, K., T. Alerstam, M. Hake, and N Kjellen, 2003. Bird orientation: compensation for wind drift in migrating raptors is age dependent. *Proc R Soc Lond* B (Suppl.) 270, S8-S11.

Acknowledgments

Appendix - **Importing DEM Data Files**

Warning: the Model Principles and Rules of Motion discussed in Section 3 apply to Pennsylvania. Additional model rules are necessary to simulate raptor migration pathways in regions with differing terrain, geography, and land cover. For example the current model has limited input parameter options and has no built-in mechanisms for the effects of high elevation terrain, water barriers, or land cover such as snow, desert, or urban regions.

The model requires digital elevation model (DEM) datafiles that must be provided by the user. Data files of 3 arc sec resolution (approximately 90-m) corresponding to blocks of 12 DeLorme PA Gazetteer map pages are provided with the program. For simulating migration in other regions, the user will have to provide the corresponding data files. These user-specified regions should be sized the same as a two-page spread in the DeLorme Gazetteer (with a 1.75(L):1(W) aspect ratio) for the graphics to be displayed properly.

A good source of data is the USGS Seamless Data Distribution System at http://seamless.usgs.gov/. Zoom to the region of interest using the interactive viewer. You can turn on and off different data layers under the "Display" tab on the right side of the screen.

When you are ready to download data, change to the "Download" tab on the right side of the screen and select the data you need. Typically you would select Elevation and click the box for 3 arc sec data. The 1 arc sec data (approximately 30-m resolution) can also be used, but these are not recommended for regional-scale simulations because the resulting input files will be very large and may exceed the processing power of most desktop PCs. 3 arc sec data are sufficiently detailed to resolve the terrain features (ridges, river valleys, escarpments) of interest.

From the toolbox on the left side of the screen select the Download tools and define the region of interest by its coordinates. Once finished, click the Select Area button and wait while your data (in Arcgrid format) are prepared as a zip archive. You will eventually be prompted regarding where to save the data. Extract the data from the archive.

To convert the datafiles to a format usable by the program you must convert them to ASCII form - this can be done with ArcMap. Open ArcMap with a new empty map. Click on the Add Data icon and select the DEM file (it will have an icon that looks like a small gold-colored grid). You should now see a shaded DEM in ArcMap. Under the ArcToolbox menu, select Conversion Tools, then From Raster, then Raster to ASCII. Double-click, select the DEM file as the input raster, and type in the name (and location or path) for the output ASCII file. You should get a file that has the following format (the example shown is for a 15 min X 15 min region of 3 arc sec data centered on Hawk Mountain Sanctuary):

```
3arcsecdem.txt - Notepad                                            _|□|x|
File  Edit  Format  View  Help
ncols            301                                                    ▲
nrows            301                                                    ▤
xllcorner       -76.083749996967
yllcorner        40.49958333219
cellsize         0.0008333333332999
NODATA_value    -9999
291 289 285 279 282 289 295 293 296 291 281 268 262 259 245 245 249 252
251 252 246 244 245 241 241 244 245 244 246 250 255 261 266 270 272 281
285 283 279 286 303 313 333 340 359 379 392 396 398 389 380 375 367 355
337 328 324 324 326 320 310 309 308 310 309 311 310 308 305 300 297 296
299 306 311 316 314 310 308 307 310 323 326 329 334 343 347 362 375 385
398 413 423 427 430 431 433 427 423 420 413 408 399 386 372 360 349 364
379 384 376 364 348 330 317 300 291 281 278 276 276 289 291 284 277 266
262 253 251 257 262 257 261 265 269 262 253 244 239 239 232 219 212 209
209 214 217 217 211 212 219 221 226 224 216 207 208 211 217 214 217 217
216 224 227 241 263 286 317 348 370 372 366 355 352 346 331 313 302 294
293 294 306 310 311 308 314 321 314 320 325 322 322 326 329 329 329 330
331 328 329 328 331 324 317 318 316 319 320 320 319 311 308 304 303 300
298 301 294 291 288 287 287 288 284 285 281 288 298 310 316 320 319 317
313 309 306 304 298 292 287 280 264 265 272 270 264 263 267 271 274 274
272 268 274 274 272 268 264 262 261 259 261 260 259 251 249 256 256 254
247 248 254 257 256 253 252 247 246 246 247 251 251 250 249 251 253 256
257 262 267 272 274 274 274 274 271 266 261 257 261
267 268 265 270 282 293 286 281 284 281 276 264 252 244 241 242 244 248
248 246 243 242 238 234 238 242 242 244 252 254 261 262 267 274 283 287
291 295 300 307 323 336 346 368 386 399 409 414 409 388 376 360 356 344
```

There are six header lines, and then many rows of numbers which represent the elevations of the region of interest. *Delete the six header row descriptions (but not the numbers that come after them).*

It is not uncommon for DEMs to have small tears or holes, which will appear as -9999 values. It is necessary to replace these values by averaging the surrounding values. This should be done as symmetrically as possible, i.e., average surrounding values from opposite directions in both x and y, not all in one direction. This can get a bit tricky when chunks of values are missing. Once the DEM file has been patched up (if necessary), place it in the FlightPathdatafiles folder.

A background graphic is useful for interpreting the simulation results. To create one, first add a color scale to the DEM layer in ArcMap. Typically a green to yellow to brown to white color bar is used for topography. There are many options in ArcMap for scaling the color bar – a "Natural Breaks (Jenks)" scheme with ~25 classes works well.

To create the graphic file, under the File menu, select Export map, and save the image as a jpg. The white space around the image can be cropped out with a photo editor program (e.g. Adobe Photoshop).