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Ecological Model Development: Toolkit for interActive Modeling (TAM)

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OVERVIEW: Ecological models provide crucial tools for informing many aspects of ecosystem restoration and management, ranging from increasing understanding of complex ecological functions to prioritizing restoration sites and quantifying benefits for project reporting. The diversity of ecosystem types and restoration objectives often precludes the use of existing models; as such, model development is commonly required to inform restoration decision-making. Index-based habitat models are a common approach for assessing ecosystem condition. These models relate habitat quality to species' distributions. Habitat suitability (quality) typically ranges on a scale from 0 to 1. Habitat models have been developed to assess habitat suitability for specific taxa, communities, or ecosystem functions. Restoration-project timelines often require that these models be developed rapidly and in conjunction with many external stakeholders or partners. Here, the Toolkit for interActive Modeling (TAM) is proposed as a platform for rapidly developing index-based models, particularly for US Army Corps of Engineers' (USACE) ecosystem-restoration or mitigation planning processes. The TAM is a consistent quantitative framework that allows for development of a generic platform for index-based model development.

RAPID MODEL DEVELOPMENT: Ecological models are powerful tools for documenting current understanding of an ecosystem, developing additional insights, assessing the consequences of management alternatives, and many other purposes. But regardless of model purpose, development proceeds through a predictable process of conceptualization, quantification, evaluation, and application, each of which may require communication with interested parties (Grant and Swannack 2008). USACE has embraced each component of this process in restoration decision-making and instituted policies and best practices for model development and evaluation, such as key directives for agency-wide model review and certification (USACE 2005; USACE 2011).

Since 2012 USACE projects have been planned under the SMART Planning paradigm (that is, *specific*, *measurable*, *attainable*, *relevant*, and *time bound*, or *SMART*), which emphasizes rapid planning timelines (typically three years), reduced planning costs, and close integration across agencies and partners (USACE 2012). As such, USACE restoration teams often require rapidly developed tools to inform decision-making, which is highly consistent with the academic recommendations of iterative model development and rapid model prototyping (Starfield 1997; McKay, Richards, and Swannack 2019). Furthermore, restoration is rarely, if ever, conducted in a vacuum, and many partners and stakeholders are often interested in not only the outcome of a project but also the processes used for decision-making. Given this need for stakeholder integration, it is not surprising that a growing body of guidance is available to inform collaborative model development and stakeholder engagement (for example, Langsdale et al. 2013; Crawford, Katz, and McKay 2017; Herman et al. 2019).

This technical note addresses the need for a toolkit to facilitate rapid development of index-based models by presenting the underlying theory and structure of TAM as well as instructions for application to restoration and mitigation planning studies. It also briefly reviews index-based models and highlights the common structure and function of these tools.

INDEX-BASED MODELS: Understanding the relationships between species and habitat is a complex and evolving field of study, and index-based models are one of many different types of models used to quantify these relationships (see reviews by Peterson 2006 and Elith and Leathwick 2009). While index-based models are "not predictive in nature" (Swannack, Fischenich, and Tazik 2012 as cited in Herman et al. 2019, 9), they are "useful for rapid assessments and scenario-based comparisons in environmental decision-making" (for example, the habitat evaluation procedure, or HEP, used by the US Fish and Wildlife Service and the index of biotic integrity, or IBI, used by the EPA; Herman et al. 2019, 9). Index-based approaches "distill the complexity of species-habitat relationships" into a 0–1 scale, with 1 representing a favorable or optimal relationship and 0 representing a poor or unsuitable relationship (that is, uninhabitable) (9). These suitability indices (SI) (sometime referred to as *suitability curves*) are "generally quantified as step functions, with the break point values of the steps representing species-response thresholds" (9). For example, break point values may represent the lowest salinity oysters can tolerate before they die or the minimum amount of inundation wetland vegetation requires. Equations are often generated by linearly interpolating between the steps. A given SI can have multiple steps and multiple equations. Logistic functions and categorical valuations can also quantify an SI. Regardless of the functional form of individual species-habitat relationships, model variables are quantified according to the scientific literature, empirical data, and expert opinion on how a species responds to a particular environmental stimulus, which can be biotic or abiotic.

While suitable habitat can be assessed using a single SI, they are more commonly assessed using multiple indices combined into a composite score that estimates suitable system-level habitat quality (for example, a single composite index can be comprised of several variables of the species' habitat requirements, such as water quality, substrate, and connectivity). Using one or multiple SI is at the discretion of the modeling team; however, the importance of each SI to the species or community being modeled should be considered. If an SI is not critically important, then it should not be included. Composite scores are commonly calculated from the geometric mean, arithmetic mean, or minimum SI values, although some models specify variable weighting or nested forms of aggregation. Each has strengths and weaknesses, and the aggregate technique should be decided by the modeling team. Note that a discussion of aggregate techniques is beyond the scope of this technical note.

TOOLKIT FOR INTERACTIVE MODELING (TAM): The TAM is an Excel-based platform that allows users to rapidly develop, quantify, and document suitability indices. There are four tabs in the TAM: Instructions, Linear Function, Categorical Function, and Logistic Function. The Instructions tab provides guidance on TAM usage and lists the assumptions used for the Linear, Categorical, and Logistic Function tabs. The description of each type of function is included below. Each tab contains four components: data, y-intercept slope and equations for index values, documentation, and a figure (Figure 1).

ENTER DATA INTO HIGHLIGHTED CELLS

Breakpoint #	Turbidity (tss)	Index Value (Y)
1	0	1.000
2	30	1.000
3	40	0.800
4	50	0.450
5	60	0.2
6		
7		
8		
9		
10		

Values	Intercept	Slope	Equation
0 -30	1.00	0.0000	Y= 1 + (0 * Turbidity (tss))
30 -40	1.60	-0.0200	Y= 1.6 + (-0.02 * Turbidity (tss))
40 -50	2.20	-0.0350	Y= 2.2 + (-0.035 * Turbidity (tss))
50 -60	1.70	-0.0250	Y= 1.7 + (-0.025 * Turbidity (tss))
60 -	0.00	0.0033	Y= 0 + (0.0033 * Turbidity (tss))
-			
-			
-			
-			
-			

Documentation

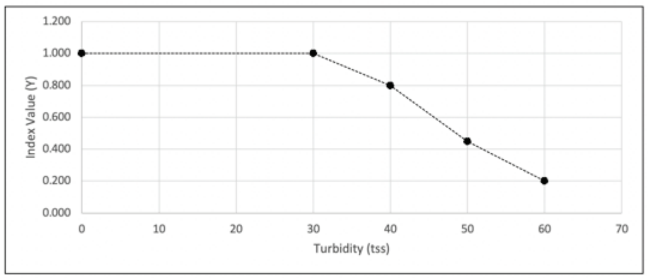


Figure 1. Components of the TAM: Data (*top left*); y-intercept, slope, and equations for the index values (*top middle*); Documentation (*top right*), and figure of the functional form of the index function (*bottom*).

Populating the TAM proceeds as follows:

1. Start the application of the TAM spreadsheet by determining the number of variables, specifying their respective functional forms, and creating a separate worksheet for each variable.
2. Enter data associated with a given functional form.
3. Document data sources.
4. Export equations, figures, and documentation.

Step 1. Set up TAM environment. TAM is best used if users have a conceptual model of critical system components (variables) and how they interact. The conceptual model should be used as a template of TAM. Before TAM is applied, the functional form of the relationship between the variable and ecological response (for example, how a species, community, or system responds to changes in the specific variable) must be estimated. That is, the general shape of the response relating habitat suitability to the variable must be defined. Stakeholder groups along with the model developers should determine the functional form of each variable. In the TAM, each variable requires its own tab. To create duplicate copies of the appropriate function tab for each variable, right-click on the corresponding tab, choose Move or Copy, then copy the entire sheet (Figure 2).

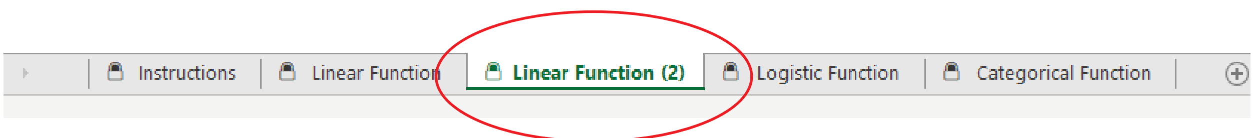


Figure 2. Create duplicate copies of the appropriate function for each variable. The *red circle* indicates the duplicate copy.

Once appropriate tabs are created, SI curves can be developed. Rename each tab to reflect the variable descriptively. Refer to the description for linear, logistic, or categorical functions below for formulating each function.

Step 2. Data entry and functions. The TAM contains three different types of functions: linear, logistic, and categorical functions. The style of input is the same for all function types, but their functional forms will vary. The inputs for each function are predetermined parameters and their data associated with break points and index values (ranges 0–1), which can be seen in Figure 1 (*top left*) above. The variables describe things such as turbidity, aquatic cover, and temperature as appropriate to the focal taxa or system. The break points are intended to represent the threshold values of ecological response to variables. Index values associated with each break point are based on a 0–1 scale, with 0 representing poor quality and 1 representing optimum quality. The break points are generally documented as a response to specific values of the variable, such as the lowest turbidity a species can survive in. The data to populate break points and their relationship to habitat suitability as index values can be based on scientific literature, expert opinions, laboratory results, in-field observation and data collection, or other sources. Once all data (for example, numbers, categories) associated with break points and index values (0–1), their functional relationship will automatically be presented in the figure. Each function type will be further discussed below.

Linear step function. Linear functions are the most common type of function used in the development of index-based models. Linear functions assume that the rate of change between each pair of successive break points is constant (that is, can be represented as a straight line). The xaxis represents the chosen variable (for example, dissolved oxygen, acres of riparian area). The mathematics for calculating linear step functions are included in the appendix. Steps for setting up a linear function are

1. Change the name of Variable[1] to the name of the variable of interest (Figure 3).
2. Assign each break point[2] a value (typically numerical, can be whole, integers, or rational) for the variable and the associated index value associated with that value of *x*.
3. Only fill in the number of break points required for that specific variable. The number of break points per variable is limited to 10. break point
4. Maximum and minimum values for $y = 0$ and $y = 1$ must be assigned (Figure 4).
5. Once all break points are assigned values, the TAM will automatically generate the following (shown in Figure 5):
   - i a graph diagramming the functional form of variable (*A*, *bottom*)
   - ii a range of values (that is, the break points) over which the equation (*E*) is applied (*B*, *first column top right*)
   - iii the slope of the line between break points (*C*, *second column top right*)
   - iv the intercept of the line between break points (*D*, *third column top right*)
   - v the linear equations for the lines formed between each pair of successive break points. (*E*, *fourth column top right*)
6. Repeat this process for each variable that uses a linear function.

Variable → **Turbidity (tss)**

Figure 3. Step 1: Change name of Variable of interest and associated unit of measurement.

Breakpoint #	Turbidity (tss)	Index Value (Y)
1	0	1.000
2		
3		
4		
5		
6	450	0

Figure 4. Variables for *x* at values for *y* = 0 and *y* = 1 must be defined. For example, Turbidity is 0 (tss) at *y* = 1 and 450 (tss) at *y* = 0. Next, input data for each break point.

1. Highlighted cells in TAM can be filled out by the users.
2. Model users are expected to understand how to develop a list of break points and thresholds.

ENTER DATA INTO HIGHLIGHTED CELLS

Breakpoint #	Variable	Index Value (Y)
1	0	1.000
2	118	0.900
3	136	0.800
4	368.4	0.275
5	400	0.01
6	450	0
7	500	0.25
8	750	0.3
9	800	0.6
10	900	0.75

Values	Intercept	Slope	Equation
0 -118	1.00	-0.0008	Y= 1 + (-0.0008 * Variable)
118 -136	1.56	-0.0056	Y= 1.56 + (-0.0056 * Variable)
136 -368.4	1.11	-0.0023	Y= 1.11 + (-0.0023 * Variable)
368.4 -400	3.36	-0.0084	Y= 3.36 + (-0.0084 * Variable)
400 -450	0.09	-0.0002	Y= 0.09 + (-0.0002 * Variable)
450 -500	-2.25	0.0050	Y= -2.25 + (0.005 * Variable)
500 -750	0.15	0.0002	Y= 0.15 + (0.0002 * Variable)
750 -800	-4.20	0.0060	Y= -4.2 + (0.006 * Variable)
800 -900	-0.60	0.0015	Y= -0.6 + (0.0015 * Variable)
900 -			

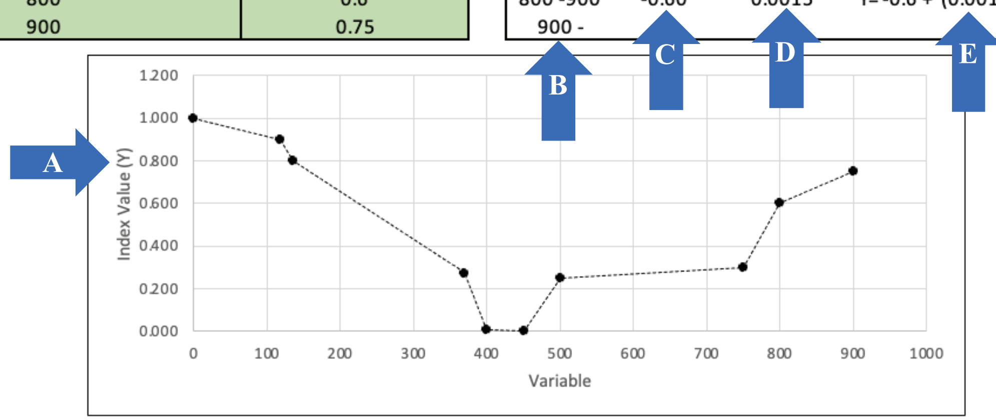


Figure 5. Screenshot of input-output screen for linear functions. Arrows *A–E* described above.

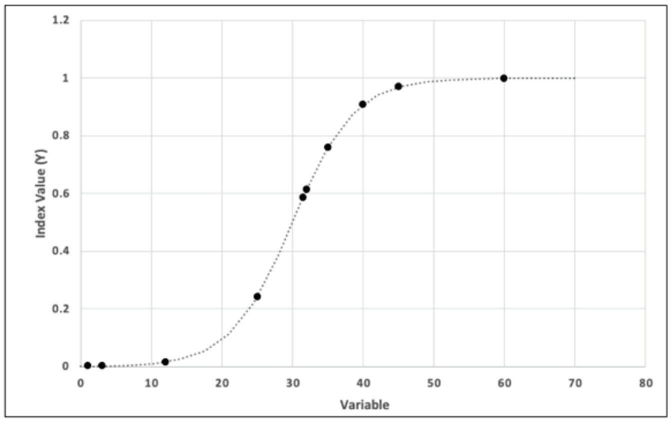
Logistic Function. Logistic functions produce an output between 0.0 and 1.0 in an S shape. These functions are useful in ecological modeling because they reproduce how species' response can be low over a wide range of conditions, high over another range, and a rapid change between those ranges. Unlike the linear equations, values generated from a logistic function are generated algorithmically. The mathematics for calculating logistic functions are included in the appendix. Logistic functions can be defined by identifying two points along any point of the curve. In the TAM, logistic functions are generated as follows:

1. The simplest approach is to identify the points where the index value is approximately 1 and where the index value is approximately 0.[3]
2. Users may experiment with different curve shapes to generate shape functions that best represent a project development team's hypothesis between the response and critical variable.
3. Users must enter the maximum threshold value (that is the value of x when y approximates 1). The maximum value of y is set at 0.9999 (Figure 6). Users cannot change this value.
4. Users must enter another x-y pair that exists on the curve, whether from data or expert opinion. This point can be anywhere on the curve, with the only restriction being that y must be >0. The TAM will not allow users to enter improper values.
5. Once the shape of the curve is defined, index values are derived by directly entering values into the variable column (Figure 6). These values will display on the graph as closed circles. Values do not need to be entered sequentially. Users are limited to 20 values.

3. Logistic formulations require that the y_1 and y_2 not be equal to 1 or 0. A common approach is to use 0.9999 and 0.0001 to approximate 1 and 0, respectively.

ENTER DATA INTO HIGHLIGHTED CELLS

Variables:	Values
1) Maximum threshold (Max X)	70
2) SI value at max threshold	0.9999
3) Threshold Value less than Max Z(X)	30
4) SI value at threshold value (#3)	0.5



Breakpoint #	Variable	Index Value (Y)
1	60	0.999000924
2	35	0.759744645
3	1	0.001257434
4	3	0.001991423
5	25	0.240255355
6	40	0.909088843
7	32	0.613135634
8	31.5	0.585497769
9	12	0.015602353
10	45	0.969345456

Documentation

Figure 6. Snapshot of input-output screen for logistic functions. *Dotted line* is the logistic function, and *closed circles* represent the index values associated with values entered for variables.

Categorical Function. The categorical function takes qualitative data and quantifies it on a 0–1 scale. An example of a categorical function would be whether there is sufficient hard substrate present for oysters to settle on. A simple Yes or No would be categories that would be used for this variable. There can be many different categories as well (for example, binary variables, ranges of variables). The steps for developing a categorical function are as follows (TAM outputs displayed in Figure 7):

1. The user specifies categorical inputs (*A*, *second column top left*).
2. The index values are entered for corresponding categorical inputs (*B*, *third column top left*).
3. The logic of categorical variables is then described to ensure consistency of terminology among developers and users (for example, What constitutes hard substrate for oysters?) (*C*, *top right*).
4. Categorical suitability values are presented graphically (*D*, *bottom*).

Step 3. Documentation. Clear and concise documentation is critical for all ecological models. Documentation should be written so that the model can be recreated without much difficulty and should include assumptions and all equations. Within USACE, well-written documentation describing the model is required for model certification (as stated in in EC 1105-2-412, USACE 2011). There are several different formats commonly used for documenting models, with all containing the same general developmental steps. A description of model documentation is beyond the scope of this technical note but refer to Schmolke et al. (2010) for a description of the TRansparent And Comprehensive Ecological modeling, or TRACE, documentation.

The TAM is designed to autodocument threshold values, model equations, and model curves, which facilitates report writing and increases model transparency. The TAM can also serve as a repository for other required documentation, including the citations that contain information to support the values used to parameterize the equations, any user notes for important logic, or assumptions used in the development of each variable. It is critical to list any form of documentation that could help the user recreate the model, whether that be data gathered from the field, knowledge obtained from papers, or data obtained from expert opinion or personal experience. Entering documentation is important to ensure that the user and future potential users can know how data were interpreted when entering in the break points for each variable. Any information used to develop the model should be added to the documentation field and exported to the eventual report. Documentation can also include any form of data that is gathered or discussed during the model development process. The most important thing in the documentation section is to make sure that all the information used to develop the model is captured so other users can recreate and better understand the limitations the model.

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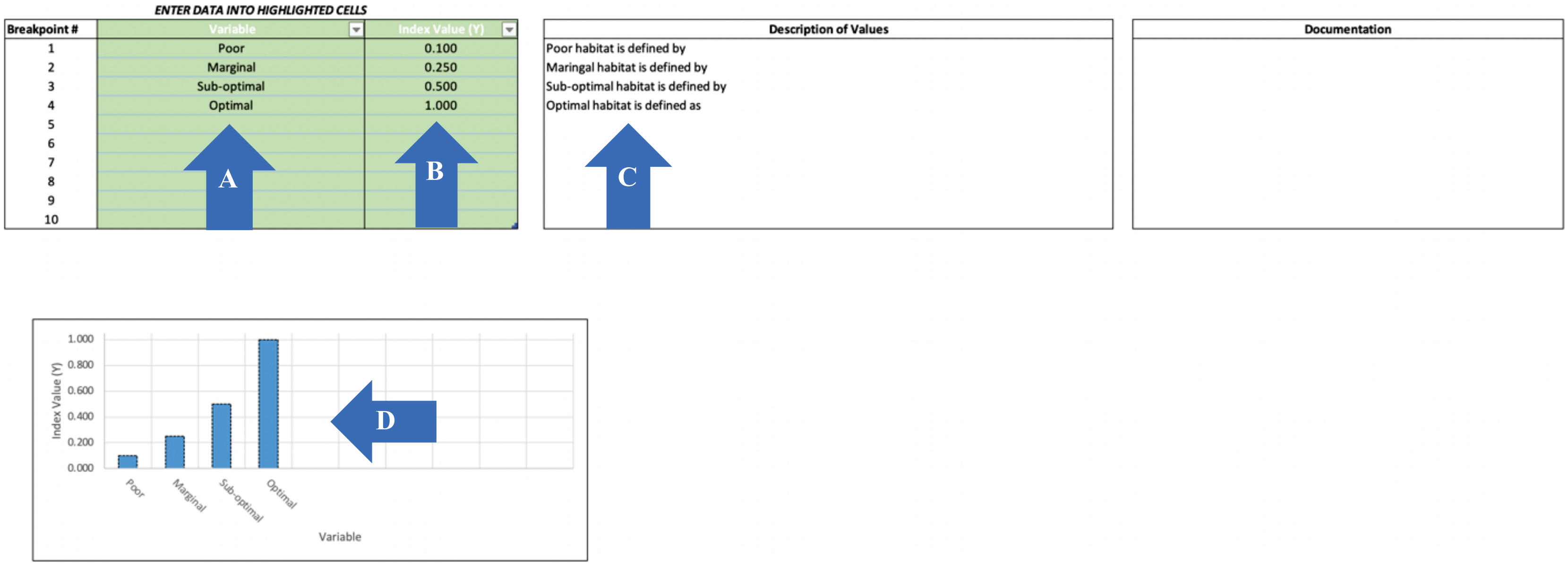

Figure 7. Snapshot of input-output screen for categorical functions. Each bar in the graph represents the index value for poor, marginal, suboptimal, and optimal variables.

Step 4. Exporting equations, figures, and documentation. The TAM will generate the graphics and equations necessary for building an index-based model. Once the TAM has been populated with all the required curves, values, and variables, the equations and graphics must be extracted and applied to the system of interest. Details on how to apply equations in a habitat suitability index framework have been described in detail elsewhere (refer to Swannack, Reif, and Soniat 2014 for an example). This section addresses extracting the figures and equations from the TAM.

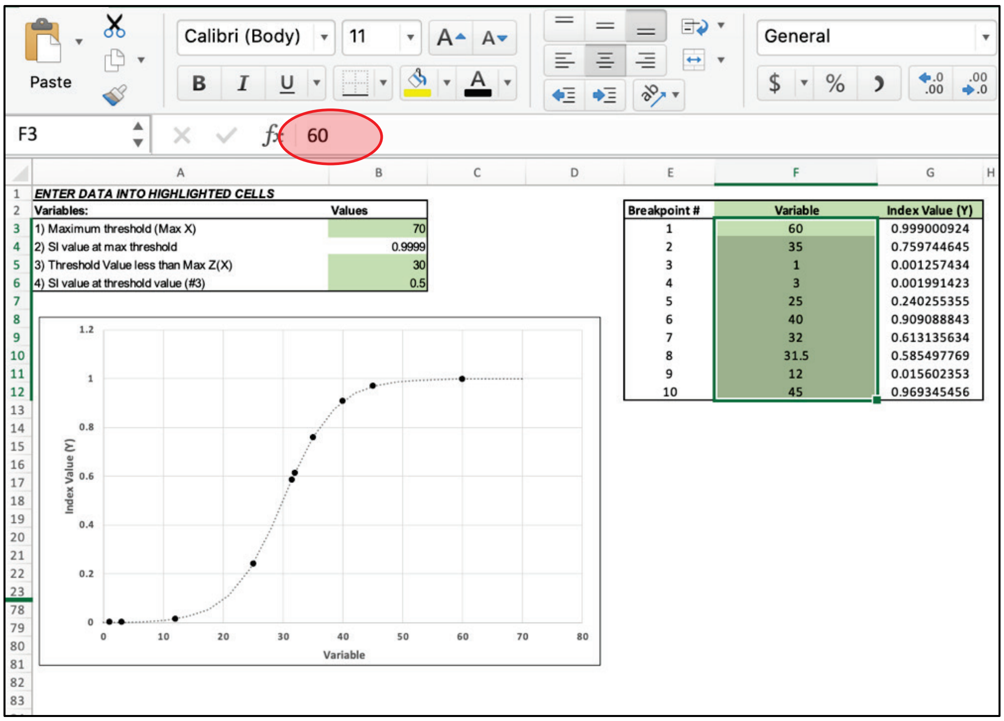

Figure 8. Example of how to extract values from TAM.

1. Extracting figures—each graph can be formatted to the user's specifications within the TAM, then copied into another application (for example, Microsoft Word, PowerPoint).
2. Extracting equations and data values—to extract the equations and data values, the user must use the select cells function (Figure 8, *red circle*), enter the cells they would like to copy, click Enter, then press Ctrl+C to copy those cells. The values can then be pasted into another application (for example, another Excel workbook, Word). The values for the cells that are commonly extracted are
   a. Linear functions
      i Variable table—E2:H12
      ii Break points—A2:C12
   b. Logistic functions
      i Table of environmental and SI values—F2:G21
   c. Categorical functions
      i Table of environmental and SI values—B2:C12

CONCLUSION: The TAM facilitates model development for ecosystem-restoration or mitigation planning modeling projects. It is a user-friendly platform for rapidly generating the equations and values necessary for developing a suite of SI curves commonly used to evaluate ecosystem restoration or mitigation project alternatives. The TAM contains the three most commonly used functional forms of index-based models: linear step functions, logistic curves, and categorical data functions. The TAM provides a way to do interactive modeling with many stakeholders by providing a real-time, easy-to-see output according to which information the user enters. A successful example of TAM application is described in Herman et al. (2019), in which the TAM was used in an interactive workshop with members from USACE–Seattle District to generate habitat suitability curves for anadromous fish in the northwestern United States. Multiple interactive workshops allowed the stakeholders to be involved in determining threshold values and which variables were most important for anadromous fish survival and reproduction. Critical model documentation (for example, equations and threshold values) is autogenerated by the TAM, which facilitates technical transfer activities. The TAM is also a tool that allows users to store all the data, references, and other information needed to recreate the model.

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APPENDIX: LIST OF LINEAR AND LOGISTIC FUNCTIONS

This appendix contains the functions used to develop the linear and logistic equations.

Linear Functions. The equations generated for each pair of successive break points are calculated using the generalized formula for a straight line:

$$y = mx + b,$$

where m represents the slope of the line, x is the value of the variable at value y, and b is the y-intercept. The slope is calculated by

$$m = \frac{y_2 - y_1}{x_2 - x_1},$$

where (x_1, y_1) and (x_2, y_2) are the Cartesian coordinates for pairs of successive break points. The y-intercept is calculated using the index value, slope, and variable:

$$b = \text{Index Value} - (\text{Variable} \times m).$$

Logistic function algorithm. The logistic function is calculated by first identifying two x-y pairs that at $y = 1$ and $y = 0$. Then, four intermediate values (A, B, G, F) are generated by

$$G = \ln\left(\frac{y_1}{1 - y_1}\right)$$

$$F = \ln\left(\frac{y_2}{1 - y_2}\right)$$

$$B = \frac{G - F}{x_1 - x_2}$$

$$A = G - (B \times x_1).$$

The intermediate values are used to generate a value between 0 and 1 (SI) for any value of x using the following:

$$Z = e^{(A + (B \times x))},$$

$$\mathrm{SI}_x = \frac{Z}{1 + Z}.$$

For index model formulation, the y-axis represents the suitability index score (SI_x).