# Designing Sustainable Landscapes: Tidal Restrictions metric

## *A project of the University of Massachusetts Landscape Ecology Lab*

*Principals*:

- Kevin McGarigal, Professor
- Brad Compton, Research Associate
- Ethan Plunkett, Research Associate
- Bill DeLuca, Research Associate
- Joanna Grand, Research Associate

# General description

Tidal restrictions include undersized culverts and bridges, tide gates, dikes, and other structures that interfere with normal tidal flushing in estuarine systems. Effects can range from mild changes in species composition and cycling of sediment and nutrients to wholesale conversion of ecological systems, such as conversion of *Spartina*-dominated salt marshes to *Phragmites australis*, or, in extreme cases, to freshwater wetlands (Roman et al. 1984, Ritter et al. 2008).

The tidal restrictions metric is an element of the ecological integrity analysis of the Designing Sustainable Landscapes (DSL) project (see technical document on integrity, McGarigal et al 2017). Consisting of a composite of 21 stressor and resiliency metrics, the index of ecological integrity (IEI) assesses the relative intactness and resiliency to environmental change of ecological systems throughout the northeast. As a stressor metric, tidal restrictions uses an estimate of the historic loss of mapped salt marshes in areas where they should occur given elevation and tidal regime to indicate the location and magnitude of potential tidal restrictions. The metric estimates the effect of potential tidal restrictions on upstream wetland systems, including intertidal systems such as salt marshes, as well as freshwater systems and low-lying nonforested uplands that may have once been intertidal. Metric values range from 0 (no effect from downstream tidal restrictions) to 1 (severe effect).

The metric is based on an estimate of the salt marsh loss ratio above each potential tidal restriction (road-stream and railroad-stream crossings). Note that tide gates not associated with roads are excluded as potential tidal restrictions, as they are not comprehensively mapped throughout the region. The salt marsh loss ratio is the proportion of a basin above a crossing that is modeled as potential salt marsh (from tide range and elevation) but not mapped as existing salt marsh in the National Wetlands Inventory (NWI) maps.

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# Use and interpretation of this layer

The tidal restrictions metric gives an estimate of the magnitude of effect that tidal restrictions may have on upstream wetlands (**Fig. 1**). Salt marshes with a high tidal restrictions score are likely to be degraded, and freshwater systems with a high value are likely to be former estuarine systems that have been converted to freshwater by tidal restrictions.

An accompanying point shapefile includes a value for each potential tidal restriction, allowing a provisional assignment of responsibility to each potential restriction (**Fig. 2**). In situations where there is a chain of multiple road-stream crossings in a basin, the model has only limited ability to assign responsibility to particular potential restrictions, so the point shapefile as well as specific locations in the raster metric should be viewed with healthy skepticism. In a chaining situation, responsibility is assigned to the lowest potential
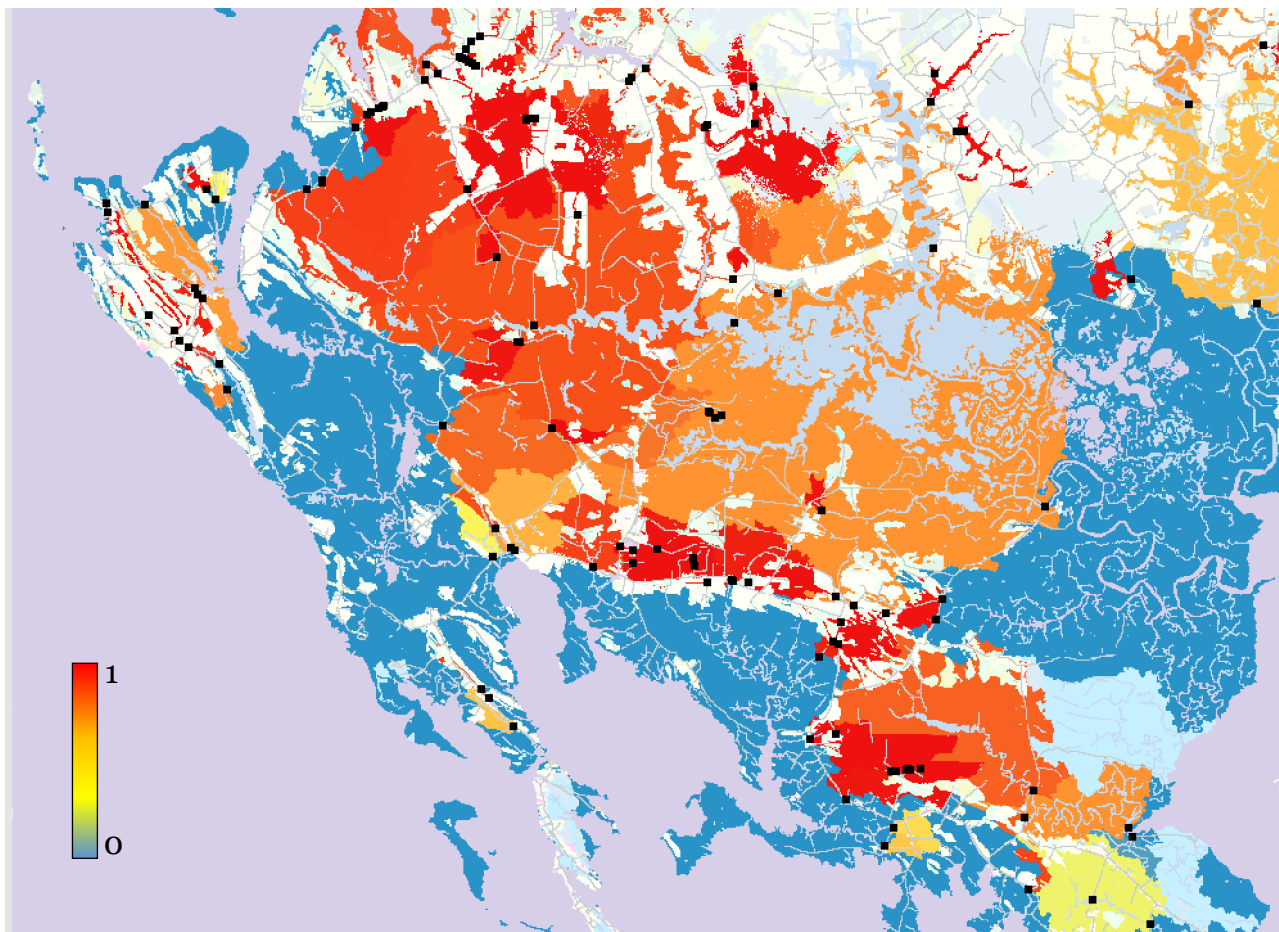
**Figure 1.** Tidal restrictions metric assigns a value to each cell within the coastal zone (elevation ≤ 5 m ) ranging from 0 (no effect of downstream restrictions) to 1 (severe effect). Shown here for Blackwater National Wildlife Refuge, Maryland. Black squares indicate potential tidal restrictions. Colors show the estimated effect of tidal restrictions on estuarine and freshwater wetlands, ranging from blue (0=no effect) to red (1=severe effect).

restriction that could be responsible (**Fig. 3**), while in reality, crossings higher in the watershed might be responsible. Therefore, this metric is best used to identify basins with a high estimated impact from tidal restrictions, to be followed up with assessment of all potential restrictions in the basin using this model, other GIS data, and, of course, field assessment, both of salt marshes and other wetlands upstream from potential restrictions, and the restrictions themselves. The gold standard for measuring the magnitude of a tidal restriction (though not its effect) is a measure of the difference in maximum water level above and below the restriction during a spring high tide.

This metric depends on data of variable quality, with some known errors. In particular, there are several holes in our digital elevation model (DEM; see below), and there are errors in the flow grid that can omit areas of watersheds from consideration.

This metric relies on a number of assumptions:

- Salt marshes are adequately mapped in NWI. In general, this assumption seems to be well-met, as salt marshes are visually distinctive and fairly easy to recognize in aerial photos, and NWI has captured them well. Note that this metric is insensitive to tidal restrictions that degrade salt marshes without converting any salt marshes in a basin to other landcover types in NWI mapping. Tidal restrictions can cause relatively subtle changes to salt marshes that will be missed by this model.

- Tides data are accurate enough to reliably predict salt marshes. The fit of the logistic regression is encouraging in this respect (see Derivation of this layer, below).



**Figure 2**. In this example on Cape May, potential salt marshes are outlined in blue, and mapped salt marshes are displayed with green stippling. Potential tidal restrictions (road-stream crossings) are each scored based on the salt marsh loss ratio—the proportion of potential salt marsh above each restriction that is not mapped as salt marsh.

- Tidal restrictions are the only cause of salt marsh conversion to freshwater wetland or upland.

- There are not dams in tidal waters. Rarely, dams in tidal waters act as severe tidal restrictions. We had to drop dams from this model due to poor data quality—many mapped dams fell incorrectly in tidal waters. Although dams were often built at fall lines, in general, it seems rare for them to have been built within tidal waters.

- Salt marsh loss due to sea level rise and breakup is not addressed, but should not affect the model's results, assuming NWI mapping adequately represents current salt marsh extent.
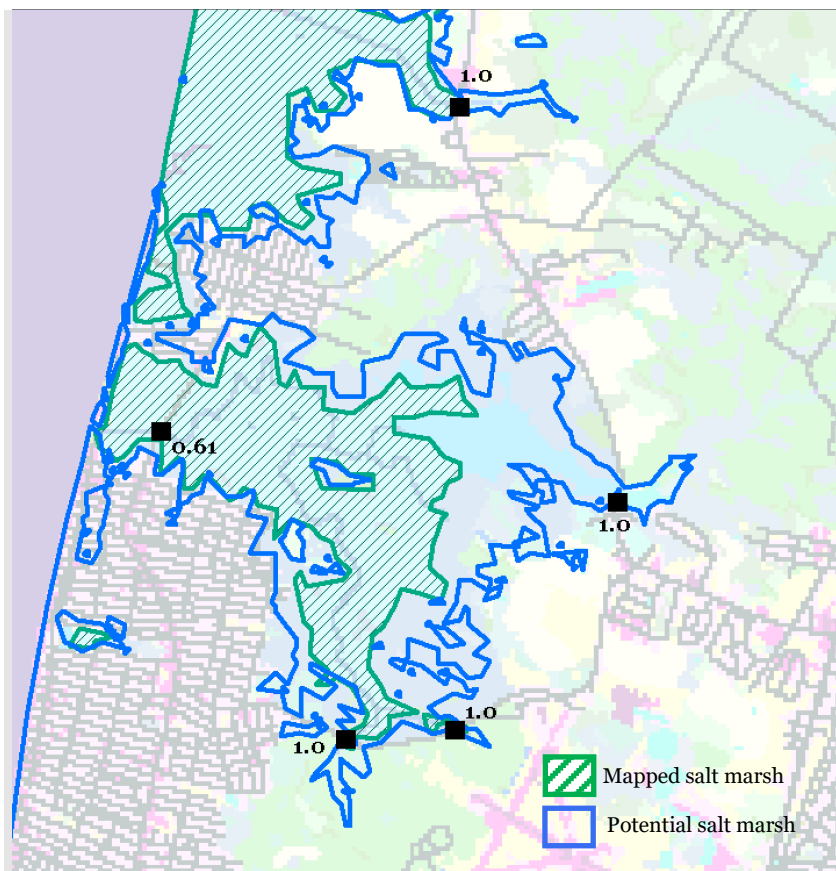
- This model is static, targeted at a nominal date of 2010, and does not include any consideration of future sea level rise or isostatic rebound.

- Crossings adequately represent tidal restrictions. Although tide gates not associated with roads or railroads are excluded from potential restrictions in the analysis, as they are not comprehensively mapped throughout the region, the effect of tide gates will usually be assigned to the nearest road crossing— downstream crossings if they exist, otherwise the next upstream crossing(s). This will result in some locational error, but should in general capture the effects of tide gates on a basin, except for basins with tide gates but no road-stream crossings. A comprehensive effort to map tide gates throughout the region could improve this model. Additionally, bridges with a watershed of greater than 1,350 km² were assumed not to act as tidal restrictions.
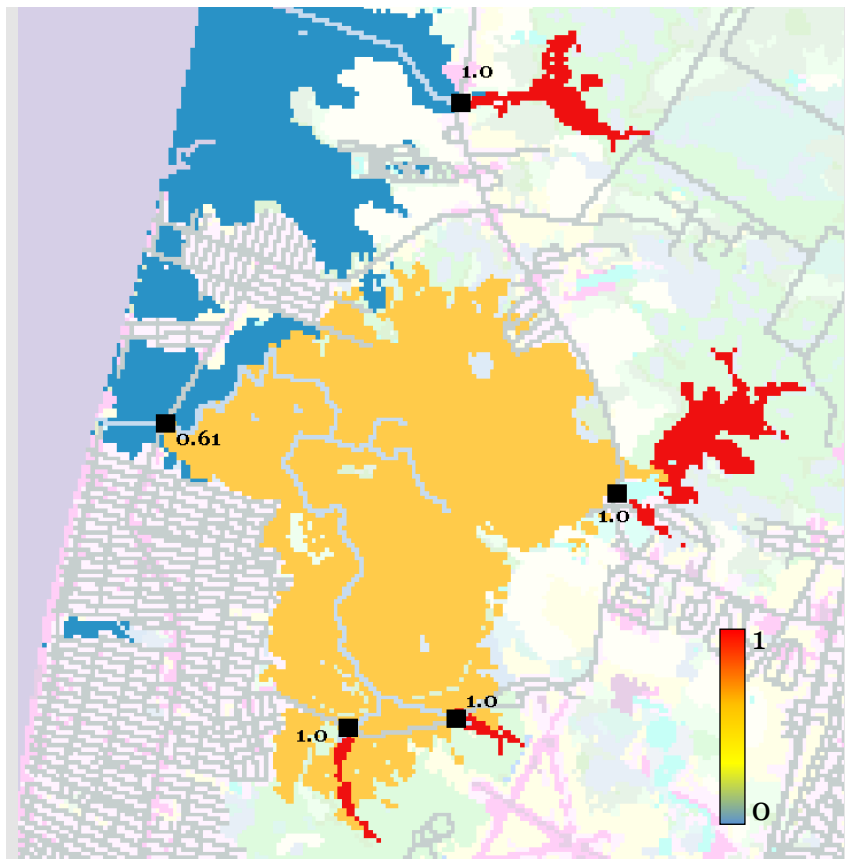


**Figure 3**. The tidal restriction metric gives the salt marsh loss ratio for the worst potential tidal restriction below each wetland in the map. Areas with orange to red are most affected by tidal restrictions.

In addition, we list a number of caveats and known data errors:

- Assignment of impact to individual potential restrictions is uncertain. Note that salt marsh loss is assigned to the furthest downstream potential restriction that could be responsible. Furthermore, the effect of unmapped restrictions, such as tide gates not associated with a road crossing, will be assigned to road-stream crossings.

- Salt marsh loss ratios in extremely small basins are poorly estimated due to the coarseness of mapping (30 m cells). In addition, we excluded areas within 1 cell of mapped streams to reduce alignment errors. These issues shouldn't have much effect on larger basins.

- The effects of tidal restrictions on freshwater tidal systems are ignored. Because we use salt marsh loss as our indicator of tidal restrictions, we have no way to estimate the effect of tidal restrictions on freshwater tidal systems. The metric stops when it reaches any streams mapped as freshwater tidal, and therefore relies on this system being correctly mapped in NWI.

- There are a number of errors in the flow grid. The flow grid was created from the National Elevation Data (NED), which has many errors. Estimating flow in low-relief coastal areas is difficult, as the signal/noise ratio in the DEM is low. This can result in flow paralleling streams and flow passing overland from coastal wetlands, thus avoiding the channels where they may encounter road-stream crossings. An example is the northern third of Great Harbor Marsh, in Marshfield, Massachusetts, where flow passes overland to the northeast. As a result, the southern part of the marsh is correctly modeled as affected by tidal restrictions, but the northern third is incorrectly modeled as unaffected. Flow errors cause parts of basins to be omitted from the model in numerous areas. (This problem could be reduced by creating a new flow grid from the NOAA DEM, but this would require burning streams into the DEM, which requires extremely labor-intensive hand-editing; this would not help with many of these issues, including parallel streams).

- There are several areas in the NOAA DEM where data was not available. The largest is on the peninsula between the Patuxent and the Chesapeake, and there are a few smaller data holes. The model returns no results in these areas.

In summary, this model uses fairly coarse landscape-scale data to attempt to detect and quantify a complex and often subtle source of environmental degradation. It has a number of shortcomings and limitations, and while we believe the results are useful, they should be used with caution.

Assessment of the quality of this model compared to field conditions was beyond the scope of this project. Such assessments could take two forms: (1) comparison of our point data with field-measured tidal restrictions, and (2) comparison of a field-based estimate of salt marsh degradation with metric results. In a previous study in Massachusetts (McGarigal et al., 2011), the water level deltas of 67 measured restrictions were compared to the salt marsh loss ratio. The relationship was significant ($P < 0.001$), with modest predictive power ($r^2 = 0.41$).

# Derivation of this layer

## *Data sources*

- DEM. We used a Digital Elevation Model (DEM) from NOAA's SLR Viewer, with modifications by TNC (Analie Barnettt, pers. comm.). This DEM is optimized for sea level rise modeling. The original had a grain of 5 m; we resampled it to 30 m to match our other data.

- Coastal zone. All modeling takes place within the coastal zone, defined as areas where elevation ≤ 5 m.

- Tide range. The tide range grid was modeled by NOAA's VDatum to give the difference between Mean High Water and Mean Low Water in meters. We extrapolated upflow where results from VDatum were unavailable by expanding the last available values upflow.

- Flow direction grid. This grid was derived from NED with high-resolution NHD streamlines burned in as part of the Designing Sustainable Landscapes (DSL) project.

- Potential tidal restrictions. These are road-stream and railroad-stream crossings within the coastal zone. These are based on NHD 1:25 k vector streams and Open Street Map roads and railroads.

- Landcover. We used the ESMplus, TNC's map of ecological systems with a number of modifications for DSL. Coastal wetlands are from the National Wetland Inventory (NWI).

## *Algorithm*

**Tides settings variable**. This settings variable estimates the probability that a cell is intertidal or wetter. We built a logistic regression using 9,919 random points in salt marshes throughout the northeast, and 9,639 random points in uplands within the coastal zone. Predictor variables were elevation and tide range. The results have a correct classification rate of 90.2% (McFadden $R^2$ = 0.57, errors of omission were 2.2%, and errors of commission were 7.6%). Note that some errors of commission are presumably caused by salt marshes lost to tidal restrictions, and are thus not meaningful errors in our model.

**Tidal restrictions metric**. The metric algorithm starts at each outflow (where the flow grid points to a nodata cell), following the flow grid upstream to the top of the watershed or to the edge of the tide mask (where elevation > 5 m). Everything above cells mapped as Freshwater Tidal Riverine is ignored, as there shouldn't be any mapped salt marshes in freshwater.

At each potential tidal restriction point (road-stream and railroad-stream crossings, excluding those with a watershed ≥ 1,350 km², which are presumed to be large bridges), the salt marsh loss ratio is calculated as

$$salt\ marsh\ loss = 1 - \frac{\sum mapped\ salt\ marsh}{\sum potential\ salt\ marsh}$$

where *mapped salt marsh* is the area above the potential restriction mapped as Estuarine Intertidal Emergent, excluding a 30 m buffer around open water and everything wetter than salt marshes (to reduce misalignment errors between the DEM and NWI), and *potential salt marsh* is the area above the potential restriction where the tides settings variable ≥ 0.5, excluding open water and wetter systems buffered 30 m. The salt marsh loss radio is assigned to each potential tidal restriction, and this result is available as both a raster and a point shapefile (see below).

The tidal restrictions metric is calculated by assigning the worst (highest-value) tidal restriction downflow from each cell of estuarine wetland, freshwater wetland, lotic (except for Freshwater Tidal Riverine), or nonforested upland within the coastal zone.

## GIS metadata

This data product is distributed as two distinct results and can be found at McGarigal et al (2017):

- **Tidal restrictions metric** (DSL_tideres_2010_v3.0.tif, 30 m geoTIFF raster) – Values vary from 0 (no effect from downstream tidal restrictions) to 1 (severe effect). This metric includes values only within the coastal zone, for estuarine intertidal systems, freshwater wetlands, nontidal rivers and streams, and grasslands and shrublands. All other cells are nodata. Additionally, several holes in the original DEM from NOAA are represented by nodata.

- **Tidal restriction points** (DSL_tiderestpts_2010_v3.0.shp, point shapefile) – This point file is an intermediate result of the tidal restriction metric. It includes a point for every mapped road-stream and railroad-stream crossing in the coastal zone, with the estimated severity of the tidal restriction in the field **tiderest**. These values correspond to the values in the tidal restrictions grid, above.

## Literature cited

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Ritter, A. F., K. Wasson, S. I. Lonhart, R. K. Preisler, A. Woolfolk, K. A. Griffith, S. Connors, and K. W. Heiman. 2008. Ecological Signatures of Anthropogenically Altered Tidal Exchange in Estuarine Ecosystems. Estuaries and Coasts, 31(3):554-571.

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# Appendix: Detailed data preparation and algorithm

This appendix describes the steps used in modeling. Software used included VDatum (from NOAA), ArcGIS, and custom code written in APL and R.

1.  Build tiderange data from VDatum, TIDERANGE, etc.

    Tide range data were built from NOAA's VDatum software. We ran VDatum for points centered on 90 m cells, splitting the northeast region into four tiles. We obtained mean high water (MHW) and mean low water (MLW) for each point, subtracting them to get the tide range. Resulting points were resampled to 30 m in ArcMap using bilinear interpolation. Because the extent of VDatum results are limited on the inland side, we extrapolated results upflow with the APL function TIDERANGE. Finally, results were clipped to the coastal zone (areas where elevation ≤ 5 m), yielding a 30 m raster, tiderange, giving the estimated range of tides in meters.

2.  Fit tides to uplands/salt marshes: fit.tides.r

    We sampled (approximately) 10,000 points each in mapped salt marshes and in undeveloped uplands throughout the coastal zone. These points were used to build a logistic regression to predict marshes vs. uplands from elevation and tiderange, using fit.tides in R. The logistic regression gave a correct classification rate of 90.2% (n = 19,558, McFadden $R^2$ = 0.57, omission = 2.2%, commission = 7.6%). Coefficients were $\beta_0$ = 1.73883, $\beta_{elevation}$ = -2.55623, $\beta_{tiderange}$ = 1.41334. The spatial arrangement of errors was assessed visually by summarizing errors in 10 km blocks and mapping them. There were no clear geographic patterns.

3.  Create tides settings variable: SETTIDES

    The tides settings variable was created in APL with SETTIDES, which applies the logistic regression model to all cells within the coastal zone. Areas mapped as subtidal were set to 1.0. The values of tides represent the probability of tidal influence.

4.  Delineate watersheds and find outflow points: MAKEWATERSHEDS

    The APL function MAKEWATERSHEDS finds outflow cells (cells where the flow grid points to nodata). Subsequent processing steps start processing at the outflow points. For the sake of computational feasibility, outflows were classified as large (watershed > 100 km²) or small. Large watersheds were processed one at a time in blocks encompassing the minimum enclosing rectangle, while small watersheds were processed in buffered tiles.

5.  Remove NOAA-introduced -0.5s in all waterbodies with FIXTIDES and FIXTIDESB

    A strange artifact in the NOAA DEM caused problems for our model: all open water was given an elevation of -0.5 m. This resulted in inland freshwater lakes being treated as tidally-influenced, giving nonsensical results in many areas. We fixed this with a pair of APL functions, FIXTIDES and FIXTIDESB (running on big watersheds and small watersheds in buffered tiles, respectively). These functions start at each outflow, walking recursively upflow until they hit 5 nontidal cells (where tides < 0.1). The tides variable is set to 0 for all cells that are never reached. This approach requires that tidal

cells be connected to marine cells via other tidal cells (with an allowance for a few cells of error in the DEM), removing inland lakes from consideration as tidal. The tides settings variable is updated by this procedure.

6. Run the metric: TR_DSL and TRB_DSL

   Finally, the tidal restrictions metric is run, using APL functions TR_DSL and TRB_DSL (running on big watersheds and small watersheds in buffered tiles, respectively). These functions call a sequential pair of recursive subfunctions. The first walks upflow recursively, then back down, counting (1) the number of cells of salt marsh above each cell (excluding a 1 cell buffer around open water), and (2) the number of cells of potential salt marsh (tides ≥ 0.5, excluding open water and wetter systems buffered 1 cell. At each potential tidal restriction, the salt marsh loss ratio is calculated as (1 – salt marsh / potential salt marsh) and assigned to the restriction's cell. Values for tidal restriction points are returned as an intermediate result. A second recursive subfunction starts at each outflow, working upflow and assigning the worst downstream tidal restriction value below to each cell. This gives the value of the tidal restriction for each candidate ecological system.