Designing Sustainable Landscapes:

Watershed habitat loss, watershed imperviousness, road salt, sediment, nutrients, and dam intensity metrics

A project of the University of Massachusetts Landscape Ecology Lab

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General description

This document describes a suite of stressor metrics that assess the various effects of development in the watershed of the focal cell, as opposed to a (usually) circular window around the focal cell, as with the other metrics. These metrics are used for lotic, lentic, and wetland systems. All effects are weighted by a the time of flow from each stressor source to the focal cell, thus, stressor sources that fall within a stream have a greater effect than those in distant uplands within the watershed. These share a common algorithm, but each has unique parameters.

These metrics are elements of the ecological integrity analysis of the Designing Sustainable Landscapes (DSL) project (see technical document on integrity, McGarigal et al 20147. 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. These stressor metrics range from 0 (no effect) to maximum values that differ for each metric (severe effect). See **Table 1** for parameters for each metric.

Watershed habitat loss (**Fig. 1b**). Assesses the intensity of past habitat loss caused by all forms of development in the watershed of the focal cell.

Watershed imperviousness (**Fig. 1c**). Assesses the amount of impervious surface in the watershed of the focal cell. Impervious surfaces can have complex effects on hydrology (Homa et al. 2013), water temperatures, detrital inputs, and the mobilization of pollutants such as automobile oil.

Road salt (**Fig. 1d**). Salt from winter treatment of roads can significantly increase the salinity of streams, wetlands, and waterbodies.

Sediment (**Fig. 1e**). Sediment from winter road sanding treatments, increased erosion of roadsides, and the road material of unpaved roads can be detrimental to fish, plants and aquatic invertebrates.

Nutrients (**Fig. 1f**). Enrichment of nitrogen and phosphorous from fertilization for agriculture and lawns in residential and commercial areas can have significant effects of plant growth and can result in lower dissolved oxygen levels via increased metabolism by bacteria.

Dam intensity (**Fig. 1g**). The number and sizes of upstream dams is a surrogate for the loss of sediment and hydrological and temperature effects of upstream dams.

Use and interpretation of these layers

These metrics rely on several assumptions:

- Land cover classes, imperviousness, and dams are correctly mapped.
- Parameterizations for each metric are reasonable. As these metrics are generic, rather than parameterized for individual species, it's not possible to use empirically-derived parameters, so the goal is to find "reasonable" parameters that adequately represent

each stressor metric across all species, usually focusing on more vulnerable, wider-ranging animals.

- Flow, based on elevation data and stream centerlines, is substantially correct.
- The time of flow model (Randhir et al. 2001) is appropriate and correctly parameterized.

Derivation of these layers

Data sources

- Ecological systems map (DSLland). All of these metrics are based on development, roads, and some formation-level ecological systems in the ecological systems map (see DSLland document, McGarigal et al 2017, for details).
- National Land Cover Database (NLCD) Percent Developed Imperviousness Layer, 2011 (https://www.mrlc.gov/nlcd2011.php).
- Dams from The Nature Conservancy, compiled from dam databases from each state.
- Flow direction grid, derived from National Elevation Dataset's (NED) elevation grid, National Hydrography Dataset (NHD) 1:25,000 flow lines, and custom editing and processing. Stream centerlines were burned into the flow direction grid to force flow direction to agree with observed streams, so errors in the DEM didn't incorrectly divert streams.
- Slope, derived from the National Elevation Dataset's (NED) 10 m Digital Elevation Model, resampled to 30 m.

Algorithm

These metrics share a common algorithm. Each is calculated as a mean of stressor sources in the watershed above each focal cell, weighted by each source's time-of-flow distance from the focal cell. Weights for stressor sources differ for each metric. Watershed habitat loss, road salt, sediment, and nutrients use weights based on landcover class (Table 1), while watershed imperviousness uses the percent impervious surface grid, and dam intensity uses the dams data. Aside from this weighting of sources, the algorithm is identical for each metric.

Time of flow is estimated using an algorithm devised by Randhir et al. (2001). For any given focal aquatic cell we determine its watershed based on the flow grid by identifying all the cells that eventually flow to that cell based on the flow grid, derived from digital elevation model and stream centerlines. For each cell within the watershed of the focal cell, we compute the time-of-flow, as follows:

If cell is in a stream channel, use revised Manning's equation:

$$t = \frac{LN}{1.49 R_h^{\frac{2}{3}} \sqrt{S}}$$

else, use the Kinematic Wave equation:

$$t = \frac{0.933 \times (LN)^{0.6}}{(CI)^{0.4} \times S^{0.3}}$$

where

t = time-of-flow
L = cell width (cell size x 1.4 for diagonal flow)
N = roughness coefficient (based on land use)
C = runoff coefficient (based on land use)
S = slope
I = rainfall intensity, inches/hour
R_h = hydraulic radius (cross-sectional area of flow / wetted perimeter)

In the revised Manning's equation, 1.49 is k/N, where k is a unit-conversion constant, and N is the roughness constant for the stream channel. The roughness and runoff coefficients (N and C) are parameterized uniquely for each land cover type, or ecological formation (groups of related ecological systems) in our case (**Table 2**). Rainfall intensity was set to a constant for the study area of 2 in/hr.

Hydraulic radius (R_h) can be approximated by the stream depth (because the wetted perimeter can be approximated by stream width), but because streams all have a very short time of flow compared to everything else and we have no legitimate way of estimating stream depth, we set R_h to a constant of 1 m.

The time-of-flow model estimates the time (t) it takes for a drop of water (or materials such as pollutants) to reach the focal cell; it ranges from zero at the focal cell to some upper bound based on the size and characteristics of the watershed. We rescale t to range from 0-1 by dividing t by the maximum observed value of t for the watershed of the focal cell and then taking the complement. In the resulting kernel, the weight ranges from 1 (maximum influence) at the focal cell to zero 0 (no influence) at the cell with the least influence (i.e., at the furthest edge of the watershed). In essence, kernel weights decrease monotonically as the distance upstream and upslope increases from the focal cell, but the weights decrease much faster across land than water so that the kernel typically extends much farther upstream than upslope. The resulting kernel can be viewed as a constrained watershed in which cells in the stream and closer to the focal cell have a lot of weight and cells in the upland and farther from the stream, especially on flat slopes with forest cover, have less weight (**Fig. 2**).

Clearly, this simple time-of-flow model does not capture the many nuances of real landscapes that influence the actual time it takes for water to travel from any point in the watershed to the focal cell (e.g., soil characteristics that influence infiltration of precipitation and vegetation characteristics that influence water loss through evapotranspiration), but it nonetheless provides a much more meaningful way to weight the importance of neighboring cells than the standard kernel estimator.

Weights by landcover class for the watershed habitat loss and road salt metrics were assigned by expert opinion; the weights for watershed habitat loss are the same ones used for the terrestrial habitat loss metric (**Table 1**). The sediment and nutrients metrics use nutrient and sediment loadings by landcover class crosswalked from the (now-defunct) MassGIS Watershed Analyst (**Table 1**). Watershed imperviousness uses the NLCD percent impervious grid as its source. Dam intensity is based on the structural height of each dam, with dams of unknown height treated as 1 m high.

All watershed metrics are applied only to cells in stream centerlines (though each assesses the entire watershed of each focal cell). The final metrics are then mixed by taking closest stream centerline value for all off-centerline stream cell, and by taking the flow-volume-weighted mean of scores for cells flowing into wetlands and lentic waterbodies, and applying them to the entire basin.

GIS metadata

These data products are distributed as geoTIFF rasters (30 m cells). The cell values are continuous, representing the intensity of each stressor in the watershed above each cell, ranging from 0 (no stress) to 1 (maximum stress). These data products can be found at McGarigal et al (2017):

- **Watershed habitat loss**
- **Watershed imperviousness**
- **Road salt**
- **Sediment**
- **Nutrients**
- **Dam intensity**

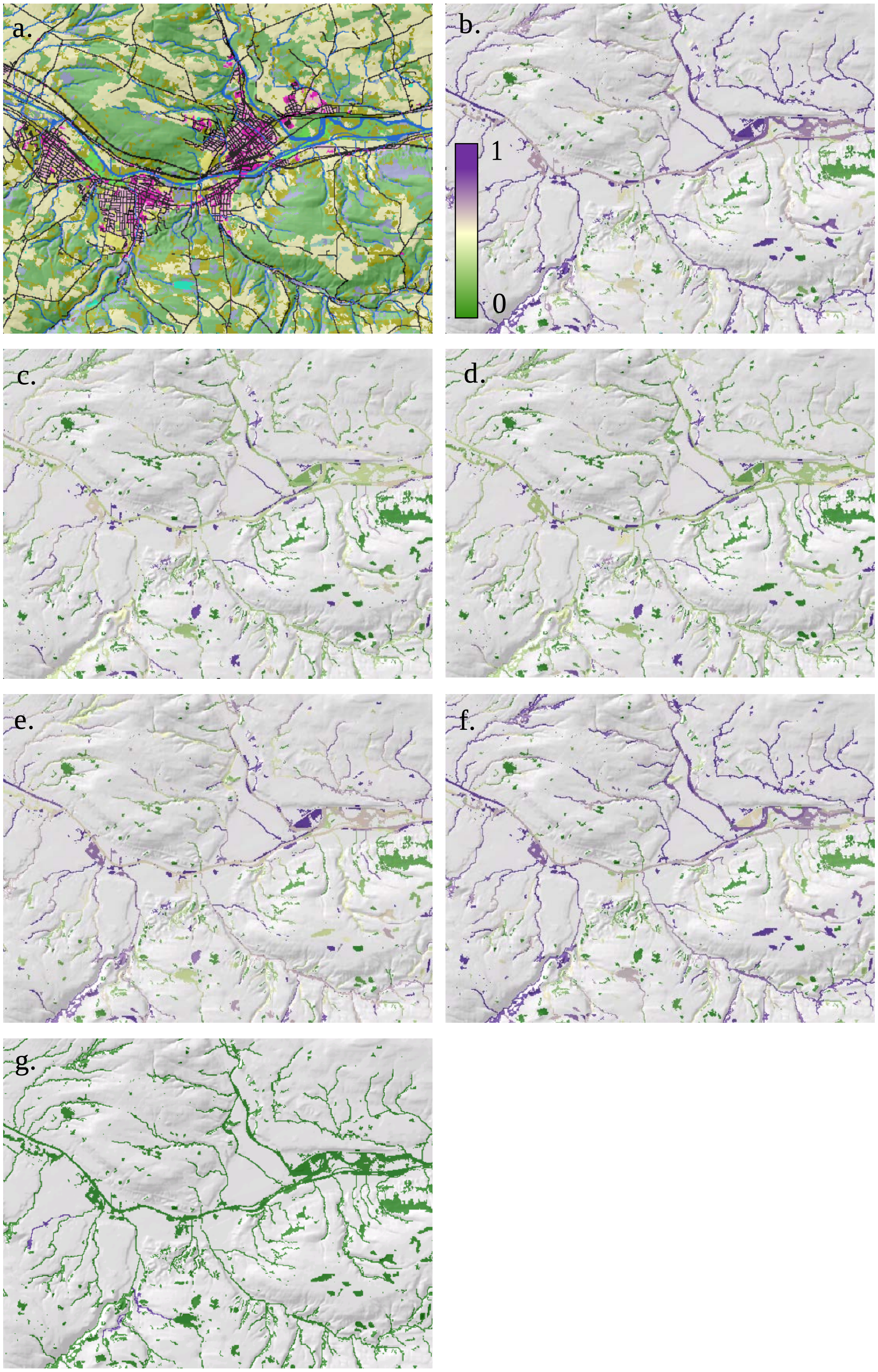

Figure 1. Examples of each metric in the vicinity of Herkimer and Frankfort, New York: (a) landcover, and each metric: (b) Watershed habitat loss, (c) Watershed imperviousness, (d) Road salt, (e) Sediment, (f) Nutrients, (g) Dam intensity, all with hillshading. Gray areas correspond to uplands, development and roads, where the metrics are not applied.

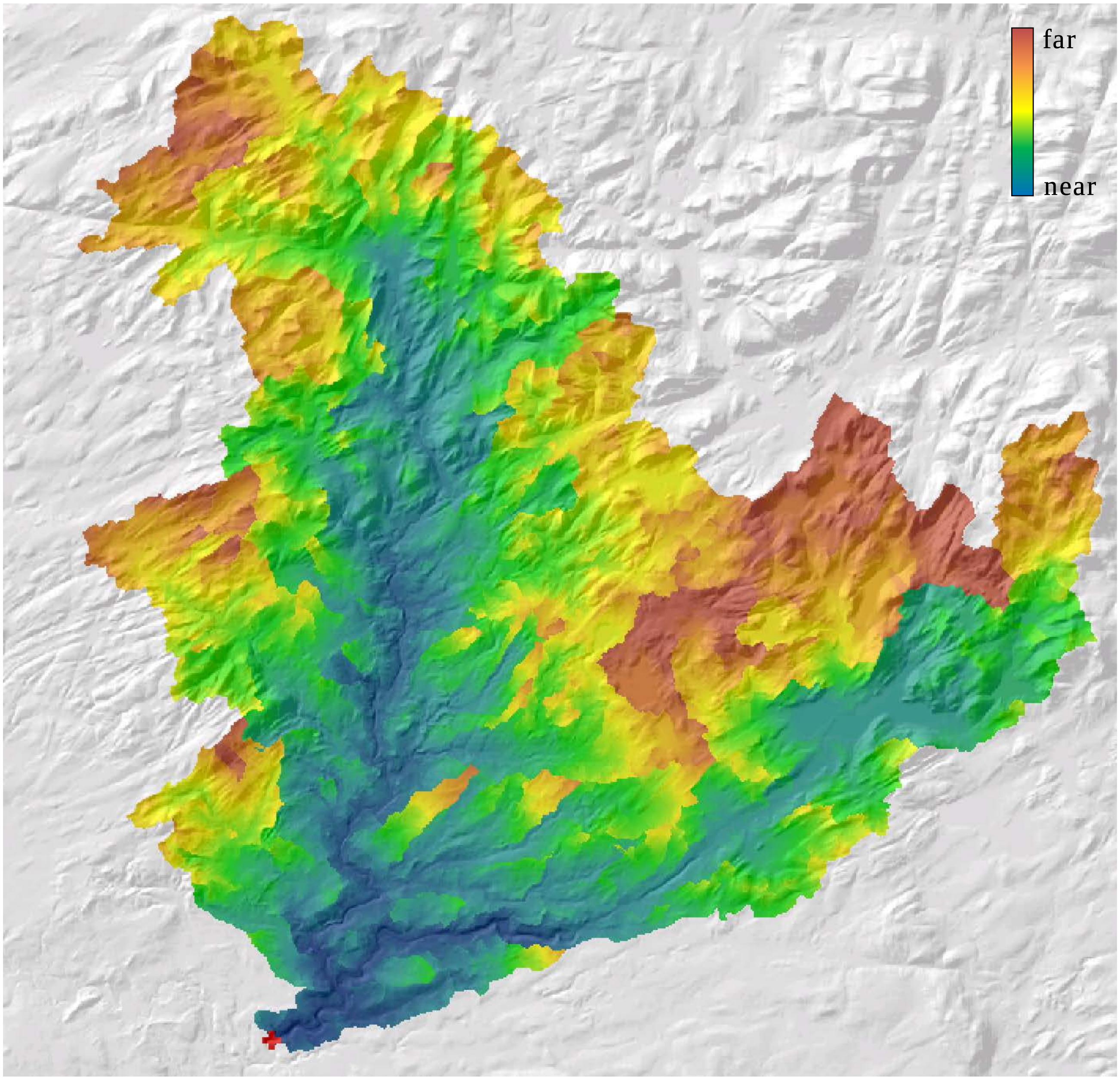

Figure 2. An example of a time-of-flow watershed kernel for a focal cell (✚) based on the time-of-flow model in the southern Adirondacks. Hillshading helps provide context.

Table 1. Parameters for each metric. Weights for each landcover class are listed for each of the metrics that uses them; weights are relative within each metric. Landcover classes not shown in the table have weights of 0 for all metrics. Watershed imperviousness uses the percent impervious grid rather than weights for each landcover class. Dam intensity uses heights of each mapped dam.

Landcover class	Watershed habitat loss	Road salt	Sediment	Nutrients
Developed — high intensity	1	1	700.804	33.39
Developed — medium intensity	0.8	0	522.311	26.98
Developed — low intensity	0.8	0	387.81	21.64
Developed — open space	0.8	0	298.143	10.94
Motorway	1	3	970.646	0
Primary road	1	3	970.646	0
Secondary road	1	3	970.646	0
Tertiary road	1	2	970.646	0
Local road	1	2	970.646	0
Track	0.5	2	970.646	0
Active train	1	0	970.646	0
Abandoned train	0.5	0	970.646	0
Culvert/bridge	1	0	0	0
Dam	1	0	116.567	0
Cultivated crops	1	0	460.665	6.14
Pasture/hay	0.5	0	116.567	6.90
Barren land	0.8	0	14.571	0
Northeastern Upland Forest	0	0	23.538	0
Boreal Upland Forest	0	0	23.538	0
Shrubland & grassland	0	0	14.571	0

Table 2. Roughness and runoff coefficients used in the time-of-flow kernel based on the model derived by Randhir et al. (2001). Coefficients are given by ecological formation or ecosystem (see Appendix A) and were based on coefficients used in Randhir et al. (2001), obtained from the author, and cross-walked to our land cover types. Ecosystem = n/a pertains to formations that contain only a single ecosystem. Time-of-flow is used to weight the influence of each cell in the watershed above a focal cell in the watershed-based stressor metrics (Table 2).

Formation	Ecosystem	Roughnesss	Runoff
Alpine	n/a	0.1	0.45
Cliff & Rock	All	0.02	0.4
Grassland & Shrubland	All	0.1	0.45
Coastal Scrub-Herb	All	0.1	0.45
Boreal Upland Forest	All	0.6	0.4
Northeastern Upland Forest	All	0.6	0.4
Northeastern Wetland	All	0.1	0.4
Peatland	All	0.1	0.4
Stream (headwater/creek)	All	0.02	n/a
Stream (small)	All	0.02	n/a
Stream (medium)	All	0.02	n/a
Stream (large)	All	0.02	n/a
Lentic	All	0.02	n/a
Freshwater Tidal Riverine	All	0.02	n/a
Estuarine Intertidal	All	0.06	0.4
Marine Intertidal	All	0.02	0.4
Agriculture	Cultivated crops	0.2	0.5
	Pasture/hay	0.4	0.45
Developed	Abandoned train	0.02	0.6
	Active train	0.02	0.6
	Culvert/bridge	0.02	0.6
	Dam	0.02	0.6
	Developed- high intensity	0.02	0.5
	Developed- medium intensity	0.04	0.5
	Developed- low intensity	0.06	0.5

Formation	Ecosystem	Roughnesss	Runoff
	Developed- open space	0.1	0.3
	Local road	0.02	0.6
	Motorway	0.02	0.6
	Primary road	0.02	0.6
	Secondary road	0.02	0.6
	Tertiary road	0.02	0.6
	Track	0.02	0.6
	Barren land	0.08	0.45

Literature cited

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