



IDW-PLUS: AN ARCGIS TOOLSET FOR CALCULATING SPATIALLY EXPLICIT WATERSHED ATTRIBUTES FOR SURVEY SITES¹

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ABSTRACT: Watershed characteristics such as land-use and land-cover affect stream condition at multiple scales, but it is widely accepted that conditions in close proximity to the stream or survey site tend to have a stronger influence. Although spatially weighted watershed metrics have existed for years, nonspatial lumped landscape metrics (*i.e.*, areal mean or percentage) are still widely used because relatively few technical skills are needed to implement them. The Inverse Distance Weighted Percent Land Use for Streams (IDW-Plus) custom ArcGIS toolset provides the functionality to efficiently calculate six spatially explicit watershed metrics which account for the Euclidean or flow length distance to the stream or outlet, as well as the probability for overland runoff. These include four distance-weighted metrics, those being inverse Euclidean distance to the stream or outlet, and the inverse flow length to the stream or outlet. Two tools are also included to generate hydrologically active (*i.e.*, runoff potential), inverse flow length to the stream or outlet metrics. We demonstrate the tools using real data from Southeast Queensland, Australia. We also provide detailed instructions, so readers can recreate the examples themselves before applying the tools to their own data.

(KEY TERMS: watersheds; streams; environmental impacts; geospatial analysis.)

Peterson, Erin E. and Alan R. Pearse, 2017. IDW-Plus: An ArcGIS Toolset for Calculating Spatially Explicit Watershed Attributes for Survey Sites. *Journal of the American Water Resources Association* (JAWRA) 1-9. <https://doi.org/10.1111/1752-1688.12558>

INTRODUCTION

The terrestrial landscape strongly influences physical, chemical, and biological processes within streams and rivers (Hynes, 1975; Townsend, 1996; Allan, 2004). Efforts to quantify these relationships at broad spatial scales have steadily increased since the early 1990s, when geographic information systems (GIS) started to be widely used in aquatic science (Johnson and Host, 2010). Lumped landscape representation metrics are arguably the most common method used to describe the landscape in these studies. Lumped

metrics are simply summary statistics that describe the percent, proportion, or mean of a landscape characteristic within an area (*e.g.*, percent urban land use or proportion of forest cover), such as the entire watershed (Johnson *et al.*, 1997) or land within a specific distance of a feature (*i.e.*, buffer) such as a stream (Strayer *et al.*, 2003) or a survey site (Comelo *et al.*, 1996). Lumped metrics may be popular because they are relatively straightforward to calculate, but there are also drawbacks to the approach. When a lumped metric is used, the implicit assumption is that land use and land cover in every part of the watershed has an equal influence on instream

¹Paper No. JAWRA-16-0214-N of the *Journal of the American Water Resources Association* (JAWRA). Received November 8, 2016; accepted June 5, 2017. © 2017 American Water Resources Association. **Discussions are open until six months from issue publication.**

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processes and condition; however, this assumption is unlikely.

There is a growing body of research showing that the relative proximity of land to the stream or survey site, as well as the potential for overland runoff, can reduce or enhance the influence of the terrestrial environment on instream processes and condition. For example, accounting for the spatial proximity of land use using a distance-weighted metric (often based on inverse distance, which weights areas in close proximity more strongly) may explain additional variation in models fit to fish (King *et al.*, 2004), invertebrate (Peterson *et al.*, 2011), nutrient (King *et al.*, 2005), metals (Comelo *et al.*, 1996), invasive plant (King *et al.*, 2007) and water bird (DeLuca *et al.*, 2008) data. Further, accounting for the runoff potential of land (*i.e.*, hydrologic activity) may also improve the statistical relationship between landscape characteristics and instream conditions (Hunsaker and Levine, 1995; Stauffer *et al.*, 2000; Peterson *et al.*, 2011). Distance-weighted metrics can be manually calculated, but having an automated tool that generates watershed metrics for a large number of survey sites represents a major advantage. Often, custom scripts are written by individuals to automate the process, but we believe that this is a barrier to many aquatic scientists, despite their general familiarity with GIS.

Our overall goal is to make spatially explicit, landscape representation methods available to users so that they can easily account for the effects of spatial proximity and hydrologic activity (*i.e.*, runoff potential) using simple landscape representation methods. We have developed an ArcGIS (ESRI, 2015) custom toolbox which can be used to calculate six spatially explicit, land-use metrics developed by Peterson *et al.* (2011). These include (1) inverse flow length to the outlet (iFLO), (2) inverse flow length to the stream (iFLS), (3) inverse Euclidean distance to the outlet (iEDO), (4) inverse Euclidean distance to the stream (iEDS), (5) hydrologically active inverse flow length to the outlet (HAiFLO), and (6) hydrologically active inverse flow length to the stream (HAiFLS). We demonstrate the tools and highlight differences in percent land-use values generated using the six metrics, using real data from Southeast Queensland (SEQ), Australia. In addition, we provide the example data and a detailed tutorial (Supplementary Information B) so that users can recreate the example presented here before applying the tools in their own studies.

METRIC DERIVATION

A number of input datasets (Table 1) are needed to calculate six spatially explicit landscape representation

TABLE 1. A Description of the Input Data Requirements for the Inverse Distance Weighted Percent Land Use for Streams (IDW-Plus) Tools, Including Data Format, a Description of the Input, and the Tools that Use the Data.

Input	Format	Description	Tools
Sites (outlets)	Shapefile or feature class	A set of points representing study sites located on a stream network	All
Digital elevation model (DEM)	Raster	Elevation data, with sinks filled	All
Flow direction	Raster	Flow direction from each cell to its steepest downslope cell	All
Flow accumulation	Raster	Number of cells upslope from each cell	All
Stream	Raster	Reclassified streams raster. Stream grid cells are NoData, all other cells are 1	iFLS, iEDS, HAIiFLS
Land use (Value raster)	Raster	Reclassified land-use or land-cover raster. Land-use cells are 1, otherwise 0	All

TABLE 2. Spatially Explicit Watershed Metric Acronym and Description.

Watershed Metric Acronym	Description
iEDO	Inverse Euclidean distance to the outlet
iEDS	Inverse Euclidean distance to the stream
iFLO	Inverse flow length to the outlet
iFLS	Inverse flow length to the stream
HAiFLO	Hydrologically active inverse flow length to the outlet
HAiFLS	Hydrologically active inverse flow length to the stream

metrics (Peterson *et al.*, 2011; Table 2) using the Inverse Distance Weighted Percent Land Use for Streams (IDW-Plus) toolbox in ArcGIS (ESRI, 2015). We describe how each of the metrics is derived below based on these datasets so that readers have a clear understanding of the similarities and differences in the way the metrics represent land use. In addition, we have provided a small example in Supplementary Information A, which readers can work through by hand to help understand how the metrics are calculated.

Assuming that a land-use characteristic is represented in raster format, the general form of a lumped land-use (LU) watershed metric is

$$LU\% = \frac{\sum_{i=1}^n I(k_i)}{n} \times 100, \quad (1)$$

where the indicator variable $I(k_i) = 1$ when the land use k is present in the i th raster cell and 0 otherwise

(land-use raster, Table 1), and n is the total number of cells in the watershed upstream of the survey site (Sites, Table 1). Hence, the lumped metric gives equal weight to every land-use or land-cover cell in a watershed, regardless of their spatial arrangement or the proximity to the stream or outlet (*i.e.*, rearranging the cells has no influence on the percent land use as long as the total number of land-use cells stays the same). Note that the outlet is the most downstream terminus of the watershed for each survey site, sometimes referred to as “pour point” watersheds. Thus, the survey site and the outlet are at the same location.

The general form for the distance-weighted landscape representation metrics (*e.g.*, iEDO, iEDS, iFLO, and iFLS) is

$$LU\% = \frac{\sum_{i=1}^n I(k_i)w_i}{\sum_{i=1}^n w_i} \times 100. \quad (2)$$

Note that Equation (2) is similar to Equation (1), except that a weighting term, w_i , has been added

$$w_i = (d_i + 1)^p, \quad (3)$$

where d_i is the distance from the i th raster cell in the watershed to either the outlet (*e.g.*, iEDO, iFLO, and HAI FLO) or the nearest location on the stream itself (*e.g.*, iEDS, iFLS, and HAI FLS). Depending on the metric, “distance” is measured using Euclidean or flow length distance (Table 3) from each raster cell in a watershed (*i.e.*, the source) to the stream or outlet (Sites or Stream, respectively; Table 1). The parameter p is the inverse-distance-weighting power.

Hydrologically active, inverse-distance-weighted metrics (HAI DW) account for proximity to the stream (HAI FLS) or outlet (HAI FLO) using the distance-

weighting term described in Equation (3). However, flow accumulation (Table 3) is also included as a proxy for hydrologic activity (*i.e.*, runoff potential)

$$LU\% = \frac{\sum_{i=1}^n I(k_i)A_iw_i}{\sum_{i=1}^n A_iw_i} \times 100, \quad (4)$$

where A_i is

$$A_i = f_i + 1, \quad (5)$$

and f_i is the downstream flow accumulation generated using the ArcGIS Flow Accumulation function (ESRI, 2015; Table 1). The flow accumulation value represents the number of upslope cells that would be expected to contribute flow into each downslope cell based on the topography of the watershed, assuming that all precipitation results in overland flow. We add 1 to each flow accumulation value to ensure that land use in cells where flow originates (*i.e.*, local high points in the watershed with $f_i = 0$) are accounted for in the metric. Thus, a hydrologically active distance for any cell in the watershed is the product of the flow accumulation (Equation 5) and the distance-weighting term (Equation 3): A_iw_i .

Clearly, each metric (Table 2) produces distinct weighting schemes that capture the proximity and runoff potential of the landscape in a different way. Figure 1 provides a schematic representation of the relative influence of each cell in a watershed by metric. Note that greater weight is attributed to land-use cells in close proximity to the watershed outlet by the iEDO and iFLO metrics. The percent land-use values produced by these two metrics may be strongly correlated (Peterson *et al.*, 2011). However, the iFLO metric may still be altered based on the topography of the watershed, which is not the case for the iEDO metric. In the iEDS and iFLS metrics, land-use cells in close proximity to the stream have a stronger influence on the percent land-use metric. Streams generally extend up into the watershed and so a larger number of cells will strongly influence the iEDS and iFLS compared to metrics based on distance to the outlet (*i.e.*, iEDO and iFLO), which is represented by a single cell. The relative influence of land-use cells in the HAI DW metrics is more complicated than the distance-weighted metrics; land use in close proximity to the stream or outlet that also has a higher chance of runoff potential (*e.g.*, intermittent streams and gullies), contribute more to the LU% estimate. However, this also means that the HAI DW metrics are less dependent on the spatial resolution of the streams dataset than the iEDS and iFLS metrics (Peterson *et al.*, 2011).

TABLE 3. ArcGIS Toolboxes and Tools Used within the IDW-Plus Toolset, Along with Their Associated License Levels.

ArcGIS Toolbox	Tool	License
Data Management	Add Field	Basic
	Calculate Field	
	Delete Field	
	Delete	
	Make Feature Layer	
Spatial Analyst	Select Layer By Attribute	Advanced
	Con	
	IsNull	
	Euclidean Distance	
	Flow Length	
	Snap Pour Point	
	Watershed	
	Raster Calculator	
	Zonal Statistics as Table	

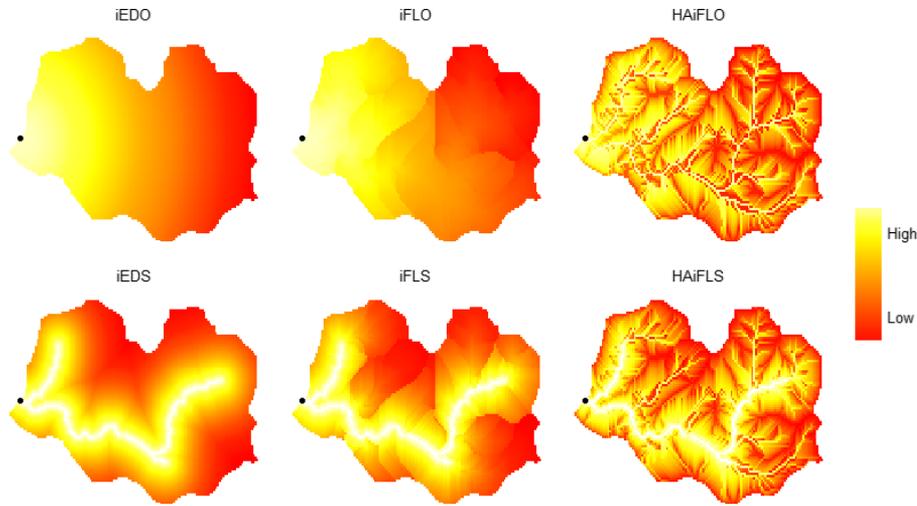


FIGURE 1. Schematic Showing the Relative Weight Assigned to Each Cell within a Watershed, by Metric for iEDO, iEDS, iFLO, iFLS, HAIiFLO, and HAIiFLS. The black circle represents the watershed outlet. For plotting purposes, the HAIiFLO and HAIiFLS metrics were standardized to the same range as the other metrics (0-1) and the quantiles of the weights were used to standardize the display between metrics.

IDW-PLUS GEOPROCESSING TOOLSET

The IDW-Plus geoprocessing toolset (Figure 2) can be used to calculate the six spatially explicit watershed attributes described in the previous section (Table 2) using ArcGIS version 10.3.1 (ESRI, 2015). A number of ArcGIS toolsets and tools are used within the IDW-Plus toolset (Table 3), and an Advanced level license is needed to run the tools, as well as access to the Spatial Analyst extension. All scripts are written using Python 2.7.8, and the source code is accessible within the toolbox.

Inputs and Data

All tools provided in the IDW-Plus toolset require similar data inputs (Table 1). The user must provide

a set of survey site locations in either feature class or shapefile format, which represent the watershed outlets. However, field survey sites do not always align with the streams when they are imported into a GIS. These sites may be manually moved, or automatically “snapped” (ESRI, 2015), to the nearest stream line by the user prior to running the tool. Alternatively, the IDW-Plus tools can snap the sites to the stream grid as it runs, provided that the stream lines are within the “Snap tolerance” set by the user (Figure 3).

The weighting scheme for the iEDS, iFLS, and HAIiFLS tools accounts for the distance to the nearest stream, and as such, a stream raster is a required input for these tools (Table 1). The streams raster may be derived from a vector dataset such as the United States National Hydrography Dataset Plus Version 2 (NHDPlusV2) (McKay *et al.*, 2012) or the Australian Hydrological Geospatial Fabric (Geofabric) Surface Network dataset (Bureau of Meteorology,

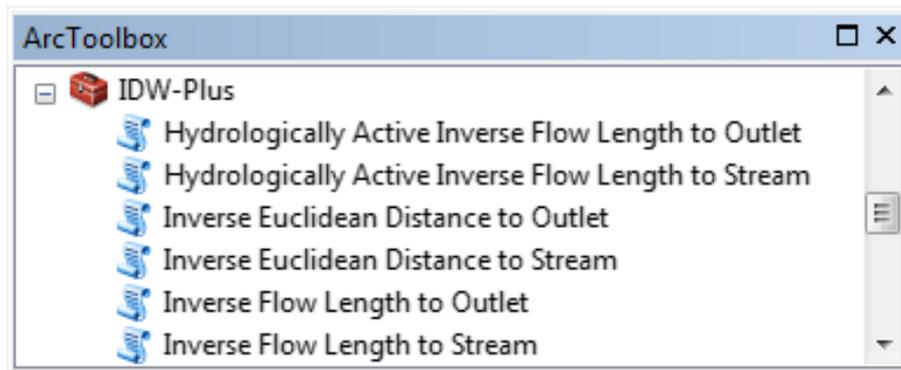


FIGURE 2. The IDW-Plus Version 1.0.2 Toolset Contains Six Tools for Calculating Spatially Explicit Watershed Attributes.

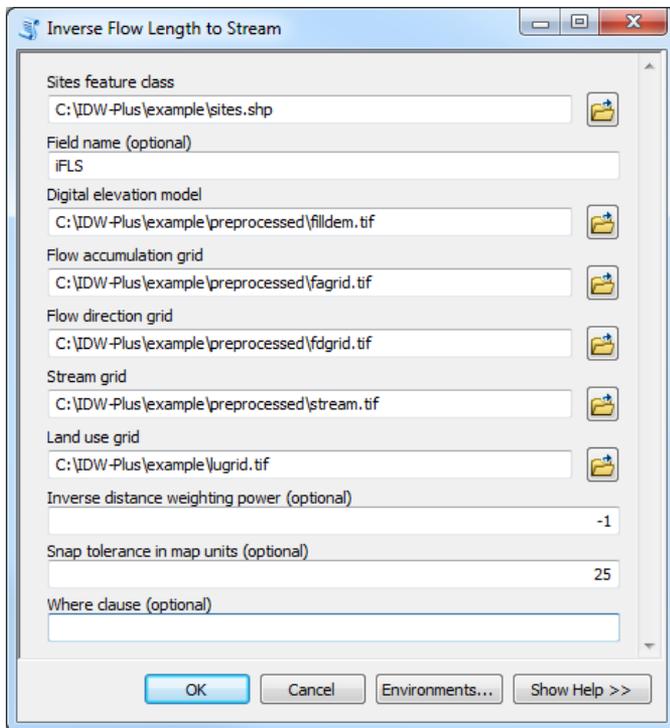


FIGURE 3. The iFLS Tool Window. All tools have similar data inputs and arguments, except that tools based on the distance to the outlet do not include the stream grid as an input.

2012). However, if the streams dataset is not derived from the same digital elevation model (DEM) used as an input for the tools here, the streams may need to be “burned in” to the DEM (sometimes referred to as drainage enforcement) prior to creating the flow direction and flow accumulation rasters (ESRI, 2015). It is also important to fill the DEM to eliminate topographical errors. Please see Supplementary Information B for a detailed description of how to burn in streams and fill a DEM.

An additional “Value” raster is required for each tool, which represents the landscape characteristic being summarized within the watershed. The values in the Value raster often represent land-use or land-cover classes, such as urban or forested areas, but could also represent a variety of variables, such as geology or soil type. The value raster must be reclassified as a binary grid, where 1 is the landscape characteristic of interest and all other cells are coded as 0.

There are also four optional arguments for the tools that can be defined by the user (Figure 3):

1. Field name: Name for the new output column. If the argument is left empty, the tool will automatically name the field based on the tool name and the landscape characteristic raster.
2. Inverse-distance-weighting power: A negative number corresponding to the parameter p in

Equation (2). The default value is $p = -1$, which is inverse distance.

3. Snap tolerance: The maximum distance (in map units) that the tools will move the survey sites to the stream grid (if misaligned), before delineating watersheds. The default value is 0 map units.
4. WHERE clause: The WHERE clause can be used to calculate metrics for a subset of sites that meet a logical criterion. The WHERE clause is empty by default.

CASE STUDY: SOUTHEAST QUEENSLAND, AUSTRALIA

In this section, we demonstrate the IDW-Plus toolset using data from the SEQ Ecosystem Health Monitoring Program (EHMP) (Bunn *et al.*, 2010). We provide the example data and a detailed tutorial in Supplementary Information B so that users can recreate the examples themselves before applying the tools in their own studies.

We selected five survey sites with nested watersheds to highlight the similarities and differences in the metrics (Figure 4). Sites 1, 4, and 5 are located in the Lower Brisbane subcatchment, while Sites 2 and 3 are located in the Logan catchment. The primary land use in the area is rural residential, but a relatively large tract of land upstream from Site 5 is owned by Australian Defence, which is relatively natural and minimally used. Pasture lands are also found throughout the area (Figure 4), with the largest contiguous patch found in the headwaters of Sites 1, 4, and 5.

We obtained a DEM with a 25-m resolution (QNRW, 2000), pasture land-use data (BRS, 2002), and a stream dataset (Moreton Bay Waterways and Catchments Partnership, 2005) for the region. The streams dataset was converted to raster format with a 25-m spatial resolution and burned into the DEM by subtracting 10 m from the DEM surface at each raster cell. Next, we filled the DEM and used it to derive the flow direction and flow accumulation grids.

Once the GIS pre-processing was complete, generating the metrics was straightforward. We provided the data and tool arguments for each tool, accepting all the defaults except for “Snap tolerance,” which was set to 25 m since the five sites did not perfectly align with the stream grid. The output from each of the six tools was automatically stored in the attribute table of the sites feature class (Figure 5).

When we compared metric values (Table 2) based on the same distance measure (*e.g.*, distance to outlet

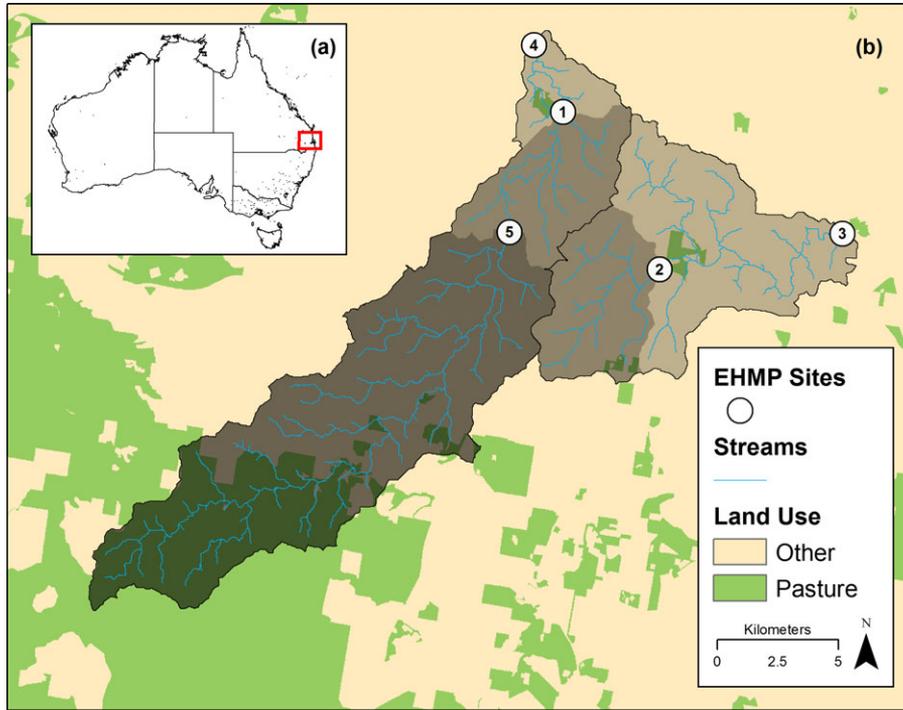


FIGURE 4. Map of the Study Area (a), which is located in Southeast Queensland, Australia. Black circles represent the five Ecosystem Health and Monitoring Program (EHMP) survey sites, which are labeled using the corresponding SiteID. Sites 1, 4, and 5 are located in the Lower Brisbane subcatchment, while Sites 2 and 3 are located in the Logan catchment. Watersheds for each EHMP site are displayed in varying shades of gray. Lighter shades of gray represent larger watersheds within which the darker watersheds are nested. The streams running through the watersheds are shown in blue.

FID	Shape	OBJECTID	SiteID	iFLO	iEDO	HAiFLO	iFLS	iEDS	HAiFLS
0	Point	1	1	11.32528	11.91965	0.28033	30.1598	30.07201	38.34532
1	Point	2	2	1.19011	1.08007	0.00501	0.68559	0.70559	0.2765
2	Point	3	3	1.48161	1.55117	0.09612	2.97795	2.96129	2.07297
3	Point	4	4	10.32413	10.21865	0.23452	28.87286	28.78164	35.85871
4	Point	5	5	12.9827	13.68368	0.47437	37.48106	37.31515	45.37297

FIGURE 5. The Output Attribute Table of the Sites Feature Class. Six spatially explicit landscape representation metrics have been added, including the iEDO, iEDS, iFLO, iFLS, HAIiFLO, and HAIiFLS.

and to stream), there were both similarities and differences in the percent pasture metrics (Figure 5). As expected, the metrics based on Euclidean distance

were almost identical to those produced by the metrics based on flow length distance (iEDO *vs.* iFLO, and iEDS *vs.* iFLS). There were greater differences

between the iEDS and iFLS metrics and the HAIFLS metric for all sites (Figure 5), depending on the spatial location and amount of pasture land use in the watershed. However, the HAI FLO metric was always considerably smaller than the iEDO and iFLO metrics because there were few pasture land-use cells in close (upstream) proximity to the outlet, and by chance, those cells had small flow accumulation values.

When we compared the percent pasture land-use values across all metrics, it was clear that metrics based on distance to stream (iFLS and iEDS) produced estimates that were at least 1.91 times as large as those based on distance to outlet (iFLO and iEDO), with the exception of Site 2 (Figure 5). However, this result is not surprising because there are more pasture cells in close proximity to the stream compared to those near the outlet (Figure 4). The exception was Site 2, where only a small amount of pasture land was located in the highest portions of the watershed.

CONCLUSION

The ability to account for the influence of the terrestrial landscape on in-stream condition at multiple spatial scales is important in many aquatic science studies. The survey sites used in this article represent a subset of the EHMP data, which was statistically analyzed by Sheldon *et al.* (2012) along with aquatic ecosystem-health indicators to (1) identify the spatial scale of land use (represented using Lumped, iFLO, iFLS, HAI FLO, and HAI FLS metrics; Table 2), or the combination of spatial scales, that most strongly influences overall ecosystem health; and (2) determine whether the most influential spatial scale differed for different indicator types (*i.e.*, fish, macroinvertebrates, ecosystem processes, water quality, and nutrients). The results of their study showed that the most influential spatial scale of land use differed depending on the indicator type and that there were also seasonal (*i.e.*, wet *vs.* dry) differences within some indicator types. This information was particularly useful because it provided guidance about the scale and watershed position of restoration activities that would result in the greatest improvement of ecosystem health in the region's streams and rivers. Thus, the IDW-Plus tools provide a convenient, efficient, and automated method that managers and researchers can use to investigate similar relationships in their own regions.

Numerous GIS toolsets have been created to generate watershed attributes, and it can be difficult to understand the similarities and differences between

them. Many tools produce attribute datasets that are spatially explicit in the sense that they represent both local-scale (catchment area where surface flow drains directly into a stream segment, excluding any upstream contributions) and watershed-scale conditions (Theobald *et al.*, 2005; Strager *et al.*, 2009; McKay *et al.*, 2012; Hill *et al.*, 2016). Some well-known examples of this approach include the Stream-Catchment (StreamCat) attributes (Hill *et al.*, 2016), the NHDPlusV2 Catchment Attribute Allocation and Accumulation Tool (CATV2) (McKay *et al.*, 2012), and the National Fish Habitat Partnership Data System (<http://ecosystems.usgs.gov/fishhabitat/>) (Tsang *et al.*, 2014). However, the line segment is the finest unit of measurement, which means that attributes can only be used with the stream network they were developed for. In addition, attributes are calculated for the most downstream node of each line segment and are non-spatial within a catchment and watershed; thus, survey sites are assigned the attributes of the line segment they reside on. Although these attributes do not represent watershed conditions for a survey site located in the middle of a line, there are many situations where they would be preferable to those produced by IDW-Plus. For example, the StreamCat attributes (Hill *et al.*, 2016) have been calculated for approximately 2.65 million stream segments in the NHDPlusV2 (McKay *et al.*, 2012). These attributes are invaluable for regional studies looking at broad-scale relationships between in-stream biological or physicochemical processes and climate, land use, and/or land cover in the conterminous United States (U.S.), especially when thousands of survey sites are involved (*e.g.*, Isaak *et al.*, 2016, 2017). In contrast, the attributes produced by the IDW-Plus tools are preferable for research questions relating to relatively fine-scale spatial relationships between land use and in-stream processes (*e.g.*, Sheldon *et al.*, 2012). The IDW-Plus tools may also be preferable when (1) the extent of the study area and the number of survey sites is relatively small (*e.g.*, <2500), (2) using a finer scale stream network, and (3) the study area is located outside of the conterminous U.S.

We anticipate that the IDW-Plus toolbox will make these spatially explicit landscape representation metrics more accessible to aquatic scientists. However, there are additional ways in which the tools could be improved. Currently, the tools only make use of the inverse-distance-weighting functions described in Peterson *et al.* (2011). However, the weights could be based on a range of distance-decay functions such as the exponential function (*e.g.*, Van Sickle and Johnson, 2008). Including additional distance-decay options would allow users to make their own decisions about the most appropriate weighting scheme, depending on their data and the variables of interest.

An additional improvement would be to make the IDW-Plus tools available in open source GIS software. ESRI's ArcGIS software has several levels of licensing and is only available on Windows operating systems. Our tools rely on the user having access to the highest level of licensing, which is a detriment to researchers restricted to other operating systems or without access to the software license. Although it was convenient for us to write these tools for ArcGIS, the advent of open source GIS, such as QGIS (QGIS Development Team, 2016), SAGA (Conrad *et al.*, 2015), and R statistical software (R Core Team, 2016), has the potential to open up new platforms for the IDW-Plus tools.

DATA AVAILABILITY

This toolbox is available for download at http://www.fs.fed.us/rm/boise/AWAE/projects/SSN_STARS/other_software.html. The download includes the example data described here, as well as a detailed tutorial on how to use the tools (also provided in Supplementary Information B).

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: Supplementary Information A provides a small example, which readers can work through by hand to help understand how the metrics are calculated. Supplementary Information B is a detailed tutorial on how to use the IDW-Plus tools.

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