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How Misapplication of the Hydrologic Unit Framework Diminishes the Meaning of Watersheds

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Abstract Hydrologic units provide a convenient but problematic nationwide set of geographic polygons based on subjectively determined subdivisions of land surface areas at several hierarchical levels. The problem is that it is impossible to map watersheds, basins, or catchments of relatively equal size and cover the whole country. The hydrologic unit framework is in fact composed mostly of watersheds and pieces of watersheds. The pieces include units that drain to segments of streams, remnant areas, noncontributing areas, and coastal or frontal units that can include multiple watersheds draining to an ocean or large lake. Hence, half or more of the hydrologic units are not watersheds as the name of the framework "Watershed Boundary Dataset" implies. Nonetheless, hydrologic units and watersheds are commonly treated as synonymous, and this misapplication and misunderstanding can have some serious scientific and management consequences. We discuss some of the strengths and limitations of watersheds and hydrologic units as spatial frameworks. Using examples from the Northwest and Southeast United States, we explain how the misapplication of the hydrologic unit framework has altered the meaning of watersheds and can impair understanding associations between spatial geographic characteristics and surface water conditions.

Keywords Watersheds · Hydrologic units · Rivers/streams · Aquatic ecology · Watershed management

The Hydrologic Unit Code (HUC) dataset provides a convenient nationwide set of geographic polygons based on drainage subdivisions of land surface areas at several hierarchical levels (U.S. Geological Survey and U.S. Department of Agriculture-Natural Resources Conservation Service 2013). However, many people, perhaps unknowingly, treat HUCs and watersheds as synonymous (e.g., Jones et al. 1997; Ruhl 1999; Alexander et al. 2000; Graf 2001; Wardrop et al. 2005; Mylavarapu et al. 2012; Foran et al. 2015; U.S. Environmental Protection Agency 2016; Eagles-Smith et al. 2016). For example, Entrekin et al. (2015) used 12-digit HUCs interchangeably with catchments throughout their paper on watershed sensitivity to natural and anthropogenic disturbances. Al-Chokhachy et al. (2010) stated that they used "…sixth field HUC watersheds (hereafter referred to simply as watersheds)". Lanigan et al. (2013, 2014) claimed to be evaluating watershed condition by sampling sites located within HUCs and extrapolating results to those HUC polygons. Hudy et al. (2008) used "fifth-level watersheds" (10-digit HUCs) in New York State to assess brook trout distributions. Nonetheless, roughly half the HUCs are not true topographic watersheds (Omernik and Griffith 1991; Omernik and Bailey 1997; Griffith et al. 1999). Omernik (2003) demonstrated how HUCs are less relevant than watersheds

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in explaining patterns in water quality and quantity in Texas waters. Van Sickle and Hughes (2000) reported that an ecoregion or a simple geographic distance measure had greater classification strengths than HUCs for western Oregon aquatic vertebrate assemblages. Daniel et al. (2014) found that entire watersheds better estimated mining effects on fish assemblages than did stream reaches between confluences (similar to what a 12-digit HUC might delineate). Therefore, our objectives in this paper are threefold: 1) we address the nature of HUCs and watersheds (catchments, drainage basins) and explain how misapplication of the HUC framework has altered the meaning of watersheds and can impair understanding associations between spatial geographic phenomena and water body conditions; (2) using 8-digit HUCs, we go beyond Omernik (2003) to demonstrate that the issue of misuse is more problematic in the Columbia Basin than in Texas; and (3) to dispel arguments that the problem does not pertain to more detailed 12-digit HUCs, we present a water quality dataset from South Carolina comparing data from HUCs that are watersheds to HUCs that drain areas comprising multiple HUCs.

Definitions, Strengths, and Limitations of Watersheds

Watersheds (also called catchments and drainage basins) are topographic areas within which surface and shallow groundwaters drain to a specific point (Omernik and Bailey 1997; Griffith et al. 1999). Webster's Dictionary (Merriam-Webster 1986) defined a watershed as “a region or area bounded peripherally by water parting and draining ultimately to a particular watercourse or body of water.” Flotemersch et al. (2015) stated that, “A watershed is a landscape that contributes surface water to a single location, such as a point on a stream or river, or a single wetland, lake or other water body.” These definitions are essentially the same and unambiguous. However, watershed has two meanings for some people. For example, Houghton-Mifflin (1982) defined a watershed as: (1) “a ridge of high land dividing two areas that are drained by different river systems, and (2) the region draining into a river, river system or body of water”. The first defines a linear characteristic whereas the second, which is the focus of this paper, defines a spatial or areal characteristic. Watersheds defined based on spatial or areal characteristics have been useful for water resource managers and scientists in associating natural and anthropogenic characteristics with water quality, discharge, fish distributions, and other aquatic-related phenomena (Vannote et al. 1980; Swank et al. 2001; Sály et al. 2011; Marzin et al. 2012; Likens 2013; Macedo et al. 2014). Hence, where watersheds can be defined, any point on a stream reflects the aggregate of the characteristics upgradient from that point.

Nonetheless, watersheds can only be approximated in many regions including those with karst topography, continental glaciation, extremely flat plains, deep sand, xeric climates, or where water is diverted from one drainage basin to another (Hughes and Omernik 1981; Omernik and Bailey 1997; Currens and Ray 2001). In those regions watersheds do not encompass the same integrating processes as in mesic and hydric areas where topographic watersheds are well defined (Strahler 1975; Omernik and Bailey 1997).

There also is a common misconception that watersheds are ideal for evaluating environmental condition and ecosystem services (Kolok et al. 2009; Jordan and Benson 2015). However, it is important to recognize that watersheds seldom circumscribe regions of similarity in multiple factors that influence water quality. Soil, physiographic, vegetative, and ecological regions do define such areas. Watersheds tend to cross those regions, but watersheds that are completely within a particular ecological region will tend to be similar to each other and dissimilar to watersheds entirely in other ecological regions (Dodds and Whiles 2004; Stoddard 2004; Zuellig and Schmidt 2012; Griffith 2014).

Definitions, Strengths, and Limitations of HUCs

Hydrologic units have evolved from the U.S. Geological Survey (USGS) framework of hydrologic unit maps described by Seaber et al. (1987). They have been modified in conjunction with the development of geographic information systems, digital orthophotoquads, and improved hydrography datasets (Horn et al. 1994; Simley and Carswell 2009; McKay et al. 2012). The hydrologic unit framework is hierarchical and shows “drainage hydrography, culture, and political and HUCs” (Seaber et al. 1987). This system, now labeled the Watershed Boundary Dataset (WBD), defines HUCs at six hierarchical levels (U.S. Geological Survey and U.S. Department of Agriculture-Natural Resources Conservation Service 2013). The 1st level divides the United States into 21 units and the 6th level comprises over 86,000 units within the conterminous U.S. The levels are also identified by code length and level names, e.g., 2-digit (regions), 4-digit (subregions), 6-digit (basins), 8-digit (subbasins), 10-digit (watersheds), and 12-digit (subwatersheds) (U.S. Geological Survey 2013). Some of these level names and the WBD title are a major source of users' misconception that all HUCs are watersheds.

The 21 HUC regions (2-digit or 1st level) of the U.S. contain the drainage area of a major river in only four cases (Missouri, Upper Colorado, Rio Grande, and Tennessee Rivers). The remaining 17 2-digit HUCs comprise combined drainage areas of a series of rivers and adjacent interstices or are based on political units (Alaska, Hawaii, and Puerto Rico). Each subregion (2nd level or 4-digit HUC) "…includes the area drained by a river system, a reach of a river and its tributaries in that reach, a closed basin(s), or a group of streams forming a coastal drainage area" (Seaber et al. 1987). Likewise, at lower hierarchical levels, each nested subdivision is an area representing part or all of a drainage basin, a combination of drainage basins, or a distinct hydrologic feature (Seaber et al. 1987). Clearly, these definitions indicate that many HUCs at all levels are not truly watersheds, catchments, or basins.

The WBD establishes a framework that accounts for all land surface areas, and the codes can provide a general location for water resources (Laitta et al. 2004). The boundary delineations are rarely affected by political units or agency missions, and the multiagency coordination resulted in a relatively consistent and nationally accepted set of drainage delineations. The HUC framework provides a national set of terrestrial polygons at roughly comparable size at each hierarchical level, and the standardized attribute structure of the hydrologic units aids aggregation of drainage information at different geographic scales. In some cases, the polygons can be used to delineate watersheds by joining, merging, modifying, or adding additional boundaries from any particular point on a stream. For example, HUCs are commonly used in ecohydrological modeling. Daggupati et al. (2016) used "head watersheds" and regions to calibrate 12-digit HUCs in the Missouri River Basin, and by doing so were able to simulate crop and water yields and distinguish topographic watersheds with strong groundwater inputs. In other modeling examples, (e.g., Affuso and Duzy (2013), Ghimire and Johnston (2013), Gurung et al. (2013), and Pai et al. (2011)) watersheds and HUCs appear confounded. If that is the case, their models could be improved by using just watersheds or by linking upstream watersheds and downstream HUCs that are pieces of watersheds into watersheds, thereby modeling the entire areas that drain to their sites rather than fractions of those areas or portions of neighboring but hydrologically disconnected areas.

Hydrologic units are sometimes seen as useful spatial polygons for subjects not specifically hydrologic (e.g., Zank et al. 2016) due to the perception of relative size uniformity. Nonetheless, hydrologic unit sizes do vary at any particular level within broad physiographic areas. At the 1st level (2-digit), the variation in size can be as much as 10×, and at lower levels, a particular HUC can be two to five times larger than that of another. The typical sizes of 5th level (10-digit) HUCs are 16,200 to 101,200 ha, although the total range is much larger; and, in some places HUC boundaries can only be approximated owing to the lack of hydrologic features or insufficient topographic relief (U.S. Geological Survey and U.S. Department of Agriculture-Natural Resources Conservation Service 2013). As with watersheds, the process of identifying HUCs is complicated by the variable representation of permanent and temporary streams on maps, even of the same scale, as well as by areas where watersheds are difficult to define.

The underlying problem regarding the misapplication and misunderstanding of the HUC framework lies in its intent to define relatively equal size watersheds relative to points on streams at several hierarchical levels and cover the entire country with those areas. However, this is impossible because streams are linear characteristics and there are literally an infinite number of points on streams. Regardless of the hierarchical level of watersheds (e.g., roughly 100, 1000, 10,000 km^2, etc.) only about half the United States will be covered. The remaining area will be composed of downstream segments of watersheds or adjacent interstices. Hence, the areas defined by HUCs are watersheds *and parts* of watersheds. The HUC framework would be less susceptible to misapplication if a clear distinction were made at each level between HUCs that are watersheds and those that are not. Although the HUC framework provides a set of polygons for locating sampling sites, alternative geographic polygons representing areas that are unambiguous include equal-sized hexagons (Rathert et al. 1999; Herlihy et al. 2000; Hughes et al. 2000), squares (Hocutt and Wiley 1986), or political units (Hughes et al. 2015).

The HUC framework is also problematic for those that use it as a convenient way of referring to the size of a watershed. First, as we noted previously, the size of HUCs at any level can vary greatly by as much as 10×. Second, roughly half of the HUCs at any level are not in fact watersheds. Finally, the number of HUCs that are watersheds represent a minute fraction of topographic watersheds upgradient from the infinite number of points on streams or water bodies. Although somewhat tangential to the usefulness of HUCs, stream size is often described by stream order. However, as an approximation of stream or watershed size, the use of stream order by itself is problematic (Hughes and Omernik 1981, 1983; Hughes et al. 2011). The reasons for this are associated with methods for determining when a stream becomes a stream, which include natural variation in the watershed area required to generate a channel and intermittent or perennial stream, imprecise and subjective field annotation of streams on maps, and inconsistent mapping between humid and xeric regions (Morisawa 1957; Hughes and Omernik 1981, 1983; Oberdorff et al. 1995).

Another limitation of HUCs lies in their intended use, which according to Seaber et al. (1987) is to provide "a standard geographic and hydrologic framework for water-resource and related land-resource planning." This purpose is questionable because large HUCs, basins, and watersheds tend to overlap dissimilar geographical regions (Omernik and Griffith 1991; Omernik and Bailey 1997; Griffith et al. 1999; Omernik 2003; Brenden et al. 2006; Hollenhorst et al. 2007). The U.S. Environmental Protection Agency adopted the HUC framework for its watershed approach for environmental management (U.S. Environmental Protection Agency 1995, 1996). However, analysis of its HUCs for the State of Washington, USA (Fig. 1), revealed that only two of the 23 (Upper Yakima and Crab Creek hydrologic units) are in fact watersheds. Many of the HUCs contain vastly different ecological regions (Omernik and Griffith 2014). For example, the northwestern part of the Upper Yakima HUC is in the forested, mountainous Cascade Range, which receives >2541 mm of mean annual precipitation, whereas the lower part of the HUC is in the Columbia Plateau, which is sagebrush steppe and grassland where mean annual precipitation is <254 mm (Fig. 2) (PRISM Climate Group 2016). Therefore, the Upper Yakima is *not* a homogeneous area for environmental management; the part of the HUC in the Cascades ecoregion is markedly different ecologically from the part in the Columbia Plateau. Similarly, Nadeau and Raines (2007) included figures intended to illustrate patterns of combined intermittent and ephemeral stream length as a proportion of total stream length within "…each 8 digit HUC watershed". In one of their figures, they extrapolate this stream characteristic to HUCs in Washington State (adapted in Fig. 2), where hydrologic units span mountainous areas with heavy precipitation and relatively flat plateaus with xeric conditions. Those two regions have very different percentages and lengths of perennial and intermittent streams. Neither watersheds nor HUCs, unlike ecoregions, capture a logical stratification in landscape characteristics that are consistent with regional expectations for developing resource management strategies and interpreting environmental research and assessment results (Bryce et al. 1999; Glover et al. 2010).

The major misapplication of the HUC framework stems from the common misconception that all HUCs at all hierarchical levels are watersheds. The second sentence in U.S. Geological Survey (2015) reads: "The WBD defines the areal extent of surface water drainage to a point, accounting for all land and surface areas." That sentence and the title of the framework both imply that HUCs and watersheds are synonymous. Moreover, there is no mention in any of the published explanations of the HUC/WBD frameworks that half or more of all HUCs at all levels are not watersheds and that many HUCs are only downstream segments of watersheds draining areas that are in many instances orders of magnitude greater in size than the defined HUC area. Even some developers of the 12-digit (6th level) HUCs, who recognized the inaccurate perception and relationship that is permeated by labeling HUCs as watersheds (e.g., Berelson et al. 2004), have not attempted to rectify the problem by appropriate labeling, thereby furthering the inaccurate perception. Maps of HUCs at any hierarchical level contain only 40 to 60% watersheds, and only about 20% in the case of 2-digit (1st level) HUCs

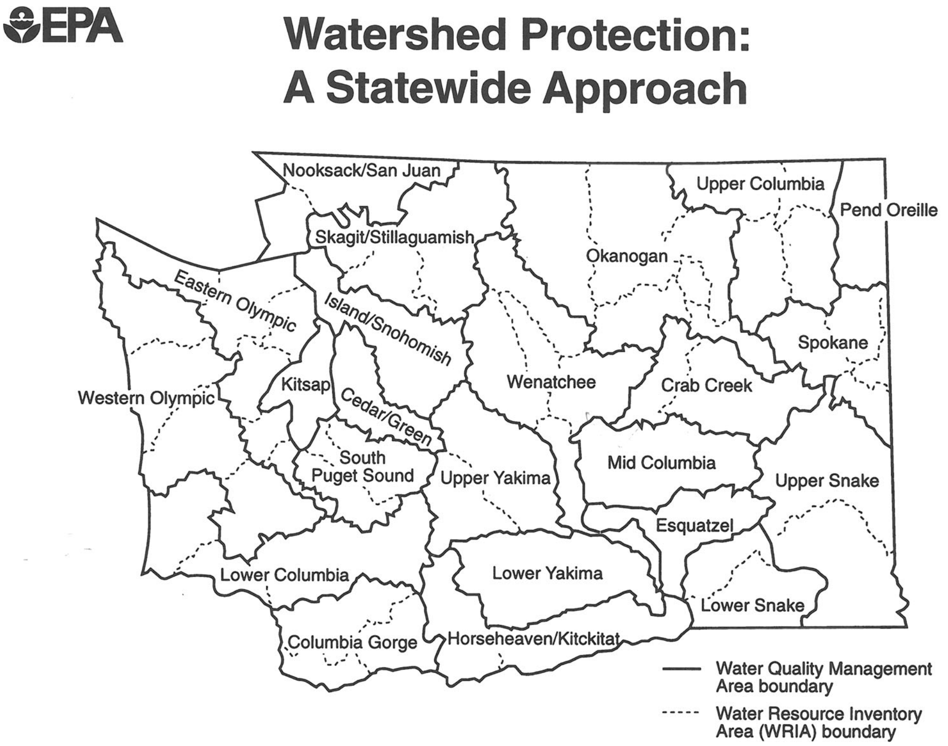


Fig. 1 Hydrologic units called "water quality management areas" for Washington State, USA, from the cover page of USEPA (1995). Note that only 2 of the 23 units, Upper Yakima and Crab Creek, are watersheds

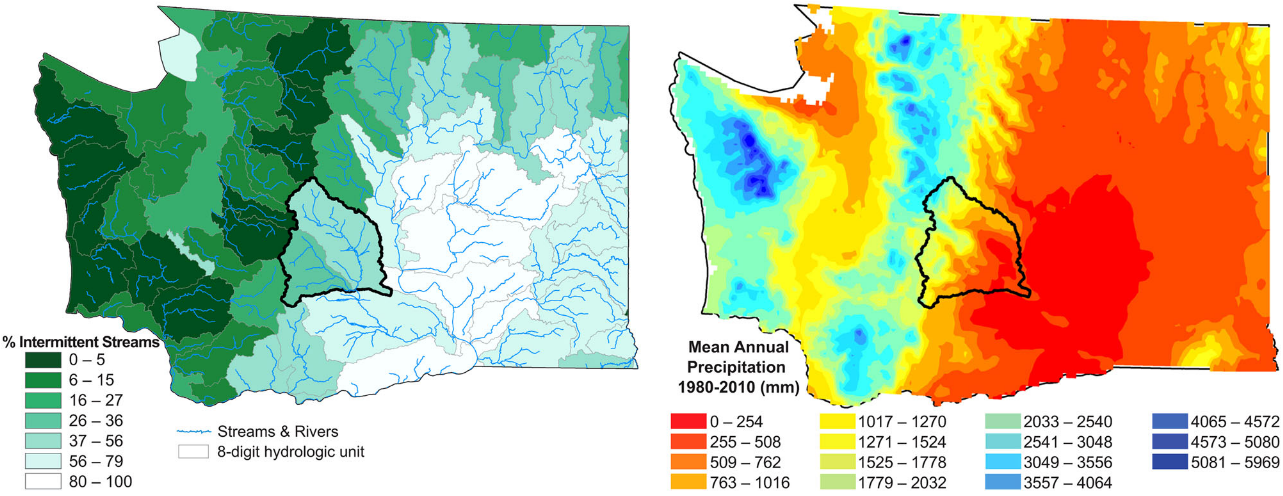
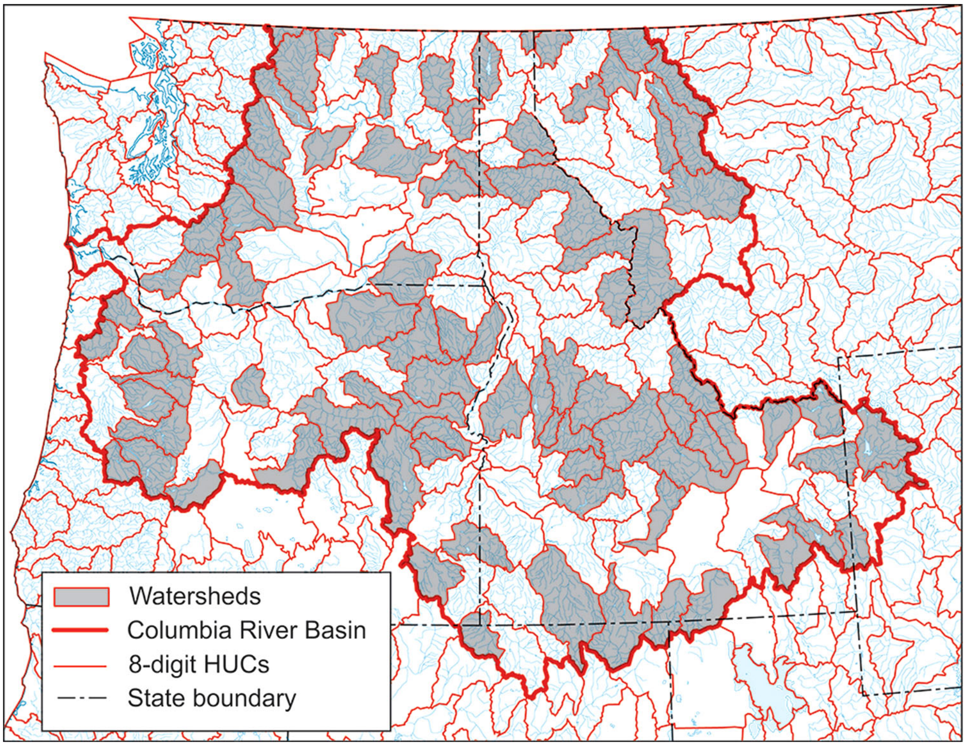


Fig. 2 Combined intermittent and ephemeral stream lengths as a proportion of total stream lengths for 8-digit (4th level) HUCs in Washington (*left*) (adapted from Nadeau and Raines 2007), and mean annual precipitation (1980–2010) in Washington (*right*) (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu). Note the dramatic contrast in precipitation amounts between the northwestern (>2541 mm) and southeastern parts (<254 mm) of the Upper Yakima watershed (highlighted)

Fig. 3 Eight-digit (4th level) HUCs that are watersheds (*shaded dark gray*) within the Columbia River Basin. Note that only 53% of the HUCs (86 of 163) within the basin are watersheds



(Omernik 2003). Therefore, many HUCs do not serve the critical purpose of watersheds.

Prompted by a peer reviewer's comment on Omernik (2003) that the limitation of the HUC framework may occur in Texas but not in the Pacific Northwest, we examined the 8-digit (4th level) HUCs in the Columbia River Basin of the U.S. Only 53% (86 of 163) of the 8-digit HUCs in this large river basin are watersheds (Fig. 3). If all HUCs were watersheds, one might expect that water quality, flow regime, or biotic condition at downstream points of HUCs within the same ecoregion would be generally similar in comparison to HUCs within adjacent ecoregions where conditions are distinctly different. For example, consider four 8-digit HUCs that lie completely or nearly completely within the Columbia Plateau ecoregion (Fig. 4). Only two of the four 8-digit HUCs (**b** and **c**) are watersheds (Fig. 5). HUC **a** is a downstream segment of the Columbia River, which drains large parts of northeastern Washington, northern Idaho, northwestern Montana, and southeastern British Columbia. HUC **d** is a downstream segment of the Snake River, which drains eastern Oregon, most of Idaho, and parts of Nevada and western Wyoming. The biota at the downstream points of HUCs **a** and **d** differ from those of HUCs **b** and **c** (Lomnicky et al. 2007; Paulsen et al. 2008; Stoddard et al. 2008; Pont et al. 2009).

To rectify misconceptions that the limitations of HUCs at the 8-digit (4th level) (Omernik 2003) do not exist at the more detailed 12-digit (6th level), we examined a water

Fig. 4 Four 8-digit (4th level) HUCs **a**, **b**, **c**, and **d** in the Columbia Plateau (10) Level III ecoregion

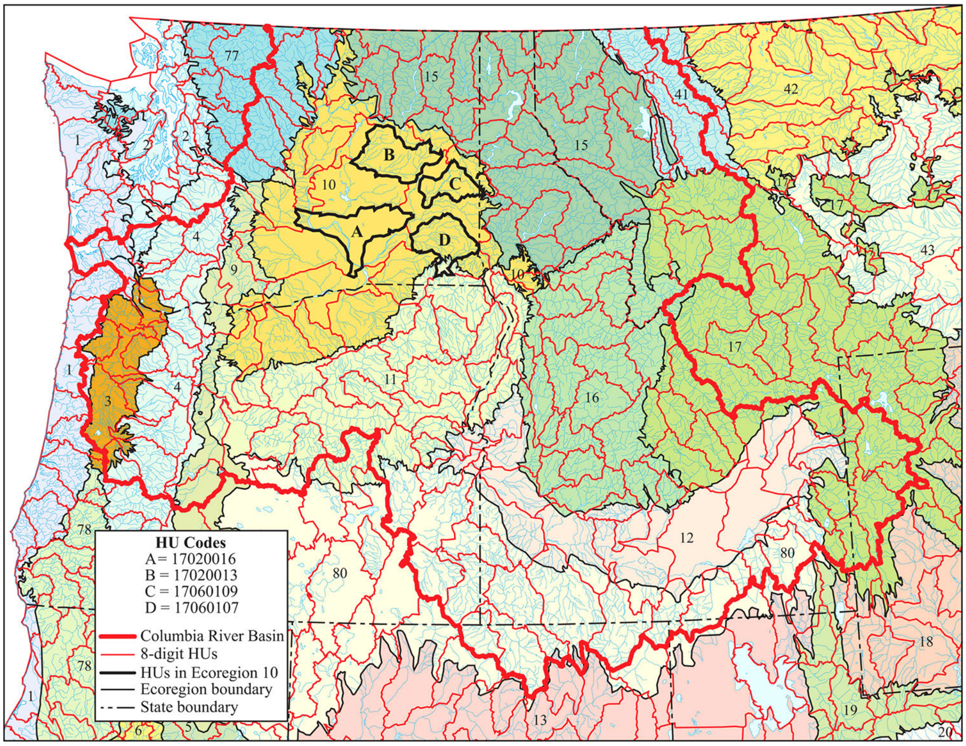
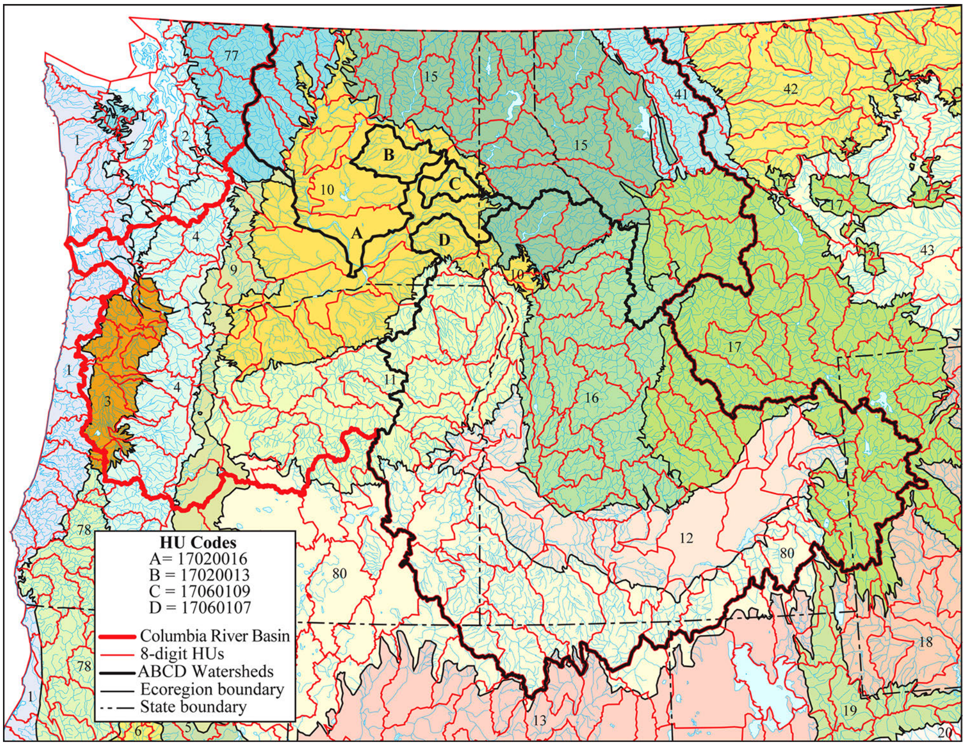


Fig. 5 Watersheds (*bold black outlines*) associated with downstream points in HUCs **a**, **b**, **c**, and **d**. Note that **b** and **c** are watersheds whereas HUCs **a** and **d** (shown in Fig. 4) are merely downstream segments of vast watersheds, respectively, of the Columbia (which drains a similar area in Canada) and Snake Rivers



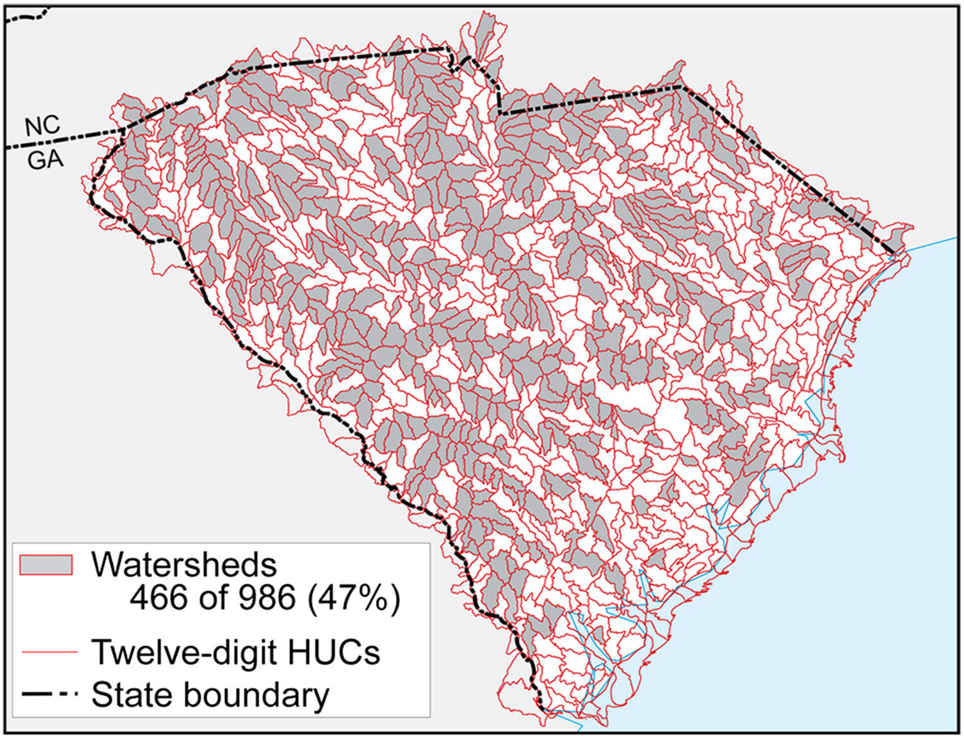


Fig. 6 Twelve-digit (6th level) HUCs in South Carolina that are watersheds (*shaded dark gray*). Only 47% of the HUCs (466 of 986) are watersheds

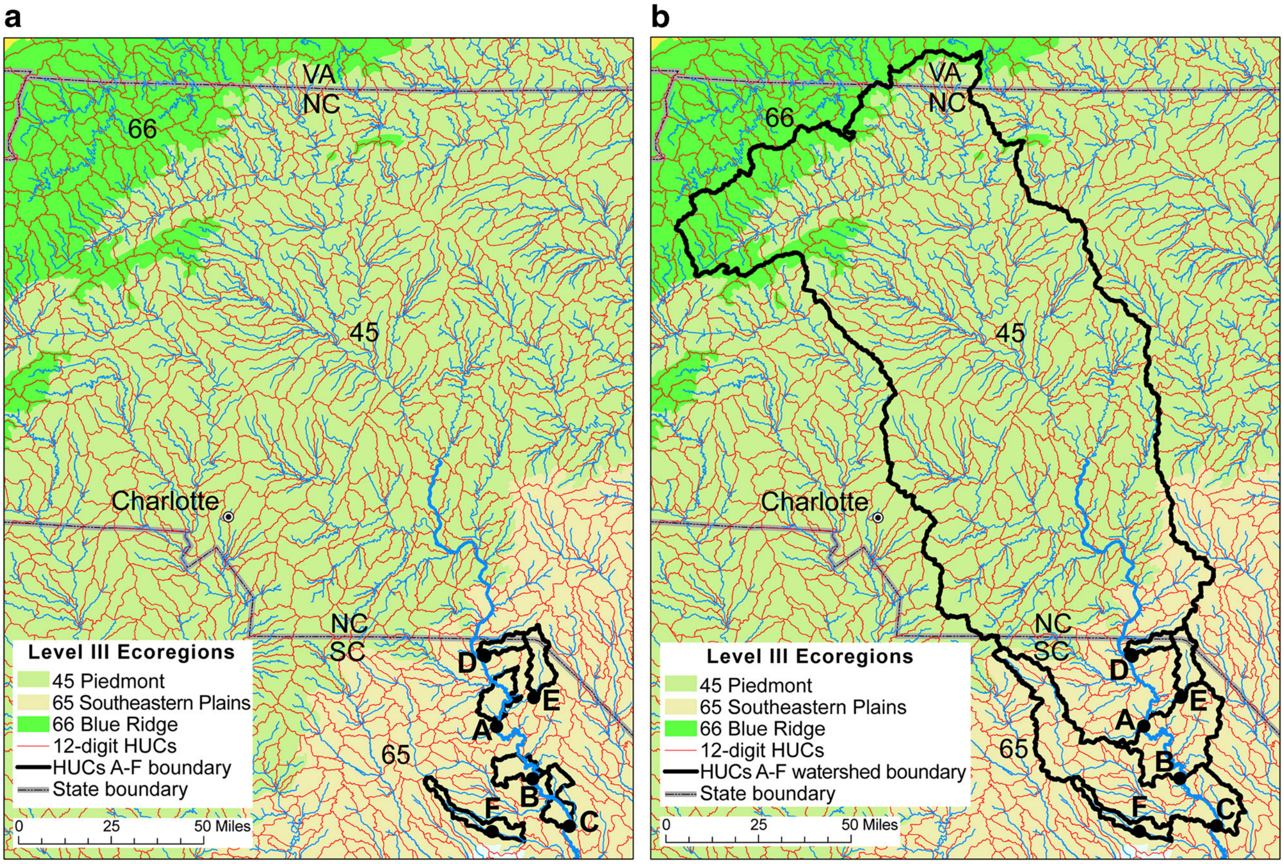


Fig. 7 **a** Stream sampling sites at or near downstream locations of six 12-digit (6th level) HUCs (A, B, C, D, E, and F) in the Southeastern Plains Level III ecoregion of South Carolina (*left*). **b** Watersheds (bold black outlines) associated with downstream points in HUCs A, B, C, D, E, and F. Note that only HUCs D, E, and F are watersheds within the Southeastern Plains ecoregion whereas HUCs A, B, and C are downstream segments of larger watersheds comprising multiple HUCs that drain different ecoregions in parts of North Carolina and Virginia (*right*)

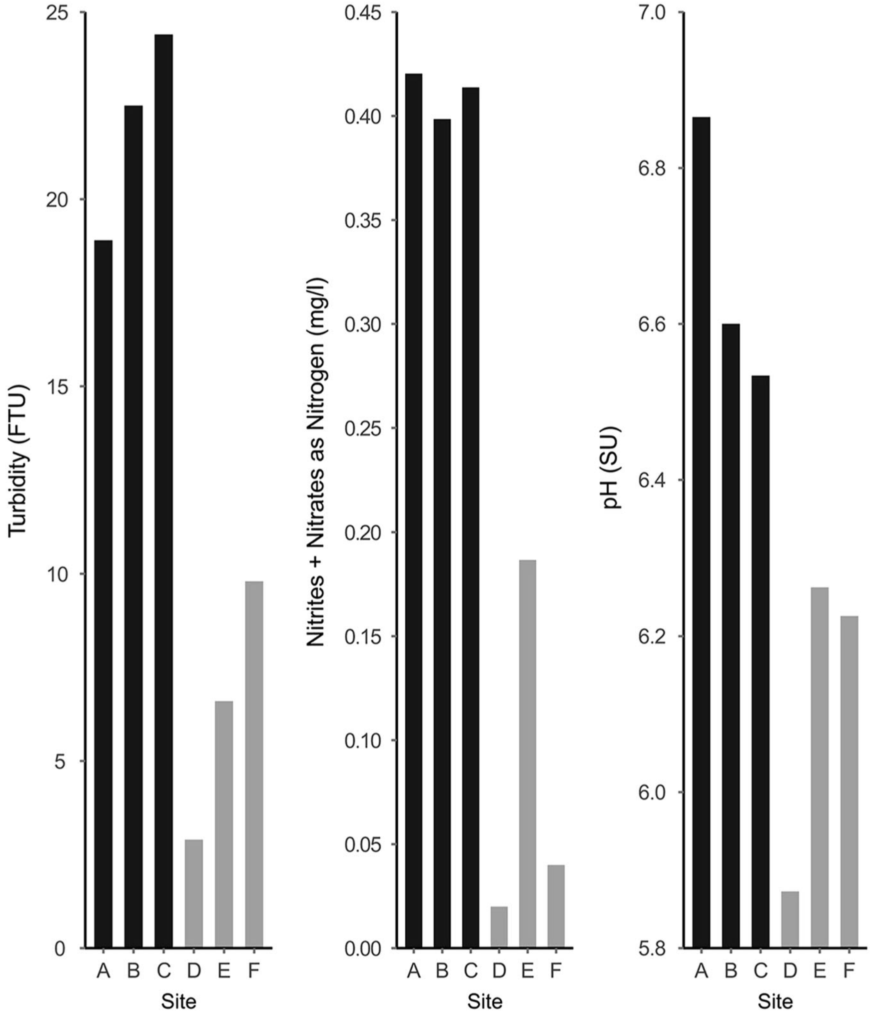


Fig. 8 Water quality mean values for sampling sites at or near the downstream points of HUCs **a**, **b**, **c**, **d**, **e**, and **f** in South Carolina. HUCs **d**, **e**, and **f** are watersheds; HUCs **a**, **b**, **c** are downstream segments of larger watersheds. Turbidity in Formazin Turbidity Units (FTU), nitrites plus nitrates as nitrogen in milligrams per liter (mg/l), and pH in standard units (Data from Bureau of Water, South Carolina Department of Health and Environmental Control; see Table 1)

Table 1 Surface water quality parameters collected by South Carolina Department of Environmental Control (SCDHEC) water quality monitoring program

Parameter	STORET Station # Fig. 8 Site Code	PD-015	PD-028	PD-337	PD-191	PD-107	PD-256
		A	B	C	D	E	F
Turbidity (FTU)(STORET Parameter Code 00076 Method APHA 2120 (B))	Count	29	17	30	11	18	17
	Mean	18.9	22.5	24.4	2.9	6.6	9.8
	Variance	79.6	155.3	175.2	1.2	75.0	229.7
Nitrites + Nitrates as Nitrogen (mg/l)(STORET Parameter Code 0630 Method EPA 353.2; APHA 4500)	Count	29	17	27	12	17	17
	Mean	0.42	0.40	0.41	0.02	0.19	0.04
	Variance	0.03	0.02	0.04	0.00	0.01	0.00
pH (standard units) (STORET Parameter Code 00400 Method APHA 4500 OG)	Count	29	17	30	11	18	17
	Mean	6.87	6.62	6.53	5.87	6.26	6.23
	Variance	0.17	0.10	0.17	1.05	0.20	0.12

Note: Stations located on the Great Pee Dee River and select tributaries within the Southeastern Plains ecoregion of South Carolina

Water quality parameters collected as part of the SCDHEC water quality monitoring program and available through the EPA STORET database at www.epa.gov/waterdata/storage-and-retrieval-and-water-quality-exchange#warehouse

Data for the years 1994–1998 and months May-October quality dataset from South Carolina. Of the 986 12-digit HUCs completely or partially in South Carolina, only 47% are watersheds (Fig. 6). We selected six different 12-digit HUCs that lie completely within the Southeastern Plains ecoregion for analysis (Fig. 7a). This region is characterized by a mosaic of cropland, pasture, woodland, and forest, and the irregular plains are lower in elevation and have less relief than the Piedmont ecoregion to the northwest. Three of those HUCs (**d**, **e**, and **f**) are watersheds whereas three (**a**, **b**, and **c**) are downstream segments of the Pee Dee/Yadkin River watershed, covering a large part of the Piedmont ecoregion and a small portion of the Blue Ridge ecoregion (Fig. 7b). Patterns in water quality characteristics measured at or near the downstream points of HUCs **a**, **b**, and **c** are relatively similar to one another and dissimilar to those of HUCs **d**, **e**, and **f** as illustrated by the three parameters shown in Fig. 8 and Table 1.

The watershed for the downstream point of HUC **c** near the sampling site is more than 22,950 km^2, which is over 150 times greater than the 150-km^2 HUC itself (Fig. 7a and 7b). The differences in water quality between the sites with much of their watersheds in the Piedmont and the smaller ones that are completely within the Southeastern Plains are associated with more fertilized pasture lands, greater relief, erodible soils, and urban and exurban land cover in the Piedmont vs. more woody wetlands and low gradient streams in the Southeastern Plains (Glover et al. 2010).

Summary and Conclusions

For many years, watersheds served as a fundamental geographic unit to study the effects of natural and anthropogenic characteristics on the quality and quantity of water. Examples include classic watershed studies (Likens 2013; Swank et al. 2001), paired watershed studies (e.g., Bisson et al. 2008; King et al. 2008), river basin commissions and river basin studies (White 1969; Mulvey et al. 2009), disturbance partitioning studies (e.g., Sály et al. 2011; Marzin et al. 2012; Macedo et al. 2014), and studies on basic aquatic ecology principles (Hynes 1975; Vannote et al. 1980; Fausch et al. 2002). Indeed, until about 30 years ago most scientists and resource managers were in agreement on the spatial meaning of the term watershed. The HUC framework has changed this understanding, with many persons treating all HUCs as watersheds—despite the fact that only about half are truly watersheds.

Revising the guidance and documentation for the HUC/WBD framework at all hierarchical levels by using more precise language to more clearly identify what units are and are not watersheds would reduce the misunderstanding and misapplication of HUCs. Renaming the WBD as the Hydrologic Unit Dataset, identifying the various HUC levels by their level number or code digit length only, and clearly identifying the HUCs that are and are not watersheds at each hierarchical level would further reduce the misunderstanding of HUCs. These steps would facilitate a better understanding of the strengths and limitations of this type of spatial framework for the research, monitoring, assessment, and management of aquatic and terrestrial resources.

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Conflict of interest The authors declare that they have no competing interests.

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