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RESEARCH ARTICLE

Effects of stream map resolution on measures of riparian buffer distribution and nutrient retention potential

Matthew E. Baker · Donald E. Weller · Thomas E. Jordan

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Abstract Riparian ecosystems are interfaces between aquatic and terrestrial environments recognized for their nutrient interception potential in agricultural landscapes. Stream network maps from a broad range of map resolutions have been employed in watershed studies of riparian areas. However, map resolution may affect important attributes of riparian buffers, such as the connectivity between source lands and small stream channels missing in coarse resolution maps. We sought to understand the influence of changing stream map resolution on measures of the river network, near-stream land cover, and riparian metrics. Our objectives were: (1) to evaluate the influence of stream map resolution on measures of the stream network, the character and extent of near-stream zones, and riparian metrics; (2) to compare patterns of variation among different physiographic provinces; and (3) to explore how predictions of nutrient retention potential might be affected by the resolution of a stream map. We found that using fine resolution stream maps significantly increased our estimates of stream order, drainage density, and the proportion of watershed area occurring near a stream. Increasing stream map resolution reduced the mean distance to source areas as well as mean buffer width and increased the frequency of buffer gaps. Measures of percent land cover within 100 m of streams were less sensitive to stream map resolution. Overall, increasing stream map resolution led to reduced estimates of nutrient retention potential in riparian buffers. In some watersheds, switching from a coarse resolution to a fine resolution stream map completely changed our perception of a stream network from well buffered to largely unbuffered. Because previous, broad-scale analyses of riparian buffers used coarse-resolution stream maps, those studies may have overestimated landscape-level buffer prevalence and effectiveness. We present a case study of three watersheds to demonstrate that interactions among stream map resolution and land cover patterns make a dramatic difference in the perceived ability of riparian buffers to ameliorate effects of agricultural activities across whole watersheds. Moreover, stream map resolution affects inferences about whether retention occurs in streams or riparian zones.

Keywords Riparian buffers · Stream map resolution · Rowcrop agriculture · Nutrients · Land cover · Threshold analysis · Landscape metrics

M. E. Baker · D. E. Weller · T. E. Jordan
Smithsonian Environmental Research Center,
P.O. Box 28, Edgewater, MD 21037-0028, USA

M. E. Baker (✉)
Department of Watershed Sciences, Utah State University, Logan, UT 84322-5210, USA
e-mail: matt.baker@usu.edu

Introduction

Non-point source pollution from agricultural and urban areas is a significant, well-documented challenge for resource managers, regulatory agencies, and policy makers (Carpenter et al. 1998). In particular, increases in anthropogenic inputs have led to large exports of nitrogen to rivers, estuaries, and coastal oceans (Jordan and Weller 1996). These watershed exports have caused increased rates of eutrophication and the development of anoxic zones in coastal systems (Boesch et al. 2001, Rabalais et al. 2001).

Riparian ecosystems are interfaces of aquatic and terrestrial environments recognized for their nutrient retention potential in agricultural landscapes (Dosskey 2001). Installing riparian buffers is a major focus of watershed restoration activity aimed at reducing non-point pollutant loads to streams (Dosskey et al. 2005, Hassett et al. 2005). Yet the ability of any buffer to intercept dissolved nutrients is dependent upon its placement along flowpaths between upslope source areas and a receiving stream channel (Weller et al. 1998, Dosskey et al. 2002, Baker et al. 2006a).

Individual riparian zones along headwater streams may be disproportionately important for nutrient retention (Dosskey et al. 2005; Polyakov et al. 2005). McGlynn and Seibert (2003) found that surface runoff from 85% of a 280-ha watershed in New Zealand entered streams through only 28% of the riparian zone, and Wondzell and Swanson (1996) observed a sharp decrease in direct surface runoff to the channel with increasing stream order in an Oregon watershed. Similarly, Tomer et al. (2003) found that 23% of the riparian zone in an Iowa watershed received no surface runoff, 57% had a contributing area of less than 0.4 ha, and 6% received water from more than 10 ha. Thus the location of relatively small channels can influence connectivity from source lands through riparian buffers and into a river network. Most field studies of riparian buffers have been conducted along small first or second order streams (e.g., Lowrance et al. 1997) and seasonal nutrient retention can occur along intermittent streams in some regions (Bren 2000).

Geographic study of riparian buffers, watershed nutrient losses, and stream nutrient concentrations has involved hydrographic data from a broad range of spatial scales. A few studies have used stream channel delineations obtained from interpretation of aerial photography (e.g., Osborne and Wiley 1988; Weller et al. 1996), but investigations across broader landscapes have relied on existing stream maps at 1:24,000 (e.g., Roth et al. 1996), 1:100,000 (e.g., Johnson et al. 1997; Jones et al. 2001; Seitzinger et al. 2002), or 1:500,000 (e.g., Smith et al. 1997) map scales. Use of such coarse hydrography data continues even though streams where both substantial riparian (e.g., Peterjohn and Correll 1984) and in-stream (e.g., Peterson et al. 2001) nutrient loss have been observed do not necessarily appear on 1:24,000-scale maps. In fact, inadequacies of 1:24,000 datasets have prompted the State of North Carolina to begin an ambitious effort to create state-wide, local-resolution hydrography maps based on high-resolution topography and orthoimagery (Joe Sewash, N.C. Center for Geographic Information and Analysis, Personal Communication, October 23rd, 2006).

Accurate delineation of stream networks is critical for distinguishing the effects of hillslope and channel processes (Montgomery and Dietrich 1988; Hancock and Evans 2006). Stream maps can influence estimates of hydrologic transport distance and travel time, as well as the concentration and magnitude of runoff. For example, the location of mapped streams affects the empirical partitioning of nutrient loss to uptake on land versus uptake during stream transport (Seitzinger et al. 2002). Also, periodic expansion and contraction of river networks due to seasonal or event-driven water availability can alter connectivity among patches within the channel as well as within the surrounding landscape (Stanley et al. 1997; Fisher and Welter 2005). Such observations suggest that the location and relative density of stream channels have profound impacts on connectivity between streams and their watersheds.

Recent research has highlighted the importance of spatially explicit and conceptually precise measures of riparian configuration along streams. Hollenhorst et al. (2006) showed that land cover information derived from 30-m satellite imagery could miss narrow bands of riparian forest observed in aerial photos and lead to marked inaccuracies during riparian assessment. In addition, a common measure estimates riparian buffering using percent land cover within a fixed, but relatively arbitrary, distance of streams (e.g., 100 m). Such ''fixed-distance'' riparian metrics are often referred to as ''buffers'' and interpreted as a predictor of expected nutrient interception (e.g., Jones et al. 2001). However, fixed-distance estimates are insensitive to variation in the spatial configuration of nutrient sources and riparian patterns within watersheds (Johnson et al. 1997; Weller et al. 1998), and fixed-distance metrics are also highly correlated with whole-watershed land cover proportions (Baker et al. 2006a).

We have developed new, functionally based metrics to more precisely quantify spatial patterns of nutrient filters (Baker et al. 2006a). Initially, we defined ''riparian buffers'' as patches of forest or wetland cover that are contiguous with stream channels and that fall along a flowpath *between* a nutrient source and a stream. This approach improves on the conventional fixed-distance method in two ways: (1) it allows for analysis of variable buffer widths across a river network and (2) it excludes near-stream areas not involved in nutrient transport from source areas to streams. Using our new metrics to explore how patterns of riparian buffers might influence expected nutrient yields from watershed sources, we found that potential nutrient retention by existing riparian land cover was not linearly related to percent watershed source area and that this pattern was strongly influenced by regional land use patterns. Such functional measures remain dependent on land cover resolution and classification accuracy, yet they allow us to relate findings from field studies of source-to-stream transects to patterns of buffer variability within and among watersheds while avoiding the interpretive problems inherent in fixed-distance approaches.

Riparian zones are defined and mapped by their relationships (topographic, geomorphic, hydrologic, or simple proximity) to stream channels. Riparian metrics are likely sensitive to the location of mapped streams because channel locations affect the delineation of near-stream zones and the characterization of transport pathways within watersheds (Fig. 1). In this study, we sought to understand the influence of changing stream map resolution on descriptions of the stream network and of riparian buffers. Our objectives were: (1) to evaluate the influence of stream map resolution on measures of the stream network, the extent and character of near-stream zones, and measures of riparian buffers; (2) to compare patterns of variation among different physiographic provinces; and (3) to explore how assessment of nutrient retention potential from existing land cover might be affected by using a stream map with fewer channels.

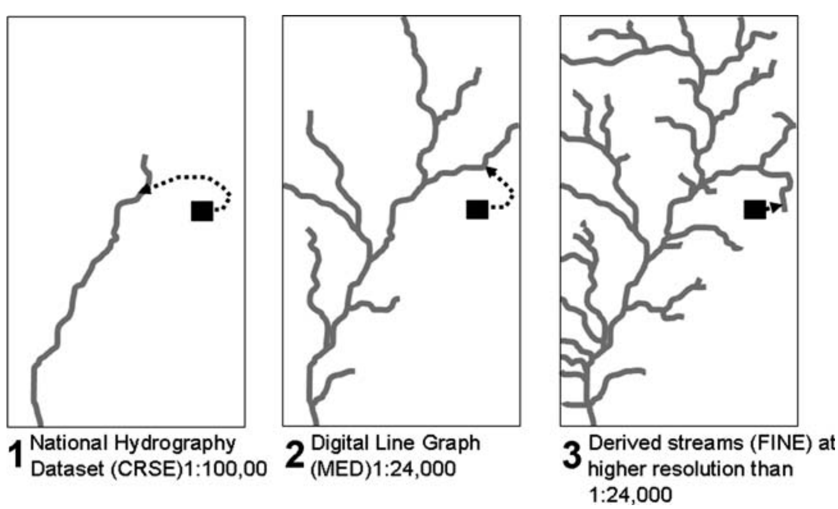

Fig. 1 Conceptual diagram illustrating the potential for different stream map resolutions to affect the distance (dashed lines) from a nutrient source area (rectangle) to the stream network and the presumed location of potential riparian buffers

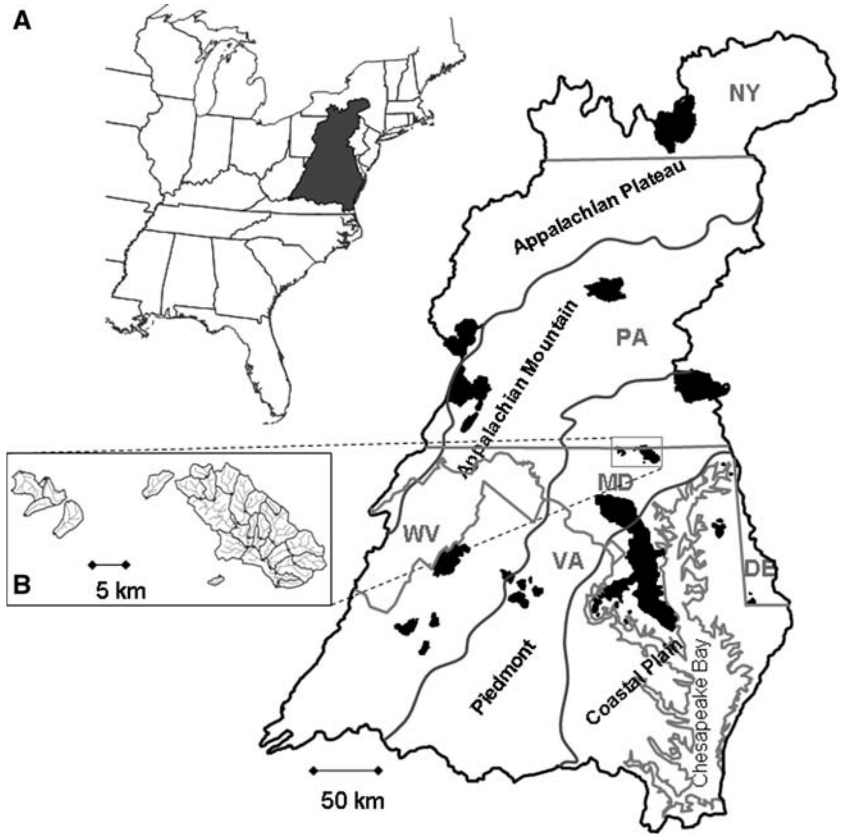

Fig. 2 Location of study watershed clusters in the Chesapeake Bay drainage basin. Insets show the extent of the basin across the eastern U.S. (**A**) and the distribution of watersheds in a single cluster (**B**)

Methods

Study watersheds

As part of a larger, ongoing effort to understand regional patterns of watershed nutrient discharge, we studied 503 rural watersheds selected for their contrasting physiography, differing proportions of land cover, variable population densities, and lack of sewage outfalls. The watersheds are located in 14 clusters distributed across four major physiographic provinces (Langland et al. 1995) of the 166,000 km^2 Chesapeake Bay Drainage (Fig. 2): Coastal Plain (143 watersheds), Piedmont (172), Appalachian Mountain (including Blue Ridge and Great Valley; 109), and Appalachian Plateau (65). Watershed sizes in our sample ranged from 5.5 to 48,010 ha. Liu et al. (2000) provide detailed descriptions of land cover, physiography, and water chemistry; and Baker et al. (2006a) provide a general comparison of land cover patterns and riparian metrics among and within physiographic provinces.

Geographic data

We analyzed publicly available geographic data sets for elevation, stream channels, and land cover using the Arc/Info (ESRI, Inc) geographic information system (GIS). Land cover information was derived from the National Land Cover Dataset (NLCD 1992; Vogelmann et al. 1998a, b; USEPA 2000). Elevation information was obtained from USGS 1:24,000 topographic maps and 30-m digital elevation models (DEM) (National Elevation Dataset; http://www.ned.usgs.gov). We investigated buffer patterns relative to stream maps at three different resolutions. At the coarsest level of resolution (CRSE), we used stream lines from the 1:100,000 National Hydrography Dataset (NHD). The NHD is an improved version of EPA's RF3 digital stream maps, which include streams mapped on

1:100,000-scale USGS topographic maps (http://www.nhd.usgs.gov). Medium-resolution stream maps (MED) were obtained from 1:24,000 digital-line-graph data derived from USGS topographic quadrangles (http://www.edc.usgs.gov/products/map/dlg.html). According to USGS standards, horizontal accuracy for these data is approximately 51 m for the 1:100,000 CRSE maps and 12 m for the 1:24,000 MED maps. The finest resolution stream maps were generated empirically as described below.

Watershed outlets were located in the GIS by manually digitizing stream sampling points marked on 7.5-min quadrangle maps. Watershed boundaries were initially manually interpreted from contour lines and streams on paper topographic maps and county ditch maps, and then digitized into a GIS dataset (Liu et al. 2000). These manual boundaries were later modified to match those inferred from a modified DEM using a normalized excavation method for automatic watershed delineation based on elevation and stream maps (Baker et al. 2006b). Watershed boundary, land cover, and stream maps were converted to rasters at the pixel resolution of the DEM, so that all digital datasets were represented on a common grid. Stream rasters were also thinned to the width of a single pixel, and the DEM was modified within 100 m of the channel using the AGREE algorithm and normalized excavation (Baker et al. 2006b) so that topographic flow lines would connect to mapped streams. AGREE excavates channels in the DEM using stream maps, then raises or lowers the elevation values of DEM surfaces near streams so that discrepancies between topographic flow lines and stream maps do not create the appearance of parallel channels (Hellweger 1997; Saunders 2000).

In addition to the CRSE and MED stream maps, we used the DEM to generate a third, higher-resolution extension of the river network in each watershed to evaluate potential riparian patterns that might be detected using more detailed stream maps (FINE; Fig. 1). After altering the DEM to correct for registration errors between MED streams and the DEM surface, we estimated the number of pixels contributing to each raster cell using standard topographic analysis techniques (O'Callaghan and Mark 1984; Jenson and Domingue 1988) implemented in Arc/Info (i.e., *flow accumulation*; Fig. 3A). The value of the flow accumulation surface at the head of each mapped stream line thus defined the contributing area threshold for that stream channel. Headwater nodes from stream lines within each watershed cluster were used to sample contributing areas leading to a perennial "blue-line" stream shown on 1:24,000 topographic maps. This sampling resulted in a distribution of different drainage areas specific to each watershed cluster (Fig. 3B). We selected the 25th percentile of these drainage areas to serve as a contributing-area threshold for generating new streams that were subsequently used to augment and extend the MED lines (Fig. 3B). In selecting this threshold, we sought to generate an empirical, high-resolution map where contributing areas fell within a local range of natural variation. We assumed that the resulting map would fail to identify some headwater streams receiving water from natural springs or anthropogenic sources while incorrectly showing other stream lines in catchments where rapid transport or infiltration has actually prevented stream channel formation. Thus, the "high resolution" results obtained using the FINE stream map should be considered a hypothetical representation of what landscape configuration relative to streams might look like if more detailed stream maps were available.

River networks and land cover proximity

Before interpreting riparian differences among stream maps, it was first necessary to understand more general differences in river network attributes among different physiographic provinces. We quantified stream metrics and compared the distributions of drainage density (channel length per unit drainage area), stream order (Strahler 1964), and land area within 100 m of streams (near-stream area) as a percentage of watershed area across stream map resolutions among and within each physiographic province. To quantify land cover proximity to streams, the distance along flow pathways from each cropland pixel to the nearest stream was calculated within each watershed for each stream map resolution.

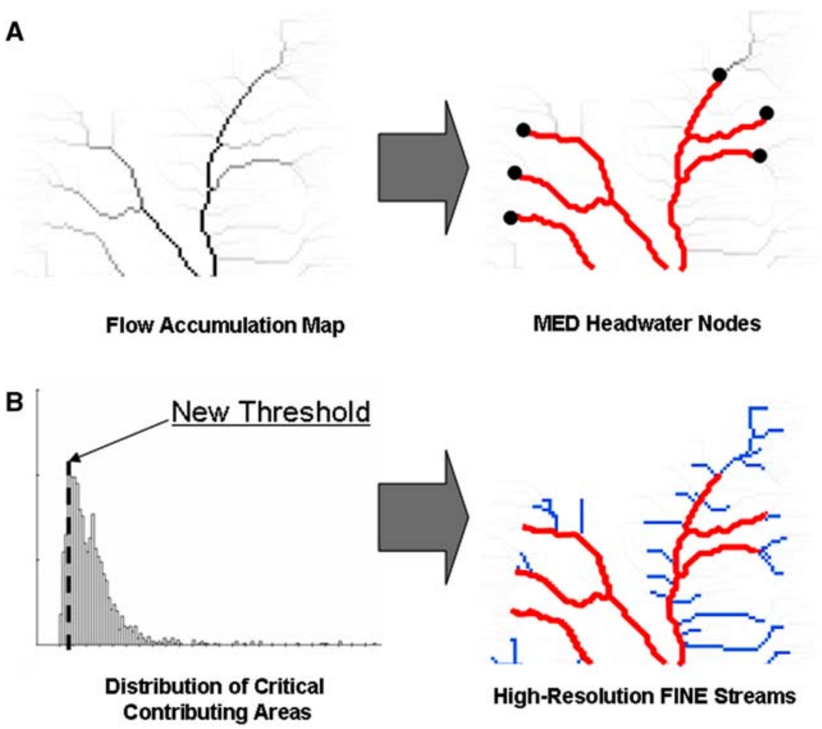

Fig. 3 The method for generating high-resolution stream maps: (**A**) Headwater nodes are overlain on a flow accumulation surface derived from a modified DEM, (**B**) the distribution of contributing areas resulting in a headwater stream is used to select a new threshold for the high-resolution stream map

We also described and compared near-stream cover as a percentage of total watershed cover. This measure provided an index of whether a particular land cover tended to be located near a stream. For each province, we compared each river network and land cover proximity measure using one-way Analysis of Variance (ANOVA) with multiple comparisons based on the T-method (Sokal and Rolf 1995).

Buffer metrics

We described riparian buffer configurations using conventional fixed-distance measures and more advanced functional buffer metrics. We quantified percent cropland as well as percent forest plus wetland (hereafter for + wet) within 100 m of mapped stream channels in each watershed using each stream map resolution. These fixed-distance measures were generated for comparison with the functional buffer measures described below. Functional measures of buffer width were generated using surface topography to link each cropland pixel to the stream (Baker et al. 2006a). Briefly, we used the DEM to identify a surface transport pathway following the steepest descent from each source (cropland) pixel to a stream. Using only these pathways, we identified for + wet cover that was connected to the stream channel by an unbroken chain of for + wet pixels (i.e., contiguous with the stream). We identified contiguous for + wet cover to restrict buffer quantification to streamside areas without enforcing an arbitrary ‘‘one size fits all’’ fixed-distance definition of riparian zones. We then measured the width of contiguous buffer between every pixel of cropland and a stream.

For each watershed, we calculated percent buffer gaps and both the mean and coefficient of variation (CV) of buffer width across all cropland cells at each stream map resolution. We focused on cropland because it is a major source of stream nutrients within the study area (Jordan et al. 1997a,b; 2003; Liu et al. 2000). We compared buffer metrics among stream map resolutions for each province using one-way ANOVA with multiple comparisons based on the T-method (Sokal and Rolf 1995).

Buffer retention potential

Our characterization of buffers produced an additional, watershed-scale metric related to buffer nutrient retention potential given existing land cover patterns: the mean inverse buffer width. We calculated the inverse of buffer width as $1/(w + 1)$ for each cropland pixel where w is the transport distance from cropland through for + wet cover contiguous with the stream channel. The inverse of buffer width along a single source-to-stream transect represents an expected nutrient delivery to streams from a unit source area (i.e., a single cropland pixel). A pattern of decrease in delivery with increasing buffer width is consistent with empirically observed changes in nutrient concentrations during transport through highly effective buffers (e.g., Lowrance et al. 1997). We refer to nutrient retention ''potential'' due to spatial and temporal uncertainty in actual nutrient retention by specific buffers, which can vary with hydrologic transport dynamics, interactions with plant roots or microbial activity, and subsurface stratigraphy (e.g., Jordan et al. 1993; Hill 1996; Correll et al. 1997; Vidon and Hill 2004). We assumed that all buffers were uniformly effective in order to isolate and evaluate the influence of stream map resolution on buffer patterns. This assumption provided us with a ''best-case'' buffer retention scenario. The mean of inverse buffer widths across all cropland cells is then a relative estimate of the potential for existing buffers to reduce nutrient delivery to streams from cropland within a watershed.

Relationships between mean inverse buffer width and percent cropland were non-linear and revealed a possible threshold relationship, so we evaluated the impact of stream map resolution in each province using a non-parametric technique for change-point analysis. Change-point analysis (nCPA) is a form of binary partitioning that estimates the numerical value of a predictor, x, resulting in a threshold in a response variable, y (Qian et al. 2003; King and Richardson 2003; King et al. 2005). Like classification and regression tree (CART) analysis, nCPA minimizes the sum of squared deviations from the mean in each partition. In addition, nCPA uses a bootstrapping procedure to estimate uncertainty associated with the partitioning; the results of which are represented as the cumulative probability of a threshold for every measured value of the predictor. We interpreted the bounds of a 95% confidence interval as a conservative estimate of the cropland proportion above which *even highly retentive* buffers were unlikely to be effective at reducing overall watershed nutrient losses. If stream map resolution had a large impact on assessment of buffer potential, then we expected that threshold levels of cropland proportion leading to low buffer potential would be distinct when using stream maps of different resolution. This analysis assessed the influence of stream map resolution on our ability to detect large differences in buffer retention potential across a range of current land use conditions.

The effects of stream map resolution on buffer retention potential could lead to strong differences in watershed nutrient discharge estimates based on different stream maps. To further explore this possibility, we selected three example watersheds (#314, #428, and #526) with differing proportions of cropland. For each watershed, we assumed a unit nutrient loading (source strength of 1) from each pixel of cropland. We then assigned riparian-buffer retention fractions per-unit buffer width and simulated the average annual N-uptake. Any nutrient not utilized by riparian buffers was assumed to enter the stream network. Reports of N-uptake efficiency during transport through a buffer (Jordan et al. 1993; Lowrance et al. 1997;Vidon and Hill 2004) were used to estimate the likely performances of both relatively leaky and retentive buffers. From these empirical observations, riparian buffer uptake was either 5% (relatively leaky) or 60% (relatively retentive) of a unit N-load for every 10 m of buffer width. By calculating the buffer width for each source pixel and applying the retention terms, we estimated the proportion of source loadings retained by riparian buffers under universally leaky or retentive scenarios.

Because different stream maps would also provide different measures of stream length, we also used estimates of a range of N-uptake lengths from low-order streams to explore the relative importance of stream versus riparian uptake. Based on reports from disturbed landscapes or from nutrient additions in pristine watersheds (Alexander et al. 2000; Peterson et al. 2001; Mulholland et al. 2004; Royer et al. 2004), streams took up 0.1% (leaky) to 10% (retentive) of a unit nutrient load for every 1 km of channel. Much of the work in streams has either focused on uptake over shorter time periods in relatively pristine systems (e.g., Mulholland et al. 2004) or across broader spatial scales (e.g., Alexander et al. 2000) than our simulation, so our results should be interpreted with caution. However, because the scenarios captured the range of observed uptake values, they were useful in illustrating the importance of stream map resolution in estimating nutrient delivery.

Results

River networks and land cover proximity

Drainage density for all provinces showed significant differences among stream maps ($P < 0.0001$; $N = 503$), roughly doubling with each increase in stream map resolution (Table 1). CRSE density ranged from < 0.1 to 1.8 km/km^2 with a median of 0.6 km/km^2 for all provinces. MED density ranged from < 0.1 to 3.1 km/km^2 with a median of 1.1 km/km^2, and FINE density ranged from <0.1 to 3.4 km/km^2 with a median of 2.2 km/km^2. Within provinces, there were significant differences in stream density ($P < 0.0001$) among stream maps, but the rank order of provinces varied (Table 1). For example, Appalachian Mountain watersheds showed the smallest drainage densities using CRSE maps, but the greatest densities using MED and FINE maps. Appalachian Plateau watersheds showed the largest densities using CRSE maps and the smallest densities using FINE maps, but with MED maps Coastal Plain watersheds had the least dense networks. Thus, differences in drainage density among map resolutions depended on physiographic province.

Stream order and fixed-distance near-stream area as a fraction of watershed area also showed significant differences among stream resolutions in the Chesapeake Basin ($P < 0.0001$ $N = 503$; Table 1). Mean and median values of the maximum stream order within each watershed increased by two from CRSE to FINE maps throughout the Chesapeake Basin. Again, significant differences ($P < 0.05$) due to map resolution were province-dependent, with the greatest change occurring in the Appalachian provinces and the least in the Coastal Plain (Table 1). The fraction of watershed area within a fixed-distance of stream channels (Near-stream area in Table 1) and drainage density showed similar patterns among stream map resolutions. Near-stream area within 100 m of CRSE streams contained an average of 15% of total watershed area, whereas MED and FINE streams doubled (27%) and tripled (48%), respectively, the proportion of watershed area contained within the near-stream zone (Table 1).

Both cropland proximity to streams and the fraction of watershed cropland occurring within 100 m of streams responded to differences in the resolution and relative density of mapped stream channels (Table 1). Increasing stream map resolution reduced the mean distance-to-cropland in our sample from 825 m to 375 m to 167 m, respectively, for CRSE, MED, and FINE streams ($P < 0.0001$, $N = 503$; Table 1). Because the locations of cropland patches remained the same throughout the analysis, significant within-province differences ($P < 0.05$) among stream maps were due solely to stream map resolution (Table 1). Using CRSE maps, cropland occurred farther away from streams in the Appalachian Mountains than in any other province, whereas cropland occurred closest to streams in the Appalachian Plateau watersheds. Using MED maps, cropland in both sets of Appalachian provinces appeared closer to streams than did cropland in either the Piedmont or Coastal Plain. However, using FINE maps, Appalachian Mountain cropland occurred closer to streams than cropland in all other provinces and Appalachian Plateau cropland occurred farther away than cropland in the Coastal Plain (Table 1).

The mean proportion of watershed cropland falling within 100 m of streams increased similarly from 9.7% using CRSE maps, to 20% using MED maps, to 40% using FINE maps across all provinces ($P < 0.0001$, $N = 503$; Table 1). Using

Table 1 Mean* and standard deviation (in italics) values of stream metrics and measures of land cover proportion and proximity for three stream map resolutions; CRSE (1:100,000), MED (1:24,000), and FINE (higher resolution than 1:24,000);across the Chesapeake Basin and within four physiographic provinces

	Sensitivity to stream map	Chs. Basin (503)			App Plat. (65)			App. Mtn. (113)			Pied. (174)			Coastal Pln. (151)		
		CRSE	MED	FINE	CRSE	MED	FINE	CRSE	MED	FINE	CRSE	MED	FINE	CRSE	MED	FINE
Stream metrics																
Drainage density (km/km^2)	High	0.6	1.2	2.2	0.7	1.2	2.0	0.5	1.2	2.5	0.6	1.2	2.1	0.6	1.1	2.2
		0.01	*0.02*	*0.02*	*0.01*	*0.03*	*0.04*	*0.02*	*0.03*	*0.04*	*0.02*	*0.03*	*0.04*	*0.02*	*0.03*	*0.03*
Strahler stream order	Moderate	2.4	3.7	4.4	2.9	4.1	4.8	2.4	3.9	4.6	2.4	3.7	4.4	2.3	3.5	4.0
		0.7	*0.9*	*1.1*	*0.5*	*0.8*	*1.0*	*0.7*	*0.7*	*0.9*	*0.7*	*1.0*	*1.4*	*0.6*	*0.9*	*1.0*
Near-stream area (%)	High	15.1	27.4	47.6	18.2	27.6	42.6	12.4	29.0	53.9	15.5	27.6	45.3	15.2	25.9	47.5
		5.8	*7.2*	*7.6*	*3.0*	*4.3*	*4.4*	*5.4*	*7.2*	*5.5*	*5.9*	*7.2*	*7.2*	*6.0*	*8.0*	*7.4*
Watershed land cover																
Cropland (%)	–		10.0			2.9			6.6			11.4			14.0	
			10.9			*3.0*			*8.2*			*8.6*			*14.5*	
For + wet (%)	–		49.8			75.0			52.5			37.2			51.3	
			24.7			*13.1*			*29.1*			*19.6*			*20.8*	
Proximal land cover																
Ave. distance to cropland (m)	High	825	375	167	594	329	186	1137	328	136	840	401	176	674	400	172
		606	*202*	*54*	*342*	*131*	*49*	*970*	*180*	*52*	*503*	*240*	*55*	*256*	*186*	*48*
Watershed cropland near-stream (%)	Moderate	9.7	20.3	39.9	12.1	21.1	38.4	11.0	26.8	51.6	8.9	19.1	37.1	8.6	16.7	35.1
		10.1	*17.1*	*17.3*	*9.5*	*12.6*	*18.3*	*10.8*	*14.4*	*15.7*	*8.7*	*13.3*	*14.3*	*11.1*	*14.6*	*15.6*

For all variables, means for different map resolutions are significantly different ($P < 0.05$) in basin-wide and within-province comparisons

*Median values showed similar patterns in comparisons across stream map resolution

CRSE maps, more of watershed cropland occurred near streams in the Appalachian provinces than in either the Piedmont or Coastal Plain. We found a similar pattern using MED and FINE maps, although observed increases with map resolution in the amount of watershed cropland occurring near streams was greatest in Appalachian Mountain watersheds.

Buffer metrics

Although fixed-distance measures of percent cropland and percent for + wet within 100 m of streams differed significantly among stream maps across all provinces ($P < 0.01$, $N = 503$), differences within provinces were less sensitive to map resolution (Table 2). In most within-province comparisons, differences in cropland or for + wet percentages within 100 m of streams did not differ significantly among stream map resolutions ($P > 0.05$). In Piedmont watersheds, differences in percentages of near-stream cropland and for + wet were marginally significant between CRSE and FINE stream maps ($P = 0.05$, $N = 174$), while proportions of near-stream for + wet were clearly distinct ($P < 0.0001$, $N = 151$) in Coastal Plain watersheds (Table 2).

In contrast to fixed-distance measures, estimates of mean buffer width varied with stream map resolution within provinces (Fig. 4A, Table 2). For all provinces together, mean buffer width was reduced significantly between CRSE and MED maps, and again between MED and FINE ($P < 0.0001$, $N = 503$). Within provinces, the same pattern was observed, except between MED and FINE maps in Appalachian Mountain watersheds. Similarly, buffer gap frequency rose with increasing stream map resolution both within and among physiographic provinces (Fig. 4B, Table 2).

Measures of within-watershed variation in buffer width revealed a more complex pattern (Table 2). Across all provinces in the Chesapeake Basin, coefficients of variation in buffer width showed a significant increasing trend with map resolution ($P = 0.002$, $N = 503$), but this was primarily due to the effect of FINE stream maps. Within provinces, a similar trend occurred in Appalachian Plateau and Piedmont watersheds, but Coastal Plain watersheds showed distinct increases in variation with each step in map resolution. Thus, we observed that buffer width was more variable within watersheds when smaller streams were included in the stream map. This general pattern remained consistent throughout most provinces, except for Appalachian Mountain watersheds, where width variation actually tended to decrease from CRSE to MED maps, but no Appalachian Mountain comparison revealed significant differences among map resolutions.

Buffer retention potential

For all provinces together, our estimate of the fraction of cropland contributions reaching streams across all provinces (the mean inverse buffer width) increased with stream map resolution ($P < 0.0001$, $N = 503$; Table 2). Buffer retention potential also decreased significantly with increasing stream map resolution within every province, except for the Appalachian Mountains. This decrease in potential retention was consistent with the decreases in mean buffer width, increases buffer gap frequency, and increases buffer-width variability observed with increasing stream map resolution. In all provinces, the greatest estimates of nutrient interception potential (widest buffers and smallest mean-inverse-buffer-width) tended to occur with very low (<10%) proportions of watershed cropland (e.g., Fig. 5). Exceptions to this trend occurred in watersheds of the Coastal Plain, where substantial retention potential was still present in watersheds with larger (>20%) cropland proportions (Table 3).

Change-point analysis revealed distinct patterns among provinces in possible threshold responses of buffer potential (mean inverse buffer width) to increasing watershed cropland proportions (Table 3). In each province, increasing stream map resolution led to a lower observed change point and often to narrower confidence estimates, especially between CRSE and higher resolution streams (Table 3, Fig. 5). For any map resolution, the lowest observed change points occurred in the Appalachian provinces, followed by the Piedmont. The Coastal Plain had the

Table 2 Mean* and standard deviation (in italics) values of buffer metrics for three stream map resolutions; CRSE (1:100,000), MED (1:24,000), and FINE (higher resolution than 1:24,000); across the Chesapeake Basin and within four physiographic provinces

Buffer metrics	Sensitivity to stream map	Chesapeake (503)			App Plateau (65)			App. Mtn. (113)			Piedmont (174)			Coastal Plain (151)		
		CRSE	MED	FINE	CRSE	MED	FINE	CRSE	MED	FINE	CRSE	MED	FINE	CRSE	MED	FINE
Fixed-distance cropland (%)	Low	6.4[a] *10.4*	7.4[a,b] *10.8*	8.6[b] *10.9*	1.6[a] *1.9*	1.9[a] *2.2*	2.2[a] *2.2*	5.4[a] *7.7*	6.1[a] *8.1*	6.5[a] *8.3*	7.2[a] *9.9*	7.6[a,b] *7.7*	9.4[b] *8.5*	8.4[a] *13.7*	10.6[a] *15.8*	11.9[a] *15.0*
Fixed-distance for + wet (%)	Low	57.4[a] *27.3*	55.4[a,b] *25.9*	53.1[b] *25.2*	80.1[a] *11.0*	77.6[a] *10.4*	76.9[a] *10.0*	45.5[a] *30.8*	48.1[a] *29.7*	50.6[a] *29.8*	45.3[a] *21.7*	43.7[a,b] *20.2*	40.9[b] *20.0*	70.5 *22.7*	64.6 *23.8*	58.8 *22.6*
Mean width (m)	High	174.6 *267.7*	86.0 *116.6*	36.7 *45.7*	232.3 *219.7*	115.3 *77.1*	65.0 *40.5*	161.5 *462.1*	56[a] *155.9*	24.6[a] *59.9*	90.1 *122.0*	47.5 *59.2*	22.1 *33.5*	249.5 *182.8*	140.2 *123.0*	50.2 *37.9*
Gap frequency (%)	Moderate	39.9 *30.7*	49.1 *28.6*	60.8 *23.8*	24.0 *20.7*	35.4 *16.1*	44.8 *15.6*	57.7 *32.6*	68.9 *28.3*	71.2 *25.6*	52.6 *26.8*	59.2 *23.3*	70.1 *18.6*	21.0 *21.8*	28.8 *22.5*	48.5 *21.4*
Coefficient of variation	Low	223[a] *275*	240[a] *204*	279 *276*	135[a] *57*	153[a,b] *63*	162[b] *53*	405[a] *486*	393[a] *299*	440[a] *472*	244[a] *188*	262[a] *168*	304 *181*	115 *67*	140 *83*	183 *123*
Mean inverse buffer width	High	0.49 *0.29*	0.54 *0.27*	0.64 *0.22*	0.30 *0.20*	0.36 *0.15*	0.47 *0.15*	0.71[a] *0.23*	0.77[a,b] *0.19*	0.77[b] *0.18*	0.59[a] *0.24*	0.62[a] *0.21*	0.72 *0.17*	0.28[a] *0.24*	0.34[a] *0.23*	0.51 *0.20*

For all variables not noted by letters, means for different map resolutions are significantly different ($P \leq 0.05$) in basin-wide and within-province comparisons

[a,b] The same letter indicates insignificant differences in basin-wide or within-province comparisons ($P > 0.05$)

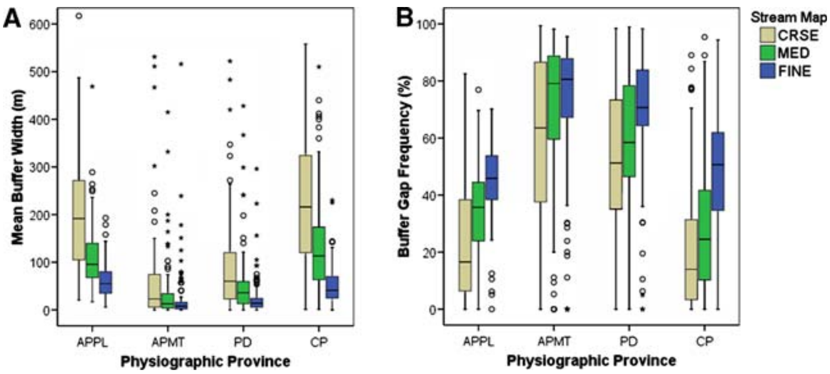

Fig. 4 Boxplots of mean buffer width (**A**) and gap frequency (**B**) across different stream map resolutions in watersheds of the Appalachian Plateau (APPL), Appalachian Mountains (APMT), Piedmont (PD), and Coastal Plain (CP) physiographic provinces. Boxes delimit the 25th and 75th percentiles, whiskers the 10th and 90th, and circles and stars represent extreme values. Solid lines indicate the median within each province

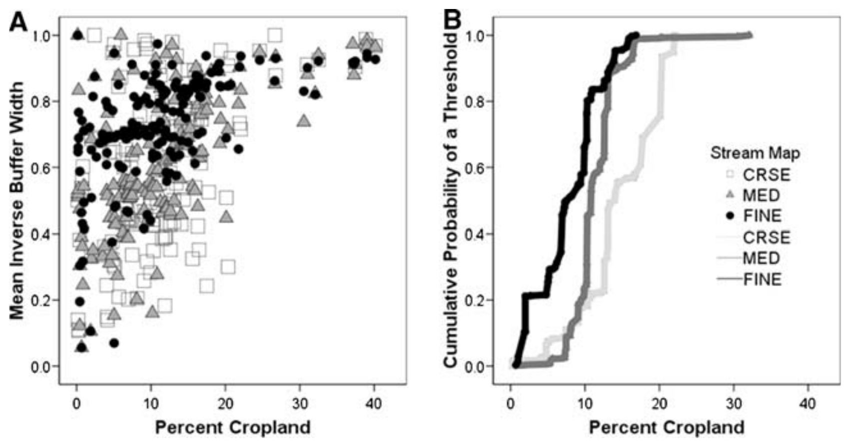

Fig. 5 Change-point analysis in Piedmont watersheds showing (**A**) scatterplots of percent cropland versus mean inverse buffer width using three different stream map resolutions and (**B**) the cumulative probability of a threshold representing uncertainty associated with change-point estimation

Table 3 Non-parametric change-point analysis of mean inverse buffer width as a function of percent watershed cropland using three stream maps; CRSE (1:100,000), MED (1:24,000), and FINE (higher resolution than 1:24,000); within four physiographic provinces

Metric (% cropland)	App. Plateau* (65)			App. Mtn. (113)			Piedmont (174)			Coastal Plain (151)		
	CRSE	MED	FINE	CRSE	MED	FINE	CRSE	MED	FINE	CRSE	MED	FINE
Observed change-Point	0.1	n.s.	<0.1	0.5	0.5	0.2	13.1	10.3	10.2	45.3	22.6	20.2
Mean bootstrap estimate	2.0	1.9	0.4	2.0	0.5	3.2	14.7	11.4	7.9	23.7	24.7	15.9
Lower bound (95% CI)	<0.1	<0.1	<0.1	0.2	0.1	0.1	4.8	7.5	1.9	0.5	19.4	7.0
Upper bound (95% CI)	9.8	8.6	3.8	5.6	5.0	7.2	21.9	16.5	14.1	45.4	32.2	20.3

*Sample size and range of cropland proportions in this province were too small for a reliable estimation

Confidence intervals indicate uncertainty in change-point estimates. Unless noted, all change points were significant ($P < 0.05$)

highest observed change-points, consistent with larger nutrient interception potential at greater proportions of watershed cropland. However, the Coastal Plain change-point also showed the greatest absolute decreases with finer stream map resolution (Table 3).

Our three example watersheds (#314, #428, #526) encompassed a range of watershed characteristics, yet showed variations in watershed metrics with stream resolution (Table 4) that were consistent with more general findings. Increasing stream map resolution increased drainage density, near-stream area, and measures of source proximity, whereas estimates of riparian buffering decreased. When we applied empirical retention coefficients in these watersheds, increasing stream map resolution led to substantial reductions in estimated overall annual N uptake, especially between CRSE and MED stream maps (Fig. 6). Differences between uptake scenarios using MED and FINE stream maps were less consistent and often less distinct. Much of the reduced uptake appeared to be driven by a marked decline in riparian buffering. Across all three watersheds, the average decrease in apparent buffer uptake attributed to increasing stream map resolution was 84%, whereas the average decrease in uptake between retentive and leaky buffers was 72%. Stream nutrient transformation was relatively unimportant when streams were leaky, but uptake by retentive streams increased as map resolution and overall channel density increased. When streams were relatively retentive, stream uptake eclipsed the relative importance of riparian buffers in all high-resolution scenarios. In fact, watershed 314 showed increased nutrient uptake with higher map resolution (FINE vs. MED), largely as a result of increased stream uptake.

Discussion

River networks and land cover proximity

Increasing stream map resolution revealed portions of the river network reaching out farther into the landscape and closer to watershed divides, dissecting the landscape more finely while simultaneously decreasing average proximity to a stream channel throughout a watershed. This shift had a dramatic effect on network characterizations. Increasing stream map resolution significantly increased stream order, drainage density, and the proportion of watershed area occurring near a stream. The effects of map resolution were relatively similar in three of four provinces, but in the Appalachian Mountains increasing map resolution led to the largest increases in drainage density and consequently the largest increases in

Table 4 Comparison of watershed and riparian conditions from three watersheds used in the N-uptake simulation across CRSE (1:100,000), MED (1:24,000) and FINE (higher resolution than 1:24,000) stream map resolutions

Watershed metric	Watershed # 314			Watershed # 428			Watershed # 526		
Physiographic province	Coastal Plain			Piedmont			Piedmont		
Area (km^2)	2.7			9.8			11.8		
Cropland (%)	28.7			17.5			4.2		
For + wet (%)	21.1			18.9			76.0		
	CRSE	MED	FINE	CRSE	MED	FINE	CRSE	MED	FINE
Stream metrics									
Drainage density (km/km^2)	0.7	1.1	2.2	0.3	1.1	1.6	0.4	1.2	2.0
Strahler stream order	2.0	3.0	3.0	2.0	4.0	4.0	2.0	3.0	4.0
Near-stream area (%)	17.0	27.0	49.8	8.8	22.6	32.9	11.1	22.7	37.6
Proximal land cover									
Ave. distance to cropland (m)	612	262	151	1,089	366	249	673	513	156
Watershed cropland near-stream (%)	12.5	30.0	60.6	1.9	8.6	15.5	4.4	10.4	49.6
Buffer metrics									
Fixed-distance cropland (%)	21.0	31.9	34.9	3.8	6.7	17.5	1.6	1.9	5.5
Fixed-distance for + wet (%)	42.4	27.7	19.4	34.3	27.9	25.8	70.4	77.7	69.6
Mean width (m)	46.0	3.0	3.0	45.0	12.0	10.0	142.0	73.0	11.0
Gap frequency (%)	27.8	85.0	89.1	21.9	76.5	85.1	12.4	76.2	78.0
Coefficient of variation in width (m)	101	359	368	117	284	354	155	256	244
Mean inverse buffer width	0.29	0.89	0.85	0.24	0.77	0.86	0.14	0.76	0.78

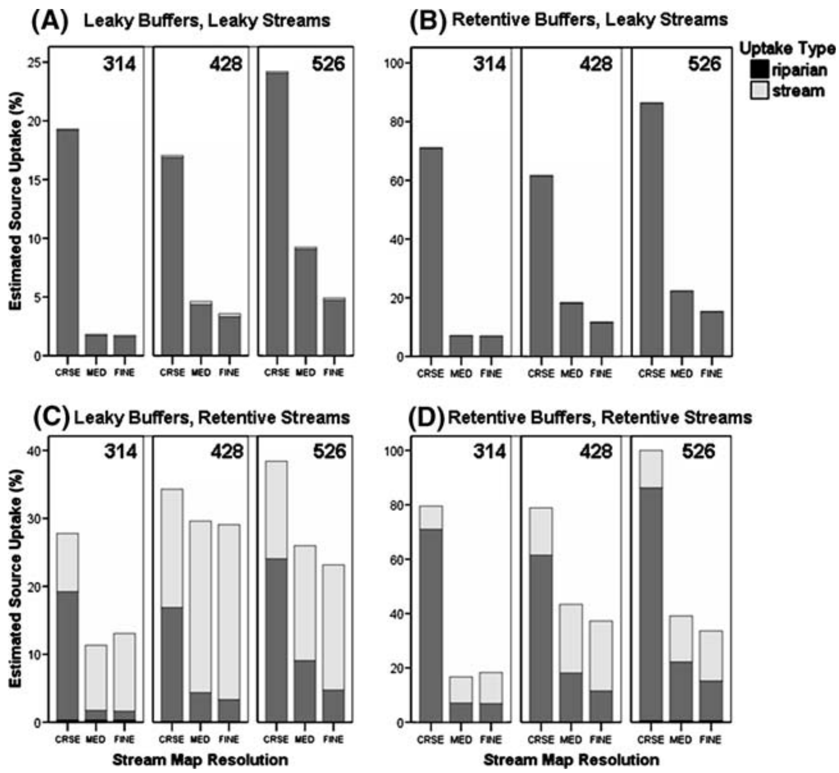

Fig. 6 Simulated proportions of mean annual watershed nutrient discharges intercepted by riparian uptake (dark bars) or in-stream transformation (light bars) in watershed #314, #428, and #526 estimated under relatively leaky or retentive landscape scenarios using different stream map resolutions. Note differences in *y*-axes showing uptake magnitude across scenarios

near-stream watershed area. This Appalachian Mountain pattern was likely caused by ridges and valleys which constrained stream networks to have many small, lateral tributaries contributing to fewer, larger-order systems in valley bottoms. The prevalence of so many small tributary streams meant that Appalachian Mountain watersheds were less likely to be well buffered when analyzing high-resolution stream maps than watersheds in other provinces. The difference between Appalachian Mountains and other provinces suggests that insight about the pattern of water delivery to stream channels from relatively resistant, mountainous terrain (e.g., McGlynn and Seibert 2003) may be less applicable in landscapes with less relief.

The choice of stream map and map resolution strongly influences the results of land cover analyses relative to river networks. Many of the differences we observed in (1) near-stream area as a fraction of watershed area, (2) mean cropland proximity, and (3) near-stream cropland as a fraction of watershed cropland appeared to be a direct result of increasing drainage density with increasing map resolution. These three measures were far more sensitive to stream map resolution than to regional physiography, although we have previously observed strong differences in land cover patterns among physiographic provinces (Baker et al. 2006a). At first glance, the fraction of watershed cropland occurring near any set of mapped streams varied only mildly among provinces. However, this occurs because of interaction between the amount of cropland and within-watershed cropland location in the two Appalachian provinces. In the Appalachian Plateau, substantial fractions of watershed cropland occur near CRSE streams only because these watersheds have relatively little cropland overall, whereas in Appalachian Mountains small cropland proportions are lower near CRSE streams and higher near FINE channels.

One limitation of our analysis is the mapping of high-resolution stream networks. Although the contributing-area thresholds we used for high-resolution (FINE) stream generation fell within the range of natural variation for each watershed cluster (i.e., 25% of mapped MED streams have a lower threshold), the thresholds are very broad generalizations of catchment water yield and they ignore variation in local physiography, soil, and hydrologic routing. For example, a particular threshold may be too high to capture streams originating from headwater springs and seeps that ''steal'' subsurface water from neighboring catchments, while the same threshold may be too low if karst topography increases infiltration rates or headwater wetlands increase catchment storage. Future analysis could improve these automated predictions with more watershed-specific characterizations of contributing area and yield using soil types and topography (e.g., Montgomery and Dietrich 1988). The high-resolution stream map is hypothetical, but it allowed us to evaluate how our results might change when additional streams not shown in the most detailed digital stream maps currently available from USGS were included. Our results comparing MED to FINE streams were consistent with the results obtained by comparing CRSE to MED streams, and this consistency in scaling among stream maps supports the plausibility of our high-resolution results. Although we focused on more accurate maps of perennial channels, a similar approach might also be used to evaluate the consequences of seasonal network expansion (e.g., Stanley et al. 1997).

Buffer metrics

Differences in stream map resolution strongly affected the calculation of mean buffer width, gap frequency, and the CV in buffer width; but not necessarily the proportions of land cover within a fixed-distance of streams. Instead, fixed-distance metrics closely tracked watershed-wide land cover proportions regardless of stream map resolution. In previous work, we reported that fixed-distance metrics can be insensitive to variation in land cover configuration and are highly correlated with watershed-wide land cover proportions (Baker et al. 2006a). The present observation that fixed-distance metrics also fail to detect significant changes in the positioning of specific land cover patches relative to stream headwaters is further evidence that these commonly used metrics provide poor measures of riparian buffering.

In contrast, riparian metrics determined from flow path analysis were far more sensitive to changes in the stream network and corresponding changes in land cover proximity than were fixed-distance metrics. Increasing stream map resolution reduced mean buffer width and increased both gap frequency and buffer variation nearly universally, with the exception of watersheds in the Appalachian Mountains and some in the Piedmont. In most watersheds throughout the Chesapeake Basin, increasing map resolution increased our ability to perceive the many small channels linking agricultural activity to river networks and lowered estimated buffer potential regardless of watershed-wide land use patterns.

In Appalachian Mountain and some Piedmont watersheds, lower slopes and more tillable soils near higher-order streams have concentrated development and agricultural activity in valley bottoms (Baker et al. 2006a). Thus, the steeper headwater catchments surrounding many smaller streams have remained forested, although the little cropland that does occur in the headwaters is near streams. Using coarse (CRSE) stream maps, buffers can appear wide for some cropland patches in valleys upstream of the end of the mapped stream network. As more channels are added to the stream network with increasing resolution (MED), more of these valleys contained a mapped stream, so both the mean and variation in buffer width decreased while gap frequency increased. However, when map resolution is further increased (using FINE streams), added channels tend to occur either as small tributaries to larger streams in agricultural valley bottoms or as first-order channels in steep headwater catchments with little cropland and therefore, little buffer potential. Thus, physiographic constraints on both channel development and land use patterns appear to explain the effects of stream map resolution on buffer width in these provinces.

Changes in functional riparian metrics due to stream map resolution were similar in magnitude to changes due to watershed cropland proportion. This result has profound implications for riparian buffer study because published geographic analyses of riparian buffers rely on very different resolutions of stream networks. For example, using 1:100,000 stream maps and 30-m land cover data, Jones et al. (2001) reported a strong negative correlation between near-stream forest cover and stream nutrient concentrations. They concluded that the observed correlation was consistent with large amounts of riparian retention in the Chesapeake Basin. We found similar patterns of near-stream forest and buffer retention potential in our analyses using CRSE stream maps, yet buffer retention potential was dramatically reduced using more detailed stream maps. Because the percent of near-stream forest remained relatively unchanged among map resolutions, differences in buffer potential were due solely to changes in watershed-to-stream connectivity tracked by functional metrics. In some cases, the difference between using a coarse and fine-resolution stream map was equivalent to perceiving a watershed as well-buffered versus almost entirely unbuffered. Because our analyses optimistically presume that *every* buffer retains nutrients effectively, the dramatic decrease in buffer potential with stream map resolution indicates that fixed-distance land cover analysis using coarse-resolution stream maps likely overestimates buffer potential and that existing buffer configurations are unlikely to result in substantial nutrient uptake.

The spatial resolution and categorical accuracy of land cover data can also affect estimates of buffering potential. A recent investigation reports that land cover data at resolutions finer than 30 m can identity substantially greater amounts of near-stream forest (Hollenhorst et al. 2006), but it is unclear whether these narrow bands are located along flow pathways connecting source lands to streams. Disagreements among land cover maps can also lead to substantial differences in estimates of non-point source areas (Weller et al. 2003). Of course, even if land cover data discrepancies lower expectations for uptake by riparian forests, nutrient transformation may still occur due to subsurface or in-stream biogeochemical processes. However, our results call into question the validity of riparian land cover analyses performed at coarse scales of stream resolution as well as those which use fixed-distance approaches for riparian assessment in a nutrient management context.

Estimates of buffer retention potential

Perhaps the most striking effect of stream map resolution is the change in nutrient interception potential estimated by mean inverse buffer width. In each province, the estimated fraction of cropland contributions reaching streams was highly variable at low (<10–20%) proportions of cropland but at higher cropland proportions the fraction reaching streams was almost always close to one. Change-point analysis identified proportions of watershed cropland in each province that led to dramatic reductions in the nutrient interception potential of existing configurations of riparian buffers.

In Appalachian Mountain watersheds, the change-point occurred at <1% cropland, but the change-point was closer to 10% in the Piedmont and 20% in the Coastal Plain. Above these threshold cropland proportions, existing buffers are unlikely to have a significant effect on nutrient concentrations expected at the watershed outlet, even when we assume that buffers can retain substantial amounts of nutrients. The change-point technique helps identify watershed cropland proportions at which partially buffered river networks tend to become indistinguishable from unbuffered networks due to the ineffective location of remnant riparian forest and wetlands. The fact that increased stream map resolution led to lower change-point estimates and more narrow confidence intervals in several physiographic provinces indicates that adequate buffer assessment and targeted buffer protection requires an accurate and detailed mapping of stream channels. Much of the broad-scale analysis of riparian buffer potential has been accomplished using coarse-resolution stream maps, so such studies may grossly overestimate landscape-level buffer retention.

Because our functional metrics describe transport distance along a flow path through a buffer, they are directly comparable with field studies along source-to-stream transects. Unlike fixed-distance approaches, our method correctly scales the measures made along individual transects to entire landscapes. Predicting the likely effects of riparian buffers across whole watersheds is an important research and management goal (Weller et al. 1998; Dosskey et al. 2005). By assuming that all contiguous forest and wetland function as a biogeochemically active and effective buffer in the change-point analysis and uptake simulation, we defined a best-case scenario that maximized the filtering expected from existing riparian configurations. Of course, we know that along many transects, variation in hydrology, soil, and vegetation will reduce actual buffer effectiveness (Osborne and Kovacic 1993; Hill 1996; Gold et al. 2001). Although we have yet to incorporate such variation, the simple spatial approach we use here represents a substantial improvement over previous geographic analyses of buffer effects on whole-watershed nutrient discharges.

Use of coarse stream maps can provide misleading expectations about riparian buffer uptake due to the effects of drainage density on watershed-to-stream connectivity and on what is attributed to ''riparian'' versus ''stream'' effects. In our simulation, the influence of increasing stream map resolution on watershed-to-stream connectivity had a greater impact on resulting nutrient discharges than did relative buffer retention in our simulation. This result is consistent with the findings of Weller et al. (1998) for hypothetical watersheds and particularly true for real landscapes where we expect to find spatial and temporal variability in unit buffer retention. Buffer effectiveness is often estimated by absolute uptake at specific locations, but our results suggest ensuring that buffers occur along all flow paths *connecting* sources to streams is at least as important as estimating uptake and should be a primary concern for managers interested in reducing watershed nutrient export (*sensu* Dosskey et al. 2005; Polyakov et al. 2005).

Compared to the large impact of watershed-to-stream connectivity on simulated nutrient discharge, changing stream map resolution had a much smaller effect on in-stream uptake due to the range of uptake lengths in our simulation. Differences between riparian efficiency and stream uptake lengths meant that the leaky-buffer, retentive-stream scenario was the least sensitive to changing stream map resolution. However, increasing stream map resolution did raise stream density and therefore increased the relative importance of uptake occurring in streams. When streams were relatively retentive, stream uptake actually eclipsed that of riparian areas in calculations based on high-resolution maps. Hydrologists and geomorphologists have long emphasized the influence of map resolution on channel location and the ability to distinguish hillslope from channel processes (Montgomery and Dietrich 1988; Walker and Willgoose 1999; Seitzinger et al. 2002; Hancock and Evans 2006). Our findings suggest that improving measurement of connectivity among sources, buffers, and streams across broad landscapes is critical for developing accurate watershed assessments as well as for realistic predictions about the relative impacts of buffer restoration and stream restoration on watershed nutrient exports.

Implications for buffer analysis

Using improved measures of riparian configuration, we sought to understand the influence of changing stream map resolution on measures of riparian buffers and their implied nutrient reduction potential. Given the imprecision of buffer assessments based on land cover within a fixed-distance of streams (Baker et al. 2006a), almost any method resolving the connection between non-point nutrient sources and landscape sinks should improve our understanding of riparian effects. However, increasing the explicit connection between streams and surrounding watersheds requires accurate stream mapping. Our analyses demonstrate that interactions between stream map resolution and land cover patterns make a dramatic difference in the perceived ability of riparian buffers to ameliorate nutrient discharges from agricultural activities. Moreover, stream map resolution affects inferences about whether retention occurs in streams or riparian zones.

Our findings have several implications. First, for many metrics the effects of map resolution are as great as the effects of physiography and nearly as great as the effects of land cover proportion. Thus, comparisons of results from different geographic analyses need to consider the possible effects of using different stream maps. The location and density of stream channels determine the nature of connectivity with surrounding source areas and the relevance of riparian buffers as nutrient filters. Because large portions of watershed area occur close to low-order channels, it makes clear sense to incorporate these channels into buffer assessments whenever possible. Second, measures of land cover within a fixed distance of stream channels were insensitive to the effects of stream map resolution, suggesting that such metrics are inappropriate for buffer assessment. Third, the degree of hydrologic connectivity between sources and buffers is more important than relative buffer retention. Even if riparian conditions create exceptionally high nutrient retention potential, buffers will be ineffective unless they are positioned along a flow path between a source area and a stream. Thus, efforts to improve buffer performance and achieve measurable restoration success throughout watersheds should emphasize precision buffer placement. Fourth, because many past geographic studies have relied upon stream maps at 1:100,000 or coarser scales, gross overestimates of buffer effectiveness are likely. We recommend that policy developed from such broad studies using coarse stream maps be reevaluated using newly released 1:24,000 NHD and perhaps even more detailed maps. From a management or policy standpoint, it is not enough to know that stream map resolution influences our ability to estimate buffer potential. We need to know how important these effects are to inform prioritization of management or restoration action. For now, the trade-off seems to be that coarse maps provide an over-rosy picture of stream buffering yet make it difficult to ascertain the importance of in-stream processes. As knowledge about the relative importance of riparian retention and in-stream transformation grows, demonstrating the efficiency of either process across whole watersheds will depend upon accurate mapping of stream channels and delineation of transport pathways.

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