Wetlands (2012) 32:461–473
DOI 10.1007/s13157-012-0279-7

ARTICLE

Enhanced Detection of Wetland-Stream Connectivity Using LiDAR

Megan Lang · Owen McDonough · Greg McCarty · Robert Oesterling · Bill Wilen

Received: 4 August 2011 / Accepted: 17 January 2012 / Published online: 14 February 2012

Abstract The spatial relationship between wetlands and streams influences their structure and function, and is currently tied to the regulatory status of wetlands. Efforts have been made to assess connectivity between wetlands and streams and possible management implications by comparing existing wetland and stream maps (e.g., National Hydrography Dataset [NHD]) but the reliability of these assessments is affected by the accuracy and inherent nature of input datasets. Stream datasets derived using semi-automated and automated interpretation of LiDAR derived digital elevation models were found to be considerably more accurate than NHD High Resolution (12% less accurate than automatically generated streams) and Plus (29% less accurate than automatically generated streams) and in general use of LiDAR derived datasets was found to significantly increase percent area and total number of wetlands that were considered connected at multiple buffer lengths ranging from 0 to 80 m. When wetland-stream connectivity as judged using NHD was compared to a semi-automatically generated highly accurate LiDAR derived stream dataset, the High Resolution NHD was found to underestimate semi-natural palustrine wetland area connected by 15% and number of wetlands connected by 13% on average while NHD Plus was found to underestimate semi-natural palustrine wetland area and number connected by 27% on average.

M. Lang (✉)
USDA Forest Service Northern Research Station;
Beltsville Agricultural Research Center,
10300 Baltimore Ave., Bldg 007, Rm 104,
Beltsville, MD 20705, USA
e-mail: mwlang@fs.fed.us

O. McDonough
Chesapeake Biological Laboratory,
University of Maryland Center for Environmental Science,
Solomons, MD 20688, USA

G. McCarty
USDA-ARS, Remote Sensing and Hydrology Laboratory,
Beltsville Agricultural Research Center,
10300 Baltimore Ave., Bldg 007, Rm 104,
Beltsville, MD 20705, USA

R. Oesterling
University of Maryland Department of Geography,
2182 LeFrak Hall,
College Park, MD 20742, USA

B. Wilen
US Fish and Wildlife Service National Wetland Inventory,
4401 North Fairfax Drive,
Arlington, VA 22203, USA

Keywords Digital elevation model · National hydrography dataset · Significant nexus · Stream mapping

Introduction

The determination of U.S. wetland jurisdiction in large part based on “significant nexus” as defined through Rapanos v. United States (2006) greatly increased the need for scientific information in support of wetland regulatory decisions, as well as future policies (Nadeau and Rains 2007; Leibowitz et al. 2008). The protective status of wetlands within the U. S. is now tied to the spatial relationship between wetlands and nearby streams, with wetlands that are closer to streams, especially larger, more permanent streams being more likely to be jurisdictional. Furthermore, the physical, chemical, and biological interactions between wetlands and streams (i.e., “significant nexus”) that are often the basis of wetland jurisdictional status will continue to strongly influence environmental conditions regardless of changes to legal and policy guidelines.

The potentially large impact of *SWANCC*, *Rapanos*, and corresponding regulatory agency responses on wetland protection under the CWA, as well as underlying environmental relationships, has led many government agencies within the U.S. and individual scientists to attempt to estimate the potential impact of these rulings on wetland jurisdiction at the landscape scale (Nadeau and Rains 2007). Multiple states, individual scientists, and other entities have used Geographic Information System based analysis to estimate the impact of recent wetland jurisdictional changes (Robb 2002; Bedford and Godwin 2003; Sharitz 2003; Tiner 2003; Nadeau and Rains 2007; Vance 2009). In fact, this type of analysis was so widespread and important that the Association of State Wetland Managers offered guidance on their website detailing how analyses could be conducted so that results would be comparable (http://www.aswm.org/fwp/swancc/gis-swan.htm). The majority of these studies relied on a mixture of established wetland (e.g., U.S. Fish and Wildlife Service National Wetland Inventory) and stream maps to quantify the spatial relationships between wetlands and streams. These studies usually used stream data which ultimately originated from hard copy U.S. Geological Survey (USGS) topographic maps that were derived from the interpretation of aerial photographs (e.g., USGS National Hydrography Dataset [NHD; http://nhd.usgs.gov]).

Although hydrographical datasets, such as the NHD, are highly valuable at national, regional, and even local scales, they are often incomplete and even inaccurate at the scale required to inform the jurisdictional decision making process (i.e., field scale) or inform certain ecologic analyses. In fact, it has long been recognized that commonly used stream maps, like the NHD, underestimate actual stream length, including non-perennial streams (Mueller 1979; Meyer and Wallace 2001; Heine et al. 2004; Roy et al. 2009). This is likely to be especially true in areas of relatively low topographic relief, areas where precipitation exceeds evapotranspiration (e.g., eastern US; personal communication; Jeff Simley, USGS), and areas where hydrography has been altered by humans (e.g., urban and agricultural landscapes) due to roads and other restrictions or redirections of flow. Entities, such as the Federal Geographic Data Committee (FGDC) in conjunction with a private company (i.e., Image Matters), have developed tools to assist wetland regulators with the jurisdictional decision making process (Davidson et al. 2009). These tools often assess the distance between mapped wetlands and streams using available datasets and spatial algorithms, but inaccurate stream data can hamper informed decision making and attempts to streamline the decision making process for regulators.

Digital elevation models (DEMs) derived from airborne Light Detection and Ranging (LiDAR) data have the potential to enhance our understanding of the location and characteristics of streams, especially lower order reaches in areas of subtle topographic variability. Previously, the spatial resolution of commonly available topographic data for the United States (vertical accuracies of 1–10 m) was insufficient to detect the small differences in elevation that are characteristic of many lower order streams and ditches. LiDAR-derived DEMs provide the vertical accuracy (15 cm–1 m, but typically closer to 15 cm; Murphy et al. 2007) and horizontal resolution (typically 50–200 cm) necessary to detect these small but ecologically important features. This information can be used to not only identify streams but to aid in the determination of their flow characteristics (e.g., intermittent versus ephemeral) through the assessment of channel width and depth, slope, landscape position, and other characteristics. LiDAR is a rapidly evolving remote sensing technology and is quickly becoming available for large portions of the U.S. Although not currently available for the entire U.S., a concerted effort is being made by U.S. federal, state, and other organizations to collect LiDAR data for the entire U.S. and it is likely that contiguous coverage will be available in the near-term.

The mapping of streams using DEMs can be accomplished through automated procedures or visual interpretation and hand digitization. A variety of methods have been developed to automatically delineate streams. The most common method generates stream lines based on user-determined thresholds of flow accumulation (Nardi et al. 2008). A number of flow routing algorithms have been developed to estimate flow accumulation but they generally seek to route hypothetical water from pixel to pixel based on slope. The user then selects a level of accumulation expressed as area beyond which a stream is likely to be present. Non-automated methods for DEM-based stream mapping involve hand digitization of stream channels based on the physical manifestation of the channel itself on the DEM with the support of ancillary data (e.g., aerial photographs).

In this article we investigate the impact of stream data source on the apparent spatial relationship between streams and wetlands in an area of low topographic variability and high anthropogenic modification of the hydrographic network in the Coastal Plain of Maryland. We specifically address the added information present in LiDAR-derived DEMs as compared with information present in aerial photography-derived stream maps. Finally, we determine the number and total area of wetlands that are connected to a perennial or intermittent stream network and whether or not wetlands with different hydrologic modifiers (Cowardin et al. 1979) are more or less likely to be connected to the stream network.

Methods

Study Site

The Tuckahoe Creek Watershed is a 398 km^2 subwatershed of the 1,756 km^2 Choptank River Watershed, located on Maryland's Eastern Shore within the Coastal Plain Physiographic Province (Fig. 1). The area is characterized by a humid, temperate climate with average annual precipitation of 120 cm/yr (Ator et al. 2005). Approximately 50% of annual precipitation is lost to the atmosphere via evapotranspiration while the remainder recharges ground water or enters streams via surface flow. Surface water levels vary throughout the year with peak expression in early spring (March/April) while levels of evapotranspiration are still relatively low. The watershed is relatively flat (max elevation <30 masl) and land cover is dominated by agriculture (~ 65%) with smaller amounts of forest (26%) and urban area (6%; Fisher et al. 2006). The vast majority of the area's wetlands are forested, including wetland depressions (e.g., Delmarva bays), wetland flats, and riparian wetlands. However, it is likely that the area of forested wetlands in the watershed was once much greater (Lang et al. 2008).

Geospatial Data

The analysis detailed in this paper used a combination of best available wetland maps for the study area (i.e., most recent and accurate), nationally available stream vector data (http://nhd.usgs.gov/), and in-house generated stream vector data derived primarily from a LiDAR based DEM. The Maryland Department of Natural Resources (MD-DNR) wetland map was used to represent wetland extent. This product was generated using the same classification system (i.e., Cowardin et al. 1979) and basic method utilized to create the U.S. Fish and Wildlife Service National Wetlands Inventory except that the MD-DNR wetland map was based on more recently collected, finer resolution aerial photographs

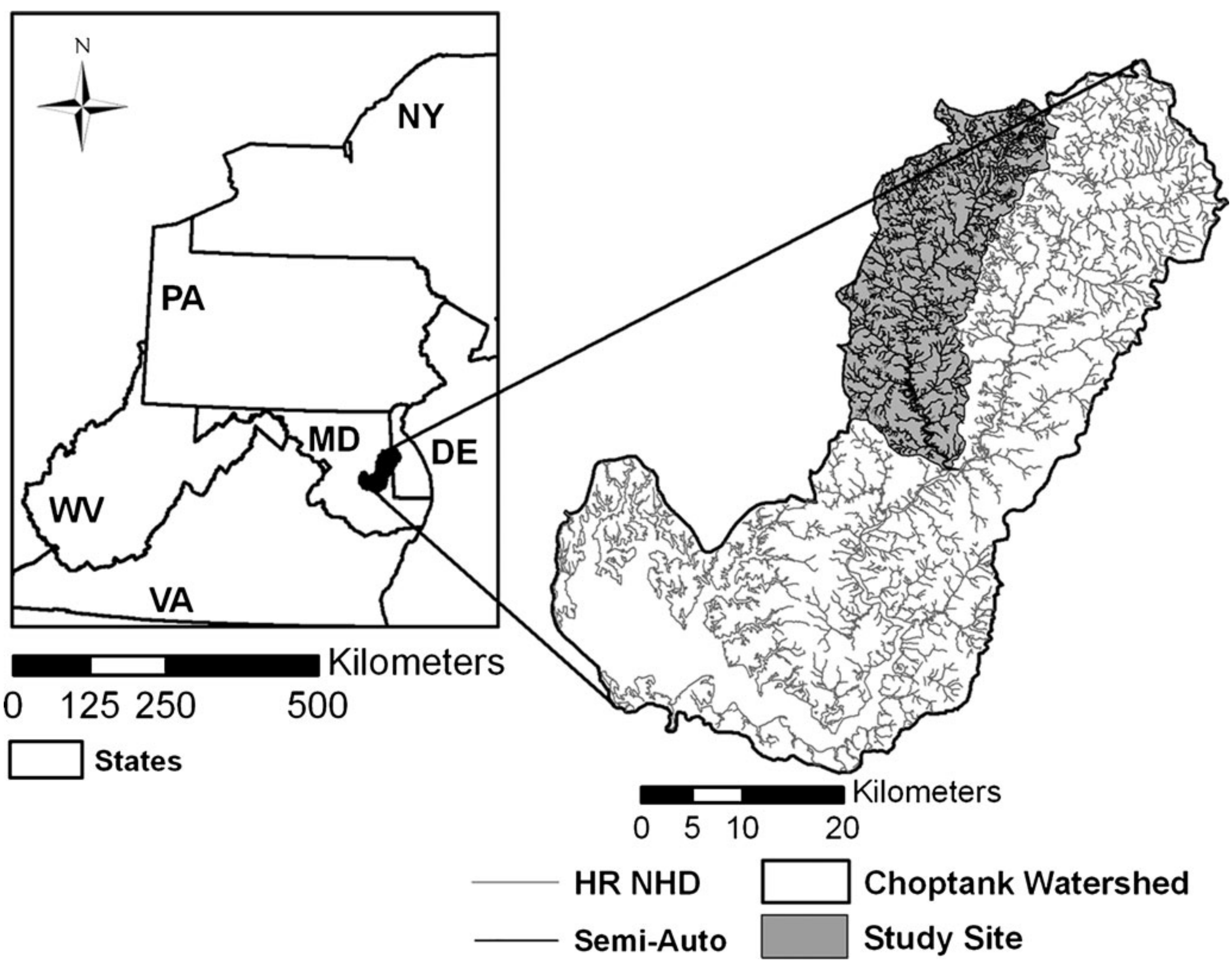

Fig. 1 The location of the study area

(late 1980s—early 1990s; 1:24,000). The National Hydrography Dataset (NHD) Plus and High Resolution are two different versions of the NHD which are generated at different scales. The NHD Plus is a recently edited version of the medium resolution NHD (1:100,000 scale; US Environmental Protection Agency and US Geological Survey 2010) and includes ~1,500,000 flow lines nationwide (personal communication; Jeff Simley, USGS). The NHD High Resolution (1:24,000) is a more detailed version of the NHD, containing ~20,000,000 flow lines nationwide (personal communication; Jeff Simley, USGS). Both versions of the NHD are primarily based on USGS topographic quadrangle maps originally created using aerial photography with field verification. These datasets were designed to meet or exceed National Map Accuracy Standards (Federal Geographic Data Committee 1998). At 1:24,000, features should be mapped within ~12 m of the feature on the ground for the hardcopy and ~14 m after scanning to digital for at least 90% of tested points. At 1:100,000, features should be mapped within ~51 m of the feature on the ground for the hardcopy and ~58 m after scanning to digital for at least 90% of tested points (US Geological Survey 2000). The LiDAR data used to derive the DEM used in this study were collected for the Maryland Department of Natural Resources during spring 2003 and spring 2006 (metadata hosted online: http://dnrweb.dnr.state.md.us/gis/data/lidar/). These datasets had a vertical accuracy of ≤18 cm RMSE and were designed to meet or exceed FGDC National Standards for Spatial Data Accuracy standards for data at 1:2,400. Estimated horizontal positional accuracy of point returns exceeds 50 cm.

Analysis

Bridges and other impediments to two-dimensional flow were eliminated before proceeding with the analysis. This technique facilitates the modeling of water movement across the landscape to more closely replicate actual flow. The adjusted bare earth point file was then rasterized to create a 1 m resolution DEM using inverse weighted distance interpolation and the DEM was clipped to the approximate spatial extent of the Tuckahoe Creek Watershed.

The adjusted bare earth DEM was used to create three stream vector products: 1) an automatically generated stream vector dataset with less detail (fewer lower order streams), 2) an automatically generated stream vector dataset with more detail (a great number of lower order streams), and 3) a semi-automated highly detailed stream vector dataset. ArcGIS ArcHydro (Environmental Systems Research Institute, Redlands, CA) tools were used to automatically delineate stream networks at flow accumulation thresholds of 100,000 and 300,000 pixels, 10 ha and 30 ha, respectively. The semi-automated stream product was created by hand editing the 300,000 threshold stream product. For the purpose of this exercise, streams were judged to be perennial or intermittent and therefore groundwater fed at some point during a year of normal precipitation when at least three of the following criteria were satisfied: 1) water appeared to be present within the channel on relatively recent (i.e., past decade) leaf-off aerial photography, 2) a vegetation buffer was present around the channel, 3) the channel was well defined and at least 0.5 m deep, 4) the channel was linear (i.e., likely human-made for the purpose of drainage) and connected a low-lying area to the stream network, 5) an area of similar elevation surrounding the channel contained wetlands, and 6) areas that appear to be similar were known to be perennial or intermittent streams based on ground observations. Streams that did not meet at least three of these six criteria (~48) were removed from the 300,000 threshold product. If they were not already present, channels meeting three of these six criteria (~1580) were added to the 300,000 threshold product by hand digitizing each additional channel to form the semi-automated stream product. The aerial photography used in the manual delineation process described directly above included: leaf-on National Aerial Imagery Program images collected during summer of 2007 and 2009 (100 cm; leaf-on), National Aerial Photography Program images collected during the spring of 1998 (leaf-off), and aerial photography data collected by the Canaan Valley Institute during the spring of 2007 (12 cm; leaf-off).

The semi-automated stream product was compared with the other stream datasets (NHD high resolution, NHD Plus, 100,000 threshold, and 300,000 threshold) to assess their character and accuracy relative to the semi-automated stream product. This was accomplished by comparing differences in overall mapped stream length and quantifying both errors of omission and commission relative to the semi-automated stream product. Accuracy was only considered for channels ≤25 m wide since it is highly probable that all stream datasets accurately delineated stream channels ≥25 m in width. Errors of omission were assessed by creating a file of over 5,000 randomly generated points that were buffered to 50 m in diameter, spaced at least 50 m apart along the entire length of the semi-automated stream dataset and then evaluating how many of these circular polygons intersected the stream dataset being assessed. If the polygon did not overlap with the stream dataset, it was considered to be an error of omission. Conversely, if it did intersect the stream dataset being considered, it was considered to be accurate. Errors of commission were assessed by creating a file of over 5,000 randomly generated points that were buffered to 50 m in diameter, spaced at least 50 m apart along the entire stream vector being assessed and then evaluating how many of these circular polygons intersected the semi-automated stream vector. If the polygon did not overlap with the semi-automated dataset, it was considered to be an error of commission. Conversely, if it did intersect the semi-automated dataset, it was considered to be accurate. Therefore all stream lines within 25 m of the semi-automated dataset in any direction were considered accurate. Overall accuracy was calculated by summing all correctly identified polygons using both approaches (i.e., omission and commission) and dividing by the total number of polygons. Ideally, validation would have been performed using ground delineation of streams, but this would have been time and cost prohibitive. Furthermore, the approach utilized in this study allows for a more robust comparison through the examination of many more locations than would have been possible on the ground, and is supported by multiple dates of leaf-on and leaf-off aerial photography as well as over a decade of in situ experience at the study site.

Wetland-stream connectivity between MD-DNR wetland polygons and multiple stream datasets was quantified using ArcGIS software. Only palustrine wetland polygons were used in the analysis since riverine and lacustrine wetlands are connected to waterbodies by definition and estuarine and marine wetlands were not present at the study site. Palustrine wetlands were initially divided into four groups based on special modifiers defined by the Cowardin classification system (Cowardin et al. 1979): 1) diked/impounded wetlands, 2) excavated wetlands, 3) farmed wetlands, and 4) semi-natural wetlands (no special modifier). Before analysis, the number of polygons in each class was recorded. Wetland polygons within each group were then aggregated using a threshold of 10 cm to combine multiple wetland polygons into one larger polygon when multiple polygons were directly adjacent to one another (i.e., abutting).

All stream line vectors were buffered 5 m, 10 m, 20 m, 40 m, and 80 m in each direction from the centerline before analysis. Aggregated wetland polygons and stream line vectors with and without buffering were then overlapped based on spatial location (i.e., joined) and only wetlands and streams that intersected one another were selected. The area of connected wetland polygons was then calculated to derive total area of aggregated wetland polygons connected to streams. Non-aggregated wetland polygon datasets were used to assess total number of polygons connected or adjacent to streams. This procedure was repeated using only the semi-automated stream dataset and semi-natural wetlands divided by hydrologic modifier to assess the relationship between hydrologic regime and wetland—stream connectivity. One-way Repeated Measures Analysis of Variance (ANOVA) was used to test for statistically significant differences between wetland connectivity detected by the different stream datasets and within the different wetland types. These tests were performed across connectivity measurements using six different buffer widths (i.e., repeated measures) and such measurements were considered to be autocorrelated. Multiple comparisons were performed using the Holm-Sidak method and pairwise comparisons were performed using the standard *t*-test. All analyses were performed using the statistical algorithms contained within SigmaPlot Ver. 11 (Systat Software, Inc., San Jose, CA).

Results

The total number of diked/impounded, excavated, farmed, and semi-natural wetland polygons in the entire study area was 31, 314, 609, and 2050, respectively, for a total of 3,004 wetland polygons. The total area of diked/impounded, excavated, farmed, and semi-natural wetland polygons in the entire study area was 67, 97, 413, and 4,870 ha, respectively, for a total of 5,447 ha. The accuracy of stream datasets relative to the semi-automated stream dataset varied considerably, as did total stream length (Table 1). As expected, wetland—stream connectivity varied based on wetland class, buffer width, and stream dataset used in the analysis (Table 2). When averaged across all buffer lengths using the semi-automated stream dataset, diked/impounded wetlands were most likely to be connected to the stream network (99% area, 89% number) followed by semi-natural wetlands (86% area, 63% number), farmed (69% area, 47% number) and excavated wetlands (65% area, 47% number). Comparisons of differences in these mean values were statistically significant ($P<0.05$) with the exception of the farmed vs, excavated wetland comparison. This pattern was similar across all stream datasets and remained consistent when wetland connectivity was considered according to area connected and number of wetland polygons connected. A greater percent of total wetland area within each class was found to be connected than percent total wetland number at the buffer widths examined but the difference decreased with increasing buffer width (Fig. 2). As expected, connectivity increased with increasing buffer width.

Wetland Area

The greatest total area of connected wetlands at all buffered distances (Table 2) was found using the semi-automated dataset when considering excavated and farmed wetlands

Table 1 Stream dataset accuracy as compared with the semi-automated stream dataset

	High Res. NHD	100,000 threshold	NHD plus	300,000 threshold
Omission error	49%	26%	77%	45%
Commission error	26%	24%	32%	4%
Overall error	37%	25%	54%	25%
% Length	66%	99%	31%	57%

Table 2 Percent of each wetland type by area and total number (second) connected to the different stream datasets. The total number of polygons analyzed for diked/impounded, excavated, farmed, and semi-natural wetlands was 31, 314, 609, and 2050, respectively. The total area of diked/impounded, excavated, farmed, and semi-natural wetland polygons in the entire study area was 67, 97, 413, and 4,870 ha, respectively, for a total of 5,447 ha

Buffer (m)	High Res. NHD (%)	100,000 Thresh. (%)	Semi- Auto. (%)	NDH Plus (%)	300,000 Thresh. (%)
	Diked				
0	99(84)	98(81)	97(81)	95(61)	96(74)
5	99(87)	98(81)	99(87)	95(65)	98(81)
10	99(87)	98(84)	99(90)	95(65)	98(84)
20	100(90)	98(87)	99(90)	95(68)	98(87)
40	100(97)	99(90)	100(94)	96(71)	99(90)
80	100(100)	100(94)	100(94)	96(77)	99(90)
	Excavated				
0	36(23)	42(22)	54(31)	20(15)	33(14)
5	39(27)	45(27)	57(37)	22(17)	34(18)
10	40(30)	47(31)	61(41)	27(19)	37(22)
20	44(36)	55(39)	67(49)	29(22)	42(29)
40	49(32)	64(47)	72(56)	34(26)	46(34)
80	62(48)	74(60)	78(66)	46(31)	56(41)
	Farmed				
0	28(13)	31(11)	50(25)	16(6)	16(5)
5	36(18)	38(16)	59(31)	16(6)	20(7)
10	42(22)	45(20)	65(38)	18(7)	23(9)
20	48(27)	54(29)	74(52)	22(9)	31(15)
40	56(36)	64(41)	83(64)	30(14)	39(22)
80	66(46)	72(51)	86(72)	40(20)	46(28)
	Semi-Natural				
0	66(44)	84(54)	79(53)	56(32)	71(42)
5	67(45)	86(57)	82(56)	57(33)	73(44)
10	68(47)	88(60)	85(60)	58(34)	75(47)
20	72(51)	90(64)	89(66)	59(36)	78(51)
40	75(55)	91(67)	90(69)	62(38)	80(53)
80	79(60)	94(73)	93(75)	64(41)	83(57)

(P<0.001) and the 100,000 threshold dataset when considering the semi-natural wetlands (P<0.001). Area of diked wetlands connected was ≥95% for all stream datasets, but was found to be highest (P<0.05) using the high resolution NHD (99.5%), and the semi-automated dataset (99.2%). The smallest total area of all connected wetland types was found at all buffered distances using NHD Plus (P<0.05). Variability (coefficient of variation) between percent total area of wetland connected to streams as measured using the different stream datasets was smallest for the diked/impounded wetlands, followed in order of increasing variability by semi-natural, excavated, and farmed wetlands, with this variability having the greatest impact on total wetland area connected for semi-natural wetlands due to their abundance (Fig. 3).

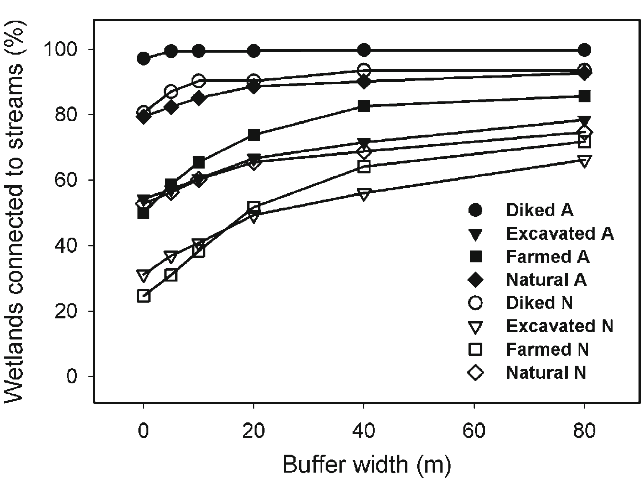

Fig. 2 Percent total area (A) and number (N) of wetlands connected to the semi-automated stream product with increasing buffer width for each wetland class

Wetland Number

The greatest number of connected wetlands was found using the semi-automated dataset at all buffer distances when considering excavated and farmed wetlands (P<0.001; Table 2). The semi-automated and 100,000 threshold stream datasets

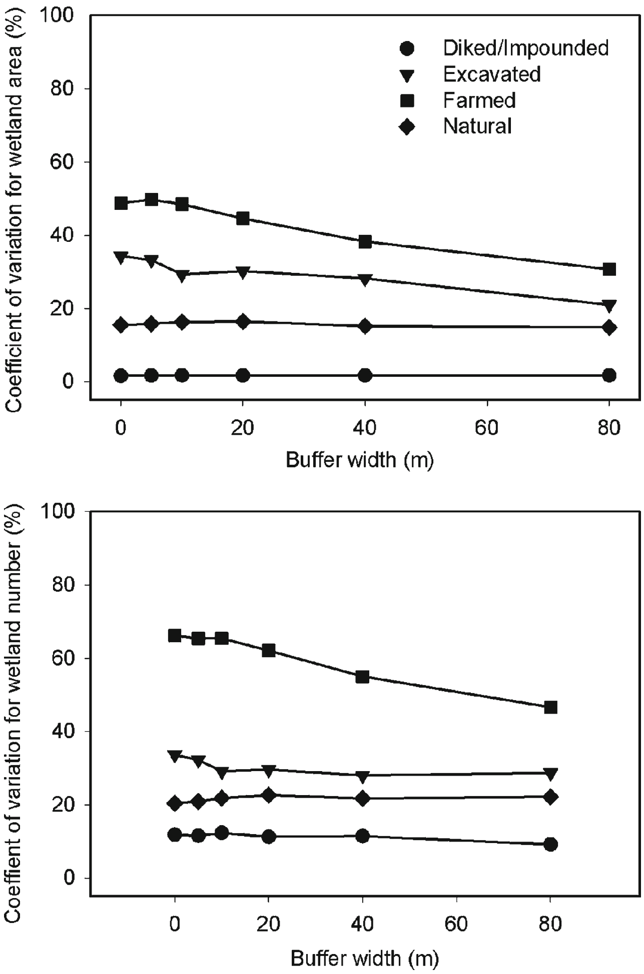

Fig. 3 Coefficients of variation for wetland-stream connectivity quantified by the five different stream datasets (semi-automated, high resolution NHD, NHD Plus, 100,000 threshold, and 300,000 threshold) with increasing buffer widths

identified the greatest number of connected semi-natural wetlands at all buffered distances ($P<0.001$). The smallest number of wetlands connected to streams was found using NHD Plus when considering diked/impounded $P<0.05$) and semi-natural wetlands ($P<0.001$). Variability (coefficient of variation) between percent total number of wetlands connected to streams as measured using the different stream datasets followed the same trend as demonstrated with percent area (Fig. 3).

Hydrologic Modifiers

Total number and area (ha; second number) of permanently flooded, intermittently exposed, semi-permanently flooded, seasonally flooded, seasonally flooded/saturated, temporarily flooded, and saturated wetlands in the study area were 327 (102), 15(4), 56 (73), 541 (1205), 261 (522), 1040 (2759), and 52 (83), respectively. Percent total area of semi-natural wetlands connected to the semi-automated stream dataset varied according to hydrologic regime more when shorter distances between wetlands and the semi-automated stream vector were considered (Table 3). Number of semi-natural wetlands connected to the stream network increased as buffer distance increased. Mean area of individual semi-natural wetland polygons connected to the stream network decreased as buffer distance increased from 0 to 80 m ($P<0.05$) with the exception of intermittently exposed wetlands ($P=0.39$), but the effect (linear model slope) on seasonally flooded/saturated wetlands was the greatest (Fig. 4).

Discussion

LiDAR-based DEMs provide a significant advantage when calculating wetland-stream connectivity at the landscape scale. The horizontal accuracy of most LiDAR based DEMs is much improved over the horizontal accuracy of digital USGS topographic quadrangles, which are the basis for the NHD, <1 m versus >18 m (NHD high resolution) or >58 m (NHD Plus). The improved horizontal accuracy of LiDAR based DEMs allows for a higher degree of horizontal accuracy in derived products (Fig. 5) while the addition of highly accurate vertical data allows improved detection of lower order streams and the characterization of these streams to aid in the differentiation of flow regimes (e.g., intermittent versus ephemeral). The ability to select an automated, non-automated, and hybrid approach to stream mapping provides flexibility to best meet project goals with limited resources. As is common, the choice between the different approaches would, to some degree, necessitate the weighing of effort and accuracy. However, the total accuracy of even the two LiDAR-based automatically generated stream datasets was higher than the NHD products: 25% (300,000 and 100,000 thresholds) versus 54% (NHD Plus) and 37% (NHD high resolution) error. These findings support those of Heine et al. (2004) who found that stream maps generated using flow accumulation thresholds based on a DEM were

Table 3 Percent of semi-natural wetlands with different hydrologic modifiers by area and total number (second) connected to the semi-automated stream dataset

0 m (%)	5 m (%)	10 m (%)	20 m (%)	40 m (%)	80 m (%)
56(32)	59(38)	62(42)	67(50)	72(57)	77(66)
19(20)	19(20)	35(27)	56(40)	56(40)	75(60)
85(25)	85(25)	85(27)	86(32)	87(34)	93(46)
61(30)	62(32)	67(35)	69(39)	74(46)	80(56)
77(19)	77(20)	78(22)	79(24)	81(28)	84(38)
68(44)	71(49)	75(55)	83(63)	86(67)	90(75)
49(29)	49(29)	49(29)	54(35)	58(40)	60(46)

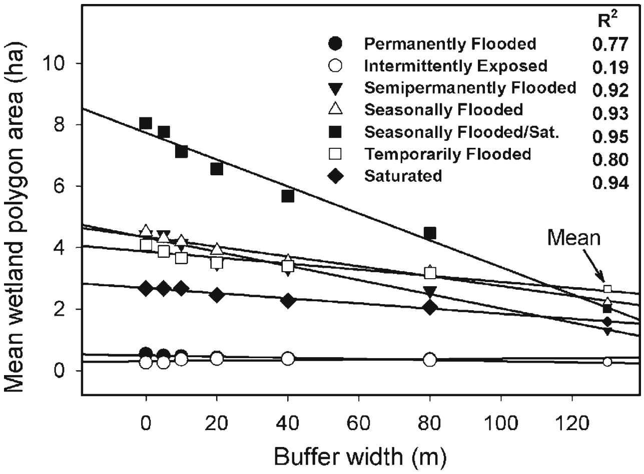

Fig. 4 Mean size of wetland polygons connected to the semi-automated stream dataset with increasing buffer width with overall class mean for different semi-natural wetland hydrologic modifiers. Note that the extrapolated linear models intercept the mean polygon areas for the different wetland types at a common distance of ~130 m

significantly more accurate than 1:24,000 stream maps based on aerial photograph interpretation. It is hypothesized that the accuracy of automatically generated LiDAR-based products could be improved further through the utilization of more advanced flow routing algorithms and perhaps by more informed selection of flow accumulation thresholds (Heine et al. 2004).

Computed stream length and error levels further support past studies which demonstrated high levels of omission in 1:24,000 aerial photography based stream maps (Heine et al. 2004; Roy et al. 2009). NHD is known to under represent stream length in wetter regions of the U.S. (personal communication; Jeff Simley, USGS), like the study area. It is therefore not surprising that the NHD high resolution dataset identified only 66% of stream length compared with the semi-automated product. However, the semi-automated dataset was designed to map streams with perennial and intermittent hydrology, not ephemeral hydrology, so percent exclusion of total stream length on the ground is likely higher. Errors contained within the NHD high resolution were primarily errors of omission (49%) rather than commission (26%). Such errors of omission could hinder the ability of scientists, managers, and regulators to assess wetland-stream connectivity at the landscape scale, leading many wetlands to incorrectly be considered disconnected from the stream network. However, the high rate of NHD commission errors is also notable (e.g., Fig. 5, image D) and could hamper efforts to determine wetland-stream connectivity remotely with high or perhaps even moderate levels of accuracy at this study site.

Due to a relatively high error rate (77% omission and 32% commission) and availability of the high resolution NHD product nationwide, it would be disadvantageous to use moderate resolution NHD products to judge wetland-stream connectivity at a local or even regional scale unless the improved attributing (e.g., mean annual stream flow and velocity) of NHD Plus was essential to project success. If that were the case, a dual high resolution/NHD Plus approach may be advisable to retain as much spatial accuracy as possible. Note the spatial offset of NHD Plus in Figure 5, image B and the improved correspondence of the high resolution NHD with the primary channel location (Fig. 5, image D). However, this gain in spatial correspondence is balanced with multiple errors of commission. In the future, the USGS and its partners plan to upgrade NHD Plus by incorporating a level of spatial detail closer to the high resolution NHD (Cooter et al. 2010).

The potential regulatory and ecologic implications of this study are strongest for the semi-natural wetlands class. The regulatory status of other wetland types (e.g., farmed wetlands) is generally guided by concepts other than “significant nexus” and since semi-natural wetlands are the most common type of wetland at the study site and arguably provide the greatest level of many ecosystem services per unit wetland, ecologic implications are also strong. Semi-natural wetlands exhibited high levels of connectivity to the 100,000 threshold and semi-automated products, relative to both NHD data sets. This increased connectivity resulted in a significantly greater area of wetlands deemed to be directly connected to streams. The slightly higher level of connectivity demonstrated by the 100,000 threshold data set relative to the semi-automated data set is likely due to the conservative nature of the semi-automated product paired with the tendency of the 100,000 threshold product to map even some ephemeral streams and areas of unchanneled preferential surface flow (Fig. 5, image C; unchanneled preferential flow through depressional wetlands). Although existing intermittently, non-perennial wetland-stream surface hydrologic connections can have a significant effect on downstream waters through the delivery of water, material, energy and organisms downstream, thereby supporting downstream communities (Richardson 2003; Leibowitz et al. 2008). Forested wetlands, which comprise the vast majority of semi-natural wetlands at this study site (Lang et al. 2008), are commonly believed to be under-mapped using aerial photography (e.g., Tiner 1990). Furthermore, wetland maps also have a minimum mapping area below which wetlands are not mapped (e.g., 0.4 ha for relatively recent NWI maps). Therefore, it can be assumed that more semi-natural wetlands are connected to surface waters than demonstrated through studies such as the one described herein.

Although semi-natural wetlands retain wetland hydrology by definition, it is not uncommon for them to be connected to the broader stream network via ditches, which may have been dug for flood control, mosquito abatement, and/or farming. As Sharitz (2003) and Richardson (2003)

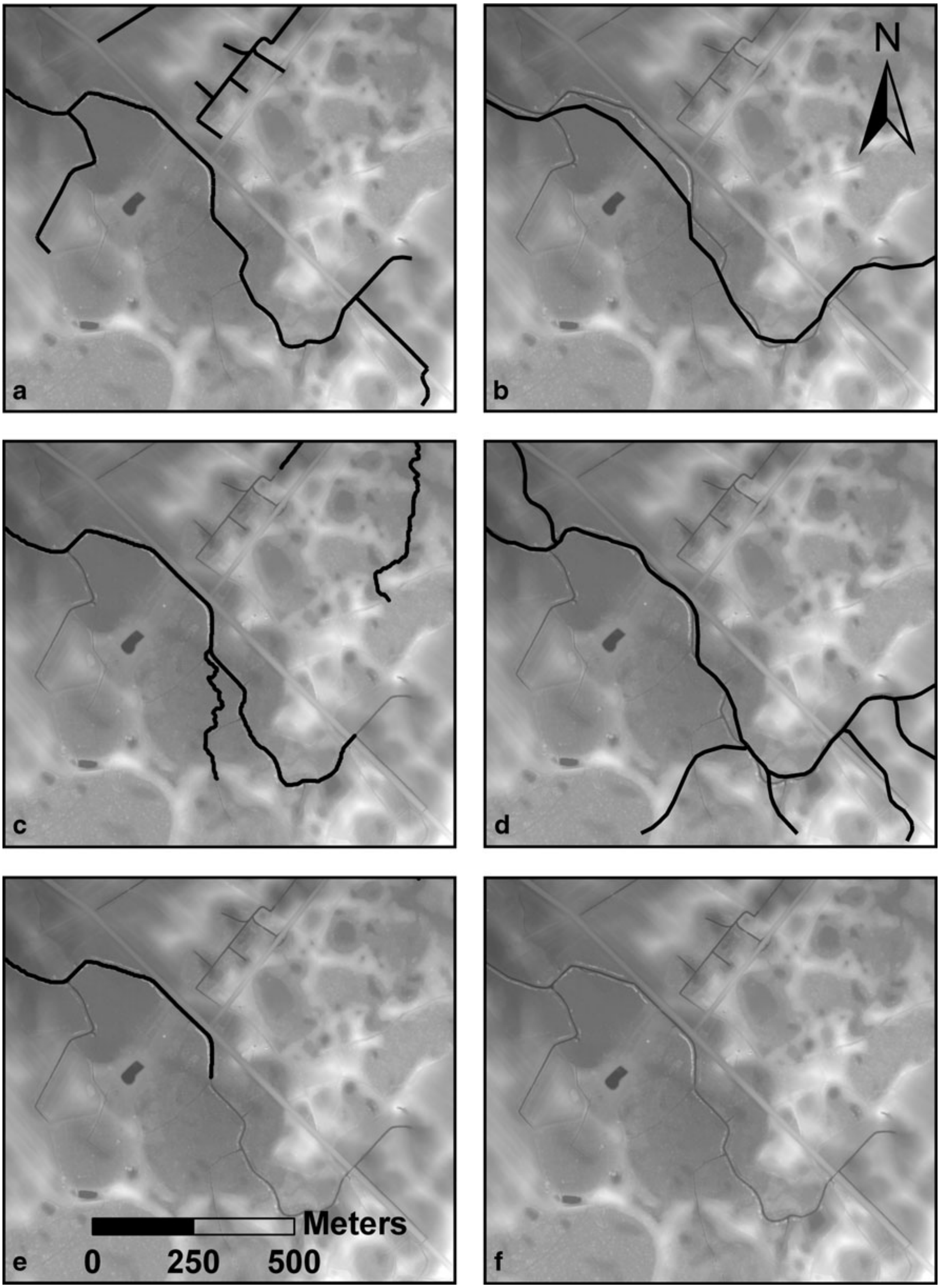

Fig. 5 LiDAR based DEM overlaid with five different stream products, including the semi-automated (**a**), NHD Plus (**b**), 100,000 threshold (**c**), high resolution NHD (**d**), and 300,000 threshold streams (**e**). A DEM without streams (**f**) is provided for comparison. Note that the stream channels are clearly evident on the DEM as narrow, dark, linear features. Circular depressions (*dark areas*) are generally current or historic wetlands

have pointed out, the presence of these ditches could potentially lead to the protection of wetlands that would otherwise be considered isolated and therefore not regulatory. LiDAR is vital to the remote detection of many of these ditches since aerial photography can often only be used to detect the largest ditches, especially where obscured by a plant canopy (e.g., forests). The high resolution NHD portrays ditches as a representative pattern, including ditches that were practical to map at the 1:24,000 scale (personal communication; Jeff Simley, USGS). It is hypothesized that the difficulty of mapping relatively small ditches at the 1:24,000 scale explains a large portion of the difference in stream length between the high resolution NHD and the semi-automated product (Fig. 5, images A and D).

Of all the wetland types examined, farmed and excavated wetlands were least likely to be connected to the perennial or intermittent stream network when all types of stream data were considered. We hypothesize that farmed wetlands were less likely to be connected to streams partially because small wetlands that are isolated from other areas of surface water accumulation are easier to convert to agriculture, but also because the small ditches which commonly drain these areas are often poorly mapped. This is partially explained by the fact that these small ditches often travel through topographic highs making them less likely to be mapped using automated processes based on flow accumulation and these ditches are often short and NHD does not always map stream segments less than 1.6 km in length (USGS 2000; Fig. 5). However, it may become easier to map these ditches in the future since automated approaches for mapping ditches using DEMs are being developed (Bailly et al. 2008).

Although the jurisdictional status of farmed wetlands is not likely to be judged based on the "significant nexus" concept, it is worthwhile to note their landscape position as it has a considerable impact on the influence of these wetlands on the structure and function of adjacent ecosystems, particularly streams. Although many of these wetlands are drier than native wetlands, they may still provide ecosystem services (Ullah and Faulkner 2006). The presence of wetlands on agricultural fields and the impact of these wetlands on stream health is likely much larger than may be inferred using the Maryland DNR wetlands dataset, since only a small portion of currently farmed, historically natural wetlands are mapped using this dataset.

Different types of wetlands were found to be more likely to be connected than others, but within all wetland types a greater percent of total wetland area was found to be connected than total wetland number (Fig. 2). The greater total connectivity of wetland area relative to number is supported by multiple studies (Sharitz 2003; Tiner 2003; Vance 2009) and is directly related to the relationship between wetland size and connectivity. That is, if wetlands are randomly placed on the landscape, larger wetlands are more likely to intersect the stream network than smaller wetlands. This trend is probably even more significant than our data or the data of other studies suggest since the smallest of wetlands are not mapped. This relationship is further emphasized in Figure 4, which demonstrates that the average size of connected wetland polygons decreases with increasing buffer width and that the strength of this relationship varies between semi-natural wetlands with different hydrologic modifiers as defined by Cowardin et al. (1979). Therefore, buffer width is an important consideration which influences not only the amount of wetlands deemed connected to streams but also the character of those wetlands. If connectivity judged in this manner was used to assign wetland regulatory status and non-regulatory wetlands were lost, the loss of smaller wetlands could have significant ecologic ramifications. Figure 4 suggests that the predisposition of smaller buffer width towards recognizing larger wetlands as connected can be avoided at the study site by selecting a buffer width of ≥130 m. Small, so-called geographically "isolated" wetlands tend to be hotspots of biodiversity (Leibowitz 2003). Loss of small isolated wetlands not only results in destruction of these biologically diverse habitats, but may also disproportionately affect the ability of certain species to disperse and maintain sufficient genetic diversity through metapopulations (Gibbs 1993; Semlitsch and Bodie 1998).

Past studies have defined various distances (e.g., buffer widths) between wetlands and streams as meeting the definition of connectivity. Selected buffer widths vary from 5 to 1,000 m. A study by Levin et al. (2002) as part of the Illinois Natural History Survey deemed wetlands greater than 76 m from a stream or 100 year floodplain as isolated. Other studies used distances of 10 m (Frohn et al. 2009; Reif and Frohn 2009), 20 and 40 m (Tiner 2003), 5 and 10 m (John Dorney 2011, personal communication), and 20 or 40 m from smaller streams and 300 m from larger streams (Vance 2009). The Association of State Wetland Managers suggests using distances starting at 12 m when using 1:24,000 scale stream data and 50 m when using 1:100,000 scale stream data and then repeating the analysis using thresholds of 100, 500 and 1,000 m (http://www.aswm.org/fwp/swancc/gis-swan.htm). The 12 and 50 m distances generally correspond to the accuracy of high resolution NHD and NHD Plus, respectively. Therefore it is assumed that these distances were selected based on accuracy of the stream product. As demonstrated by the study described herein, the selection of different buffer widths has a significant influence on percent wetlands judged to be connected to streams. A study conducted by Sharitz 2003 used buffer widths of 50, 100, 500 and 1,000 m resulting in percent total number of Carolina bays connected to the NHD of 8%, 12%, 66%, and 91% at the Savannah River Site in South Carolina. Note that this study focused exclusively on depressional wetlands and excluded ditches from the analysis. Although spatial accuracy of input datasets should be considered when determining ideal buffer width and comparability between studies is certainly a consideration, buffer width should ideally be connected to ecologic considerations. When considering the connectivity of a wetland to other wetlands or streams, Leibowitz (2003) suggests connectivity be defined with regard to a specific process or particular organism and not considered a "generic" trait of the wetland.

Similarly, the character of the connection or "significant nexus" may partially be inferred from the distance over which the two ecosystems are connected (Fig. 6). This fact would argue for the selection and analysis of multiple buffer widths, to better characterize different ecologic functions that are served across these distances. For example, wetlands in close proximity to streams may exchange water and dissolved constituents (e.g., carbon and nutrients) via the hyporheic zone, a subsurface area adjacent to the stream channel where stream and local groundwaters mix. This mixing can have a substantial effect on the quality of stream water (Naiman et al. 2002). The extent of the hyporheic zone is primarily controlled by hydraulic gradients and the character and distribution of alluvial deposits (Morrice et al. 1997). However, in headwater areas with low topographic variability similar to the Tuckahoe Creek Watershed, stream-wetland connections via the hyporheic zone can be expected on the order of meters instead of 10s of meters. On the other hand, many of the wetlands in the study area are recharge wetlands (i.e., water flows from wetland to groundwater) for at least part of the year and groundwater is known to be able to travel for hundreds of meters before entering a stream, thus sustaining base-flow (Winter and LaBaugh 2003). In a stream-wetland connectivity study conducted in 2009, Vance assumed that any wetland that was within 20 m of a perennial or intermittent stream had a permanent or stable surface or groundwater connection with the adjacent stream. Flora and fauna are also capable of moving between wetlands and streams, either passively (flora or fauna) or actively (fauna). The distance over which biota can be expected to move between wetlands and streams

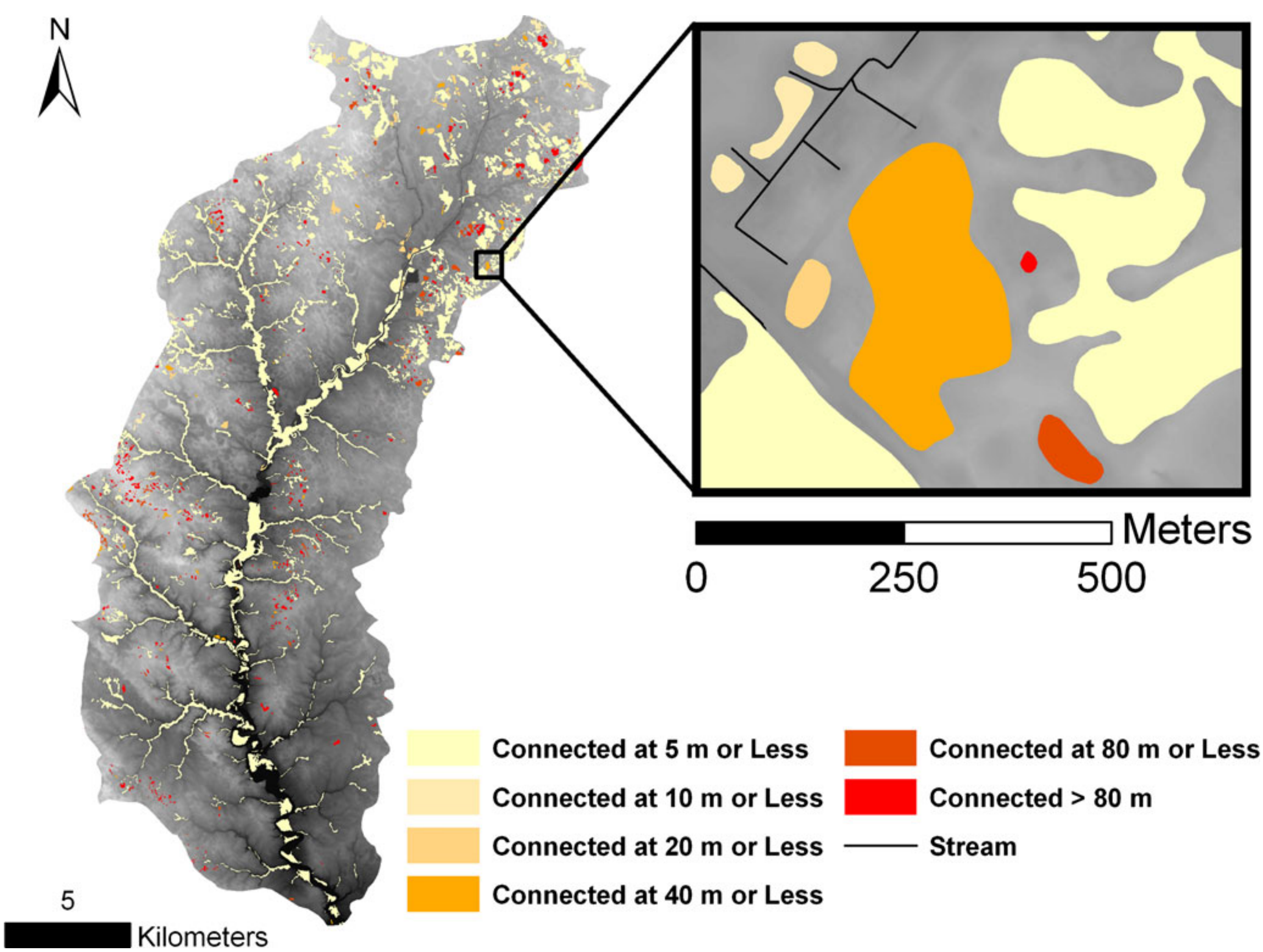

Fig. 6 DEM for the Tuckahoe Creek Watershed overlaid with wetland polygons that are connected to the semi-automated stream data set at various distances

varies according to species (Leibowitz 2003), but it would not be uncommon for an amphibian to travel tens if not hundreds of meters between surface water habitats (Gibbs 1993). Therefore, even wetlands identified as being over 80 m from streams may still significantly influence nearby streams. The creation of maps depicting connectivity of wetlands at different buffer widths (e.g., Fig. 6) pared with information on the type of ecologic connection expected for different wetland types at certain distances could provide a framework which would help classify wetlands as to the type of "significant nexus" that could be expected, thus easing regulatory determinations, assisting ecologic modeling, and helping to guide the development of decision support tools focused on the provision of ecosystem services.

Conclusions

The importance of wetland–stream connectivity has been heightened due to the current dependence of wetland regulatory status on this connectivity, although the importance of wetland function to adjacent stream health has been and will continue to be substantial regardless of government policies and regulations. LiDAR based DEMs can be used to significantly improve the accuracy of wetland-stream connectivity determinations at multiple scales, where LiDAR data are available. The degree of accuracy gained through the inclusion of LiDAR based information is likely to vary across the landscape based on a number of variables including physiographic region, finer scale geomorphology, human alteration, and meteorological conditions. If not available, users of aerial photography based data sets (e.g., NHD) should be aware of the limitations of these data and communicate these limitations to data users.

Acknowledgments This research was supported by the Wetlands Component of the USDA Natural Resources Conservation Service Conservation Effects Assessment Project. Thanks goes to Steve Strano, William Effland, Jeanne Christie, and Stephen Samuels for reviewing an initial draft of this article and to Andrew Russ for geospatial technical support. All trade names are included for the benefit of the reader and do not imply an endorsement of or preference for the product listed by the U.S. Department of Agriculture.

References

Ator S, Denver J, Krantz D, Newell W, Martucci S (2005) A surficial hydrogeologic framework for the Mid-Alantic Coastal Plain. U. S. Department of the Interior

Bailly J, Lagacherie P, Millier C, Puech C, Kosuth P (2008) Agrarian landscapes linear features detection from LiDAR: application to artificial drainage networks. International Journal of Remote Sensing 29:3489–3508

Bedford B, Godwin K (2003) Fens of the United States: distribution, characteristics, and scientific connection versus legal isolation. Wetlands 23:608–629

Cooter W, Rineer J, Bergenroth B (2010) A nationally consistent NDHplus framework for identifying interstate waters: implication for integrated assessments and interjurisdictional TMDLs. Environmental Management 46:510–524

Cowardin L, Carter V, Golet F, LaRoe E (1979) Classification of wetlands and deepwater habitats of the United States. U.S. Fish and Wildlife Service, Washington, DC

Davidson J, Dabolt T, Wilen B (2009) NSDI cooperative agreements program category 2: best practices in geospatial service oriented architecture (SOA). Available via http://www.fgdc.gov/grants/2008CAP/Reports/035-08-2-VA-FinalReport.pdf. Accessed 5 Jan 2012

Federal Geographic Data Committee (1998) Geospatial positioning accuracy standards: part 3: national standard for spatial data accuracy. Available via http://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part3/chapter3. Accessed 5 Jan 2012

Fisher T, Benitez J, Lee K, Sutton A (2006) History of land cover change and biogeochemical impacts in the Choptank River basin in the mid-Atlantic region of the US. International Journal of Remote Sensing 27:3683–3703

Frohn R, Reif M, Lane C, Autrey B (2009) Satellite remote sensing of isolated wetlands using object-oriented classification of landsat-7 data. Wetlands 29:931–941

Gibbs J (1993) Importance of small wetlands for the persistance of local-populations of wetland-associated animals. Wetlands 13:25–31

Heine R, Lant C, Sengupta R (2004) Development and comparison of approaches for automated mapping of stream channel networks. Annals of the Association of American Geographers 94:477–490

Lang M, McCarty G, Ritchie J, Sadeghi A, Hively W, Eckles S (2008) Radar monitoring of wetland hydrology: dynamic information for the assessment of ecosystem services. Proceedings of the 2008 IEEE International Geoscience & Remote Sensing Symposium I 261–I 264

Leibowitz S (2003) Isolated wetlands and their functions: an ecological perspective. Wetlands 23:517–531

Leibowitz S, Wigington P, Rains M, Downing D (2008) Non-navigable streams and adjacent wetlands: addressing science needs following the Supreme Court's Rapanos decision. Frontiers in Ecology and the Environment 6:366–373

Levin G, Suloway L, Plocher A, Hutto F, Miner J, Phillips C, Agarwal J, Lin Y (2002) Status and function of isolated wetlands in Illinois. Illinois Natural History Survey, Champaign

Meyer J, Wallace J (2001) Lost linkages and lotic ecology: rediscovering small streams. Ecology: Achievement and Challenge 295–317

Morrice J, Valett H, Dahm C, Campana M (1997) Alluvial characteristics, groundwater-surface water exchange and hydrological retention in headwater streams. Hydrological Processes 11:253–267

Mueller J (1979) Problems in the definition and measurement of stream length. The Professional Geographer 31:306–311

Murphy P, Ogilvie J, Connor K, Arpl P (2007) Mapping wetlands: a comparison of two different approaches for New Brunswick, Canada. Wetlands 27:846–854

Nadeau T, Rains M (2007) Hydrological connectivity of headwaters to downstream waters: introduction to the featured collection. Journal of the American Water Resources Association 43:1–4

Naiman R, Bilby R, Schindler D, Helfield J (2002) Pacific salmon, nutrients, and the dynamics of freshwater and riparian ecosystems. Ecosystems 5:399–417

Nardi F, Grimaldi S, Santini M, Petroselli A, Ubertini L (2008) Hydrogeomorphic properties of simulated drainage patterns using digital elevation models: the flat area issue. Hydrological Sciences Journal-Journal Des Sciences Hydrologiques 53:1176–1193

Reif M, Frohn R (2009) Mapping isolated wetlands in a karst landscape: GIS and remote sensing methods. GIScience and Remote Sensing 64:187–211

Richardson C (2003) Pocosins: hydrologically isolated or integrated wetlands on the landscape? Wetlands 23:563–576

Robb J (2002) Estimating Indiana's isolated waters through geographic information systems. National Wetlands Newsletter 24:9–12

Roy A, Dybas A, Fritz K, Lubbers H (2009) Urbanization affects the extent and hydrologic permanence of headwater streams in a Midwestern US metropolitan area. Journal of the North American Benthological Society 28:911–928

Semlitsch R, Bodie J (1998) Are small, isolated wetlands expendable? Conservation Biology 12:1129–1133

Sharitz R (2003) Carolina bay wetlands: unique habitats of the southeastern United States. Wetlands 23:550–562

Tiner R (1990) Use of high-altitude aerial-photography for inventorying forested wetlands in the United States. Forest Ecology and Management 33–4:593–604

Tiner R (2003) Estimated extent of geographically isolated wetlands in selected areas of the United States. Wetlands 23:636–652

Ullah S, Faulkner S (2006) Denitrification potential of different landuse types in an agricultural watershed, lower Mississippi valley. Ecological Engineering 28:131–140

US Environmental Protection Agency and United States Geological Survey (2010) NHD Plus user guide. Available via ftp://ftp.horizon-systems.com/NHDPlus/documentation/NHDPLUS_UserGuide.pdf. Accessed 5 Jan 2012

US Geological Survey (2000) The national hydrography dataset concepts and content. Available via http://nhd.usgs.gov/chapter1/chp1_data_users_guide.pdf. Accessed 5 Jan 2012

Vance L (2009) Geographically isolated wetlands and intermittent/ephemeral streams in Montana: extent, distribution, and function. Montana National Heritage Program. Available via http://mtnhp.org/reports/Isolated_Wetlands.pdf. Accessed 5 Jan 2012

Winter T, LaBaugh J (2003) Hydrologic considerations in defining isolated wetlands. Wetlands 23:532–540