



# Surface Hydrologic Connectivity Between Delmarva Bay Wetlands and Nearby Streams Along a Gradient of Agricultural Alteration

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**Abstract** Although recent U.S. Supreme Court rulings indicate surface hydrologic connectivity (SHC) between geographically isolated wetlands and nearby streams may be used, in part, to determine wetland jurisdictional status, and ecologic implications are considerable regardless of policies, wetland–stream SHC has rarely been quantified. Furthermore, the impact of cultivation and restoration on wetland–stream SHC is largely unknown. To help fill these knowledge gaps, we recorded SHC patterns during water year 2010 in non-perennial streams connecting Delmarva bay wetlands, which are commonly considered geographically isolated, and nearby perennial streams. We also evaluated how hydrologic wetland restoration impacts SHC relative to historical wetlands and native forested wetlands. Cumulative connection duration, number of connectivity transitions, mean connection duration, and maximum individual connection duration ( $D_{max-c}$ ) were quantified. Forested wetlands were connected to perennial streams for a greater cumulative duration but exhibited fewer connectivity transitions relative to both historical and restored wetlands. SHC between historical and restored wetlands and nearby perennial streams did not differ with respect to any of the calculated metrics. Forested wetland–stream SHC was

seasonally intermittent, exhibiting stream outflow from mid-fall to late-spring during periods of low evapotranspiration and elevated groundwater levels but lacking connectivity during summer months when evapotranspiration and groundwater were at an annual high and low, respectively. Historical and restored wetland–stream SHC was largely ephemeral, occurring in response to antecedent rainfall, particularly during winter and spring. Stepwise regression models describe cumulative connection duration and  $D_{max-c}$  as a function of wetland, watershed, and non-perennial stream metrics including watershed relief, non-perennial stream slope, non-perennial stream length, and soil saturated hydraulic conductivity. Wetland–stream SHC has potential ecological implications, including provision of dispersal corridors for biota, biogeochemical processing of nutrients, and downstream delivery of energy, matter, and organisms, and is currently tied to wetland regulatory status in the U.S.

**Keywords** Geographically isolated wetlands · Non-perennial streams · Delmarva bays · Wetland restoration · Surface hydrologic connectivity

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## Introduction

Wetlands exist along a continuum of surface hydrologic connectivity (SHC) from isolated to directly integrated with nearby waters (Leibowitz 2003). This continuum of connectivity is relative and can be defined with respect to geography, hydrology, and/or ecology (Tiner 2003). Tiner (2003) defines *geographically isolated* wetlands as those completely surrounded by upland. It is estimated that 81 of 276 wetland types in the U.S. may be considered geographically isolated (Comer et al. 2005).

Although typically small in size (Tiner et al. 2002), geographically isolated wetlands support a variety of ecosystem

functions including enhanced biogeochemical cycling, flood-water storage, groundwater recharge, habitat provision, and metapopulation support for a diverse biological community (Leibowitz 2003, Comer et al. 2005, Gibbons 2003). While the name implies they are disconnected, geographically isolated wetlands may be linked to other surface waters via groundwater, shallow subsurface flow, episodic basin fill and spill, or non-perennial stream flow (Tiner 2003, Winter and LaBaugh 2003, Wilcox et al. 2011), and there may be ecologically significant exchanges of material and energy along these flowpaths (Gibbons 2003, Leibowitz et al. 2008). Hydrologic connections between geographically isolated wetlands and other waters may facilitate carbon and nutrient transport (Nessel and Bayley 1984, Wise et al. 2000) and enable dispersal of aquatic flora (Galatowitsch and van der Valk 1996) and fauna (Babbitt and Tanner 2000). Geographically isolated wetlands may at times sustain baseflow in nearby headwaters (Sharitz 2003) and provide significant water quality benefits to receiving waters (Whigham and Jordan 2003).

While subsurface connections between geographically isolated wetlands and other waters have been reported elsewhere (e.g., Winter and LaBaugh 2003, Rains et al. 2006, Min et al. 2010), surface connections have rarely been quantified (but see Wilcox et al. 2011). Although knowledge of geographically isolated wetland–stream connectivity is generally limited, interest in the hydrological and ecological links between geographically isolated wetlands and nearby stream networks is growing (Leibowitz and Nadeau 2003, Leibowitz et al. 2008, Wilcox et al. 2011, Lane et al. 2012, Lang et al. 2012, Golden et al. 2014), in part sparked by recent U.S. Supreme Court cases creating new legal standards for determining the regulatory status of wetlands and non-perennial streams under Section 404 of the Clean Water Act (Leibowitz et al. 2008). In 2001, the Supreme Court ruled in *Solid Waste Agency of Northern Cook County (SWANCC) v. the U.S. Army Corps of Engineers* (531 US 159) that waters, including wetlands, could not be considered jurisdictional on the sole basis of their use by migratory birds (see Downing et al. 2003). Subsequently, in 2006 the Supreme Court ruled in *Rapanos v. United States* (547 US 715) that a non-navigable stream or wetland may be under Clean Water Act jurisdiction if it significantly affects the chemical, physical, or biological integrity of navigable waters (i.e., possesses a “significant nexus”) or has a relatively permanent connection to a navigable water by surface flow. In light of the extent, ecological value, and uncertainties surrounding the jurisdictional status of geographically isolated wetlands, methods to assess hydrological connections between geographically isolated wetlands and other waters are needed (Leibowitz 2003, Golden et al. 2014).

While we are aware of no studies quantifying geographically isolated wetland loss, Dahl (1990) estimated half of all wetlands in the U.S. have been lost since European settlement.

A recent study of potentially geographically isolated wetland occurrence and condition across eight southeastern and mid-Atlantic U.S. states estimated potentially isolated wetlands average 9 % of total freshwater habitat area by state and, of those, half are impacted by human land use (Lane et al. 2012). Regardless of connectivity, a majority of wetland loss is attributed to drainage for agriculture (Mitsch and Gosselink 2000). To promote wetland ecosystem services and mitigate loss, wetland restoration has become common in cultivated landscapes and typically aims to reestablish reference wetland hydrology, a master variable with respect to wetland ecological structure and function (Mitsch and Gosselink 2000). The impact of restoration on wetland function, including connectivity to nearby waters, is particularly understudied.

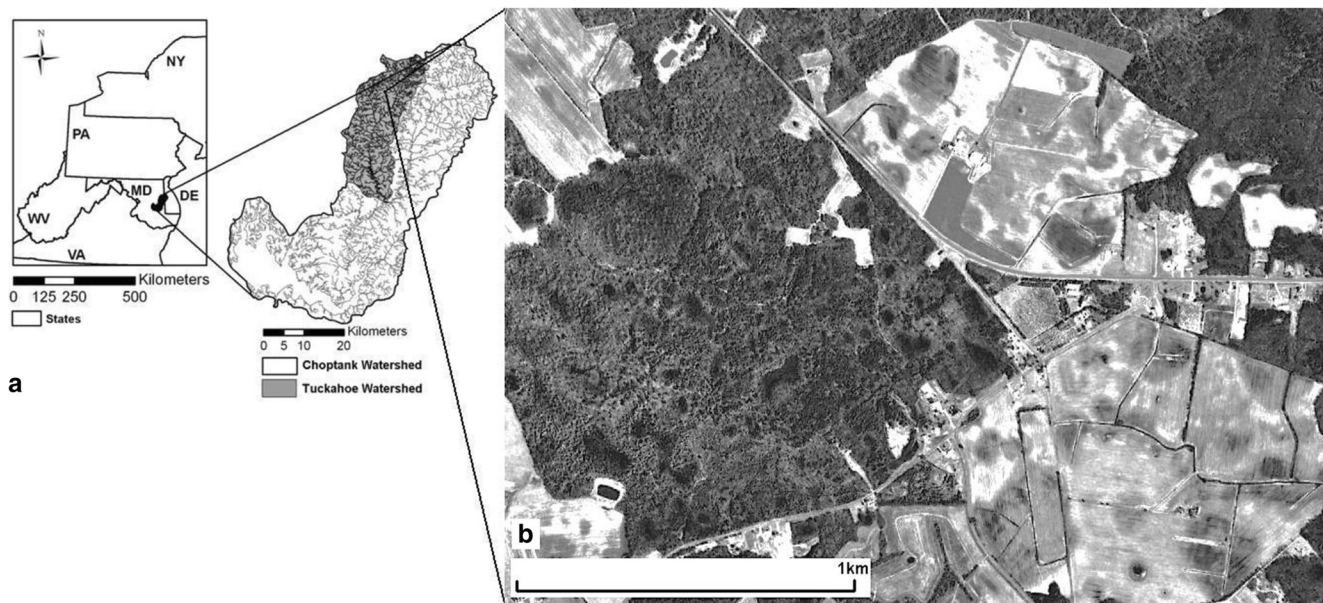
To help fill these knowledge gaps, we quantified SHC patterns between Delmarva bay wetlands, which are commonly considered to be geographically isolated (Tiner 2003), and nearby perennial streams on the Delmarva Peninsula, Maryland, USA, where wetland loss is estimated at 73 % statewide since 1780 (Dahl 1990). We also evaluated how hydrologic wetland restoration affects SHC relative to native forested wetlands and historical wetlands (i.e., *prior-converted croplands*: wetlands converted from a non-agricultural use to production of a commodity crop prior to December 23, 1985 [Code of Federal Regulations - Title 7: Agriculture; 12.2]).

## Methods

### Site Descriptions

This study was conducted in Coastal Plain non-perennial streams connecting forested, historical, and restored Delmarva bay wetlands to nearby perennial streams in the headwaters of the Tuckahoe Creek watershed, a sub-basin within the Choptank River watershed (Fig. 1a). Nearly 65 % of the Choptank catchment is in agricultural use, with smaller amounts of forest (26 %) and urban (6 %) land cover (Fisher et al. 2006, Fry et al. 2011). The region is characterized by a humid, temperate climate with average water year precipitation of 112 cm  $\pm$  3.2 cm (mean,  $\pm$  SE) distributed uniformly throughout the water year (1981–2010 30-year normals at Goldsboro, MD; PRISM climate mapping system [[www.prism.oregonstate.edu](http://www.prism.oregonstate.edu)]).

Delmarva bays are typically elliptical depressions surrounded by a sandy upland rim (Tiner and Burke 1995). It is estimated that Delmarva bays originated between 16,000 and 21,000 years ago as saturated spots in interdunal areas or wind blowouts in sand barrens (Stolt and Rabenhorst 1987). Dominant tree species in forested bays throughout the region include red maple (*Acer rubrum*), sweetgum (*Liquidambar styraciflua*), American holly (*Ilex opaca*), and red oak



**Fig. 1** **a** The Tuckahoe Creek watershed and stream network, a sub-basin of the Choptank River watershed in Maryland, USA. **b** Depressional wetlands known as Delmarva bays are common throughout the Tuckahoe

Creek watershed (near Goldsboro, MD); left side of photo shows native forested Delmarva bays, right shows historical Delmarva bays that have been drained for agriculture

(*Quercus rubra*), and the understory is dominated by roundleaf greenbrier (*Smilax rotundifolia*), coastal sweetpepperbush (*Clethra alnifolia*), and swamp doghobble (*Eubotrys racemosa*) (Yepsen et al. 2014). Delmarva bays support high biological diversity, including two-thirds of all amphibian species found across the peninsula and more than 60 rare vascular plants (Sipple 1999).

Delmarva bays are ubiquitous on the Delmarva Peninsula (Fig. 1b), numbering some 17,000 bays peninsula-wide (Fenstermacher et al. 2014). Lang et al. (2012) estimate there to be 2,050 semi-natural wetlands within the Tuckahoe Creek watershed, many of which are Delmarva bays. Many Delmarva bays can be characterized as geographically isolated (Tiner 2003), while others may be connected to nearby surface waters by streams, wetlands, or other non-upland land cover. Semi-automated stream mapping, based on light detection and ranging (LiDAR) digital elevation maps, revealed 53 % of semi-natural wetlands (by total number) were physically connected to streams (Lang et al. 2012), and thus do not fit the definition of geographic isolation (Tiner 2003). Alternatively, the same map showed 25 % of semi-natural wetlands in the watershed to be >80 m from the nearest stream. In their study, Lang et al. (2012) provide strong evidence that Delmarva bays exist along an isolation-connectivity continuum (Leibowitz 2003). In addition to accurate maps (Lane et al. 2012, Lang et al. 2012), differences in wetland-stream SHC help define the gradient from isolation to integration (Leibowitz 2003). In their native state, Delmarva bays typically serve as discharge areas from late fall through late spring when evapotranspiration is low, and recharge basins during summer months when evapotranspiration is high (Phillips and Shedlock 1993).

Due in part to agricultural ditching (Fig. 1b), Delmarva bays are among the most threatened ecosystems on the peninsula (McAvoy and Bowman 2002), where it is estimated that 65 % of bays have been impacted by agriculture (Fenstermacher et al. 2014). In our study, historical wetlands are prior-converted croplands drained via ditches, cultivated, and exhibiting brief periods of standing water following rainfall events. Historical wetlands in the region are dominated by conventional row crops corn (*Zea mays*) and soybean (*Glycine max*) (Yepsen et al. 2014).

In response to agricultural losses and the desire to increase the provision of wetland ecosystem services, USDA-sponsored hydrological restoration of wetlands in cultivated landscapes, including the Delmarva Peninsula, has become increasingly common (USDA Natural Resources Conservation Service 2009). We define restored wetlands as those that have been removed from active agricultural use and have had a more natural wetland hydroperiod restored through a variety of methods, including plugging ditches with earthen mounds. Dominant vegetation in restored wetlands in the region consists of sedges, grasses, and herbs, including common rush (*Juncus effuses*), marsh seedbox (*Ludwigia palustris*), barnyardgrass (*Echinochloa crus-galli*), and beggarticks (*Bidens* sp.) (Yepsen et al. 2014). Mature forested upland canopy had not yet developed at any of the restored sites addressed in this study.

Four forested (F1-F4), four historical (H1-H4), and three hydrologically restored (R1-R3) Delmarva bay wetlands were selected for this study. Sites were chosen based upon position within the same watershed (i.e., Tuckahoe Creek watershed), receipt of permission to work on the property, and exhibition

of characteristics indicative of Delmarva bays (e.g., elliptical shape, upland rim, alternating seasonal hydrology). Wetlands R1 and R2 were restored in 2002, and R3 was restored in 2003 (USDA Natural Resources Conservation Service confidential database). A non-perennial stream channel is adjacent to or within each study wetland through which the wetland episodically outflows to a nearby perennial stream (Figs. 2 and 3).

### Surface Hydrologic Connectivity and Climate

During water year 2010 (1 Oct 2009 to 30 Sept 2010) we used a state data logging method to monitor patterns of wetland-stream SHC at the 11 study sites. A binary polypropylene float switch (SMD Fluid Switch, Wallingford, CT) was positioned on the bed of the non-perennial stream connecting the wetland and nearby perennial stream. The float switch closed a circuit when surface water was present (wet) and opened the circuit when surface water was absent (dry) (Fig. 4). A state data logger (HOBO model U9-001; Onset Computer Corp., Bourne, MA) connected to the float switch recorded the timing and duration of SHC as state changes in the circuit (i.e., surface water presence or absence as binary events). In a lab-based flume test of the switches ( $n=11$ ), an average flow depth of  $1.0 \text{ cm} \pm 0.1 \text{ cm}$  (mean,  $\pm$  SE) was required to trigger a state change from opened to closed, and  $1.0 \text{ cm} \pm 0.2 \text{ cm}$  (mean,  $\pm$  SE) triggered a change from closed to opened.

Float switches were placed in the thalweg (center of flow) of the non-perennial streams and 2 to 5 m upstream of the non-perennial / perennial stream confluence. We avoided placing float switches in local pools or “microponds” where standing water could falsely indicate the presence of surface flow. To account for the 1 cm depth of flow required to trigger state changes, each float switch was placed in a shallow pilot hole (see Fig. 4). Loggers and float switches were visited monthly to offload data and test for proper functionality. During field visits, we walked the non-perennial streams from the perennial stream confluence to the wetland to confirm connections, if occurring, were continuous along the non-perennial stream length. Discharge ( $\text{L s}^{-1}$ ) was measured using the cross-

sectional area method (Gordon et al. 2004) or a graduated cylinder and stopwatch when flow was present at the time of a site visit. SHC results were compared to and plotted with local rainfall data collected using a HOBO weather station (Onset Computer Corp., Bourne, MA) located within 10 km of each study site. Wetland and non-perennial stream surface water depth was recorded every 30 min at forested site F1 during water year 2010 using piezometers corrected for atmospheric pressure (Solinst Ltd., Ontario, Canada; F1 wetland data from Fisher et al. 2010; F1 non-perennial stream data from TR Fisher et al. unpublished). Potential evapotranspiration (PET;  $\text{mm d}^{-1}$ ) was calculated by month using the Hamon (1963) method for water year 2010 using average daily mean temperature at the HOBO weather station. Wetland surface water depth, non-perennial stream surface water depth, PET, and regional depth to groundwater (nearby USGS well, ID 390839075515001 QA Cg 69;  $39^{\circ}08'39.8''\text{N}$ ,  $75^{\circ}51'50.8''\text{W}$ ) were plotted with SHC patterns.

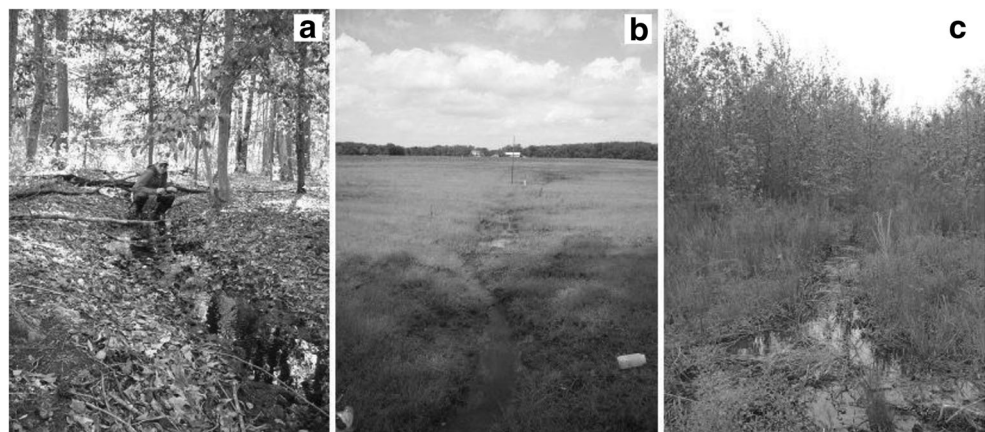
### Wetland, Watershed, and Non-Perennial Stream Physical Attributes

Physical characteristics for each wetland, non-perennial stream watershed, and non-perennial stream channel were calculated using 1 m resolution LiDAR-derived digital elevation models (Lang et al. 2012) and ArcGIS (Environmental Systems Research Institute, Redlands, CA) (Table 1). Wetland area was calculated using a threshold of a relief-enhanced topographic wetness index (Lang et al. 2013). Average soil saturated hydraulic conductivity ( $\text{ksat}$ ;  $\mu\text{m s}^{-1}$ ) was determined for each non-perennial stream watershed using USDA's Web Soil Survey (<http://websoilsurvey.nrcs.usda.gov>).

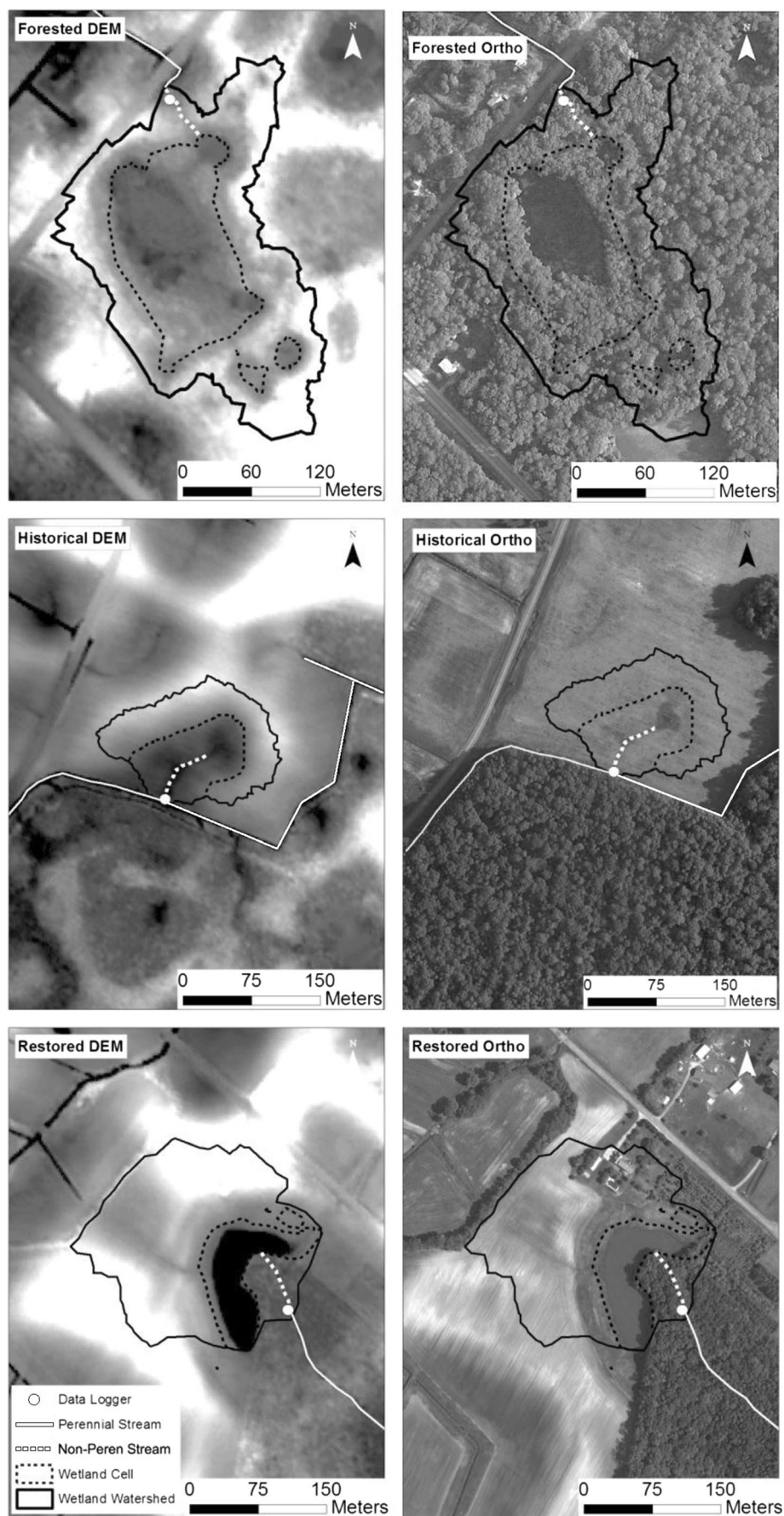
### Statistical Analyses

Cumulative duration, number of connectivity transitions (i.e., wetland–stream transitions between disconnected and connected states and vice versa), mean duration, and maximum individual event duration of surface flow events in

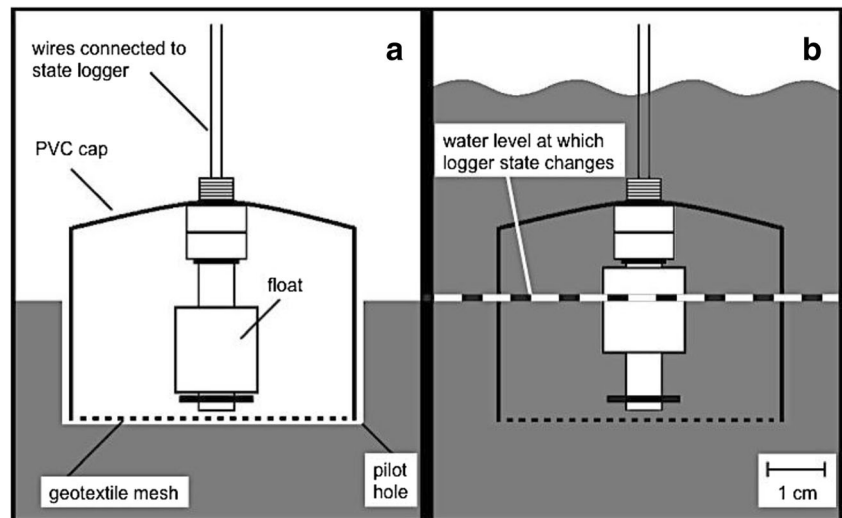
**Fig. 2** Examples of non-perennial streams connecting forested (a, site F3), historical (i.e., prior-converted cropland) (b, site H1), and restored (c, site R3) Delmarva bay wetlands to nearby perennial streams via surface flow. All photos taken looking up the non-perennial stream channel in the direction of the wetland



**Fig. 3** 1 m resolution LiDAR-derived digital elevation model (DEM) and orthophotographic (Ortho) images of example forested (site F3), historical (site H1), and restored (site R1) Delmarva bay wetland-stream pair study sites. (*Methods* section describes how site features were determined)



**Fig. 4** Schematic of buoyant polypropylene float switch. The float switch state is open when water is absent (a) and closed when water is present (b). An associated state data logger records the timing of state changes



each non-perennial stream were quantified using state data logger records. Maximum individual event duration was defined as the longest duration (in days) of continuous surface connectivity ( $D_{max-c}$ ; Leibowitz et al. 2008). Correlations between wetland area and SHC metrics were tested using Pearson's product moment correlation coefficient,  $r$ , with wetland area log-transformed to meet assumptions of normality. We tested the null hypothesis that the four metrics did not differ between the three wetland types using one-way analysis of covariance (ANCOVA) with wetland area as a covariate followed by Tukey's honestly significant difference (HSD) multiple mean comparisons test. Forward stepwise linear regression models for each connectivity metric as a function of wetland, non-perennial stream watershed, and non-perennial stream channel physical characteristics were created with a probability to enter and to leave the model of 0.05. For each wetland type, paired Student's  $t$ -tests were used to assess differences in mean 5-

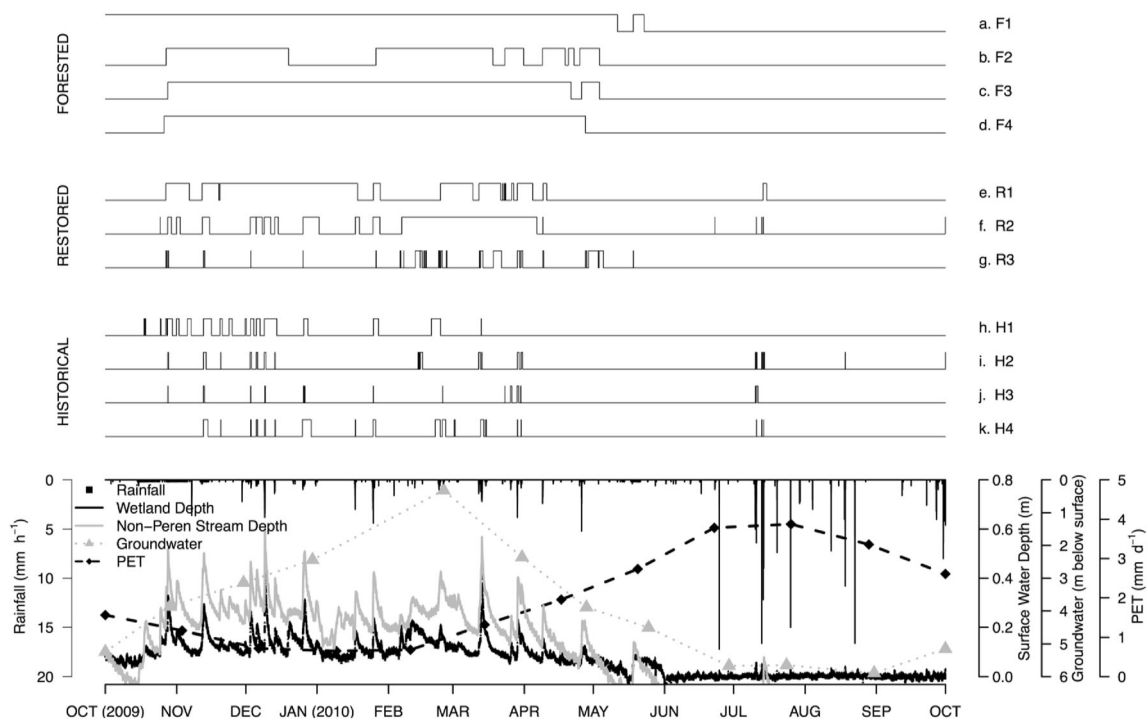
day antecedent rainfall when SHC did and did not occur between the wetland and nearby perennial stream. Five-day antecedent rainfall was chosen to best capture the cumulative impact of recent rainfall events on wetland-stream connectivity. All statistical analyses were conducted using R v2.12.2 (R Development Core Team, Vienna, Austria) with a significance level set at  $\alpha=0.05$ .

## Results

Data loggers recorded significantly different SHC patterns in non-perennial streams connecting native forested, hydrologically restored, and historical Delmarva bay wetlands to nearby perennial streams (Fig. 5, Table 2). Forested wetlands exhibited relatively continuous, seasonal SHC to perennial streams between mid-fall and late-spring (Fig. 5a–d), functioning as

**Table 1** Wetland, non-perennial stream watershed, and non-perennial stream channel physical attributes

| Site | Wetland type (year restored) | Wetland area (m <sup>2</sup> ) | Watershed drainage area (m <sup>2</sup> ) | Watershed relief (m) | Non-perennial stream length (m) | Non-perennial stream slope (%) | Watershed soil saturated hydraulic conductivity (ksat, $\mu\text{m s}^{-1}$ ) |
|------|------------------------------|--------------------------------|-------------------------------------------|----------------------|---------------------------------|--------------------------------|-------------------------------------------------------------------------------|
| F1   | Forested                     | 335,052                        | 567,304                                   | 3.6                  | 188.8                           | 0.45                           | 120.7                                                                         |
| F2   | Forested                     | 25,166                         | 36,291                                    | 2.3                  | 24.1                            | 1.15                           | 100.9                                                                         |
| F3   | Forested                     | 17,208                         | 43,400                                    | 3.1                  | 53.3                            | 1.26                           | 103.1                                                                         |
| F4   | Forested                     | 127,853                        | 324,890                                   | 3.8                  | 35.7                            | 0.86                           | 89.6                                                                          |
| R1   | Restored (2002)              | 9,334                          | 42,080                                    | 2.9                  | 73.0                            | 0.49                           | 42.0                                                                          |
| R2   | Restored (2002)              | 67,145                         | 245,387                                   | 3.1                  | 115.1                           | 0.37                           | 30.0                                                                          |
| R3   | Restored (2003)              | 1,433                          | 13,317                                    | 2.0                  | 21.6                            | 0.56                           | 89.0                                                                          |
| H1   | Historical                   | 8,060                          | 18,652                                    | 1.8                  | 76.1                            | 0.38                           | 66.1                                                                          |
| H2   | Historical                   | 2,571                          | 14,620                                    | 1.8                  | 45.2                            | 0.81                           | 70.1                                                                          |
| H3   | Historical                   | 3,955                          | 11,348                                    | 2.2                  | 49.4                            | 0.23                           | 31.1                                                                          |
| H4   | Historical                   | 10,276                         | 18,101                                    | 2.0                  | 110.6                           | 0.42                           | 28.5                                                                          |



**Fig. 5** Top Panel Water year 2010 state data logger surface hydrologic connectivity (SHC) recorded in non-perennial streams connecting forested (a–d), restored (e–g), and historical (h–k) Delmarva bays to nearby perennial streams. ‘Up’ and ‘down’ positions indicate presence and absence of SHC, respectively. Bottom Panel Rainfall, F1 wetland surface

water depth, F1 non-perennial stream surface water depth, depth to groundwater, and potential evapotranspiration (PET) for water year 2010. Top and bottom panels share the same x-axis. F1 wetland surface depth data from Fisher et al. (2010). F1 non-perennial stream surface water depth data from T.R. Fisher et al. unpublished

discharge wetlands when evapotranspiration was low and groundwater was high (Fig. 5 bottom panel). SHC was not observed among forested sites during summer and early fall when Delmarva bays typically lack surface water (Phillips and

Shedlock 1993; Fig. 5 bottom panel). Historical and restored wetland–stream SHC was largely ephemeral, occurring during and immediately following rain events, particularly when evapotranspiration was low (Fig. 5h–k). However, ephemeral wetland–stream SHC occurred on limited occasion at two restored and three historical sites following large summer rain events (Fig. 5e, f, i, j and k).

Water depth loggers in the F1 forested wetland and non-perennial stream site revealed seasonally continuous surface water presence from fall through late spring. During summer, both the F1 wetland and non-perennial stream went dry (Fig. 5 bottom panel). Water depths in both the wetland and non-perennial stream responded quickly to rainfall events when surface water was present. When the F1 forested wetland and non-perennial stream were dry, however, rain events did not trigger measureable changes in surface water depths.

On repeated site visits, we observed channelized flow in non-perennial streams connecting the study wetlands to nearby perennial streams. Observed discharge from forested wetlands ranged from 7.80–54.19 L s<sup>−1</sup>, 0.45–2.68 L s<sup>−1</sup>, 0.19–1.16 L s<sup>−1</sup>, 0.60–1.81 L s<sup>−1</sup> at F1, F2, F3, and F4, respectively (Table 3). Discharge observed in non-perennial streams connecting historical wetlands to perennial streams was minimal, ranging from 0.03–0.16 L s<sup>−1</sup>, 0.24–0.91 L s<sup>−1</sup>, 0.05–0.65 L s<sup>−1</sup>, and 0.38–0.50 L s<sup>−1</sup> at H1, H2, H3, and H4, respectively (Table 3). Discharge measured at non-perennial

**Table 2** Water year 2010 surface hydrologic connectivity (SHC) metrics in non-perennial streams connecting Delmarva bay wetlands to nearby perennial streams. Values in parentheses are standard errors of the means. *F* forested, *R* restored, *H* historical.  $D_{max-c}$ =maximum individual connection duration

| Site | Cumulative connection duration (d) | Connectivity transitions (#) | Mean connection duration (d) (SE) | $D_{max-c}$ (d) |
|------|------------------------------------|------------------------------|-----------------------------------|-----------------|
| F1   | 227.2                              | 3                            | 113.6 (113.6)                     | 222.5           |
| F2   | 133.2                              | 12                           | 22.2 (9.3)                        | 53.3            |
| F3   | 182.9                              | 4                            | 91.5 (70.0)                       | 175.2           |
| F4   | 183.1                              | 2                            | 183.1                             | 183.1           |
| R1   | 115.3                              | 26                           | 8.9 (4.2)                         | 46              |
| R2   | 86.4                               | 36                           | 4.8 (3.0)                         | 58.6            |
| R3   | 19.7                               | 56                           | 0.7 (0.2)                         | 4.3             |
| H1   | 32.5                               | 48                           | 1.4 (0.3)                         | 5.4             |
| H2   | 8.7                                | 44                           | 0.4 (0.1)                         | 1.2             |
| H3   | 3.8                                | 30                           | 0.3 (0.1)                         | 0.8             |
| H4   | 14.8                               | 38                           | 0.8 (0.2)                         | 3.9             |

**Table 3** Water year 2010 non-perennial stream discharge measurements. *F* forested, *R* restored, *H* historical, \*=no measurement taken, —=dry

| Discharge (L s <sup>-1</sup> ) |          |       |     |          |     |       |       |      |     |      |     |     |
|--------------------------------|----------|-------|-----|----------|-----|-------|-------|------|-----|------|-----|-----|
| Site                           | Oct 2009 | Nov   | Dec | Jan 2010 | Feb | Mar   | Apr   | May  | Jun | Jul  | Aug | Sep |
| F1                             | 11.68    | 9.06  | *   | 54.19    | *   | 33.9  | 15.25 | 7.80 | —   | —    | —   | —   |
| F2                             | —        | 0.45  | *   | 2.68     | *   | 1.03  | 0.80  | —    | —   | —    | —   | —   |
| F3                             | —        | 0.19  | *   | 1.16     | *   | 1.10  | 0.55  | —    | —   | —    | —   | —   |
| F4                             | —        | 0.60  | *   | 1.74     | *   | 1.81  | 1.42  | —    | —   | —    | —   | —   |
| R1                             | —        | 2.45  | *   | 9.28     | *   | 7.40  | —     | —    | —   | 1.33 | —   | —   |
| R2                             | —        | 22.54 | *   | 6.04     | *   | 18.21 | —     | —    | —   | 5.28 | —   | —   |
| R3                             | —        | 1.10  | *   | 0.12     | *   | 0.03  | 0.10  | —    | —   | —    | —   | —   |
| H1                             | 0.10     | 0.03  | *   | 0.16     | *   | 0.13  | —     | —    | —   | —    | —   | —   |
| H2                             | —        | 0.75  | *   | —        | *   | 0.24  | —     | —    | —   | 0.91 | —   | —   |
| H3                             | —        | 0.27  | *   | 0.05     | *   | —     | —     | —    | —   | 0.65 | —   | —   |
| H4                             | —        | 0.44  | *   | —        | *   | 0.38  | —     | —    | —   | 0.50 | —   | —   |

streams linking restored wetlands to perennial streams was variable and ranged from 1.33–9.28 L s<sup>-1</sup>, 5.28–22.54 L s<sup>-1</sup>, and 0.03–1.10 L s<sup>-1</sup> at R1, R2, and R3, respectively (Table 3).

All SHC metrics were significantly correlated with log-wetland area (cumulative connection duration:  $r=0.83$ ,  $p<0.01$ ; # of connectivity transitions:  $r=-0.75$ ,  $p<0.01$ ; mean connection duration:  $r=0.72$ ,  $p<0.05$ ;  $D_{max-c}$ :  $r=0.82$ ,  $p<0.01$ ). ANCOVA (covariate: log-wetland area) revealed a significant effect of log-transformed wetland area with respect to all SHC metrics (cumulative connection duration:  $F_{1,5}=46.80$ ,  $p<0.01$ ; # of connectivity transitions:  $F_{1,5}=20.92$ ,  $p<0.01$ ; mean connection duration:  $F_{1,5}=11.69$ ,  $p<0.05$ ;  $D_{max-c}$ :  $F_{1,5}=25.25$ ,  $p<0.01$ ), and the slopes of the relationships did not differ among wetland types. The effect of wetland type was only significant with respect to cumulative connection duration and number of connectivity transitions (Fig. 6a, b). Although not statistically significant, large differences in mean connection duration and  $D_{max-c}$  were recorded in forested vs. both historical and restored wetland-stream pairs (Fig. 6c, d). Cumulative connection duration between forested wetlands and nearby perennial streams was ~12 and 2.5 times greater compared to historical and restored wetlands, respectively (Fig. 6a). Forested wetlands and nearby perennial streams underwent fewer connectivity transitions relative to historical and restored wetlands (Fig. 6b). No significant differences were found with respect to SHC metrics between historical and restored wetlands (Fig. 6a–d).

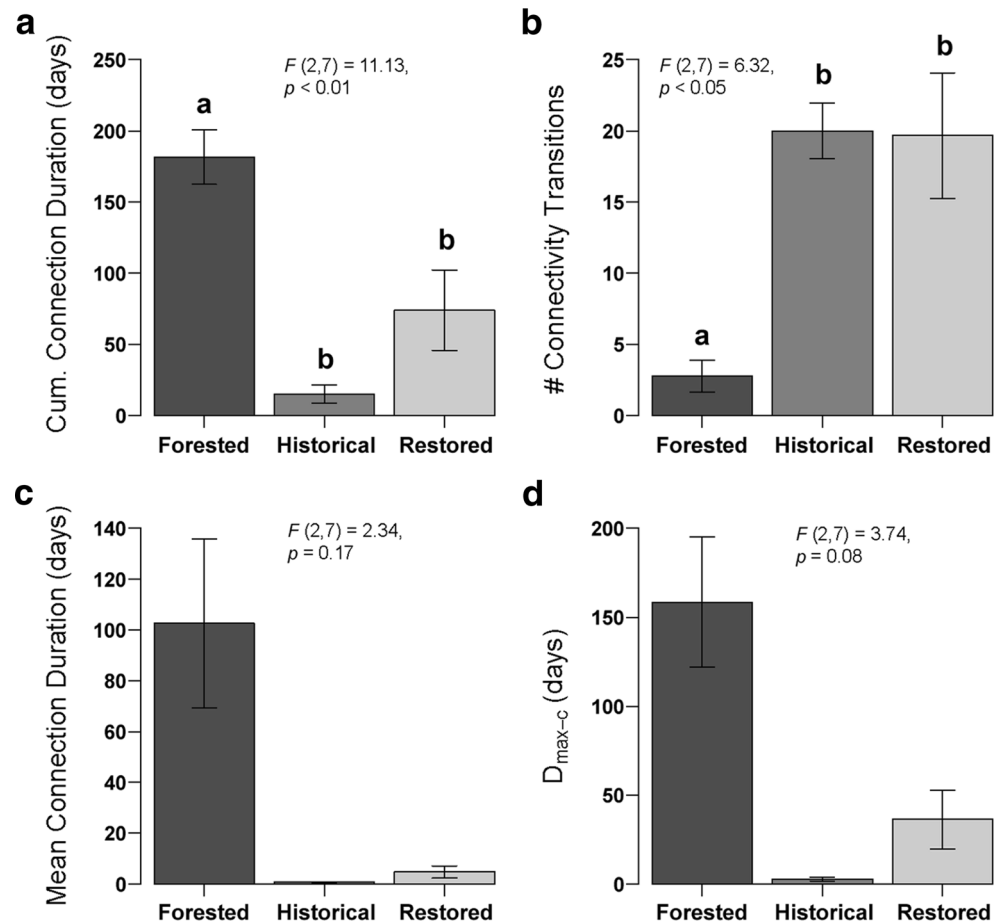
Stepwise regression revealed significant models for cumulative connection duration as a function of non-perennial stream slope and watershed relief and  $D_{max-c}$  as a function of non-perennial stream slope, non-perennial stream length, watershed relief, and mean watershed soil saturated hydraulic conductivity (Table 4). We were unable to develop statistically significant models for mean connection duration or the number of transitions between connected and disconnected states.

At historical and restored wetlands, 5-day antecedent rainfall totals were significantly greater when a non-perennial stream connection occurred between the wetland and perennial stream compared to 5-day antecedent totals when a connection did not exist (Fig. 7; restored:  $t=4.50$ ,  $df=2$ ,  $p<0.05$ , mean of the differences=7.44 mm; historical:  $t=6.67$ ,  $df=3$ ,  $p<0.01$ , mean of the differences=18.43 mm). This finding indicates SHC between historical and restored wetlands occurs in response to recent rain events. That said, SHC lasting up to 46 and 58 days was recorded at restored wetlands R1 (Fig. 5e) and R2 (Fig. 5f), respectively, during the spring, indicating SHC at restored sites was at times the result of groundwater discharge and subsequent basin outflow. No significant differences in 5-day antecedent rainfall were observed when non-perennial stream connections did and did not occur between forested wetlands and nearby perennial streams (Fig. 7;  $t=2.68$ ,  $df=3$ ,  $p=0.08$ , mean of the differences=3.14 mm), suggesting seasonal, intermittent SHC to nearby perennial streams is driven primarily by groundwater processes.

## Discussion

State data logger records coupled with climatological data, local groundwater records, and field observations provide evidence of seasonal surface hydrologic connectivity mediated by non-perennial streams between forested Delmarva bay wetlands and nearby perennial streams during water year 2010. Cumulative connection duration was significantly greater while the number of connectivity transitions was significantly less at forested wetland-stream sites compared to both restored and historical (i.e., prior-converted cropland) wetland-stream sites. SHC at restored and historical sites was mediated by recent rainfall events, while forested wetland-

**Fig. 6** Summary of surface hydrologic connectivity (SHC) metrics between forested ( $n=4$ ), historical ( $n=4$ ), and restored ( $n=3$ ) Delmarva bay wetlands and nearby perennial streams during water year 2010. **a)** Cumulative connection duration, **b)** number of connectivity transitions, **c)** mean connection duration, and **d)** maximum individual connection duration ( $D_{max-c}$ ). Error bars are standard errors of the means. Means with different letters are significantly different after accounting for wetland area via ANCOVA (Tukey's HSD,  $p<0.05$ )



stream SHC was driven by groundwater processes. The fundamentally different patterns of SHC that occurred between forested wetlands and nearby perennial streams relative to patterns at historical wetlands and hydrologically restored wetlands indicate cultivation impacts natural wetland-stream SHC patterns on the Delmarva Peninsula.

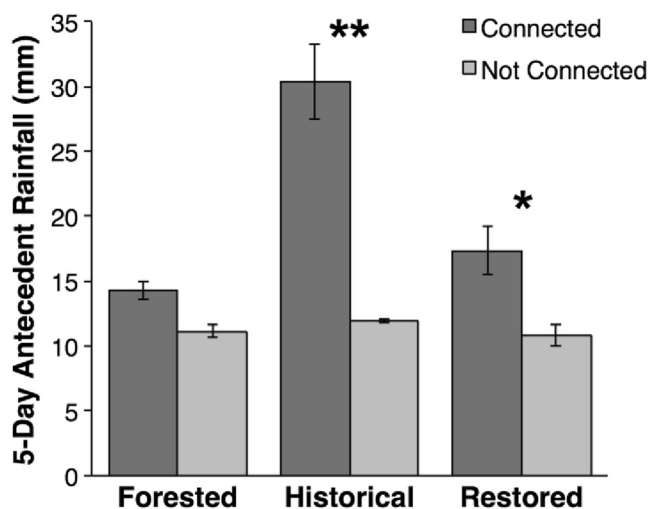
#### Hydrological and Ecological Implications of Cultivation and Wetland–Stream Surface Hydrologic Connectivity

Groundwater processes govern native forested Delmarva bay wetland-stream SHC when evapotranspiration is low,

groundwater is high, and sufficient surface water is present as a source to supply seasonally continuous outflow. Alternatively, precipitation event-based basin spillage drives ephemeral wetland-stream SHC in agriculturally altered Delmarva bays. Across the Delmarva Peninsula, an estimated 65 % of Delmarva bays have been directly impacted by agriculture (Fenstermacher et al. 2014). Similarly, high agricultural alteration has been reported among largely geographically isolated Carolina bay wetlands in South Carolina where 71 % of bays >0.80 ha have been drained and cultivated (Bennett and Nelson 1991). Wetland drainage decreases surface water storage capacity and groundwater recharge (Mitsch and Gosselink 2000),

**Table 4** Stepwise regression models predicting Delmarva bay wetland and nearby perennial stream surface hydrologic connectivity (SHC) metrics during water year 2010. *n.s.* not significant at  $\alpha=0.05$

| Surface Hydrologic Connectivity (SHC) metric | Model                                                                                                                                                                          | Adjusted $R^2$ | $p$ -value  |
|----------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------|-------------|
| Cumulative connection duration               | $\sqrt{\text{cumulative connection duration}} = -7.85 + 4.62 (\text{non-perennial stream slope}) + 5.11 (\text{watershed relief})$                                             | 0.80           | < 0.001     |
| # Connectivity transitions                   | <i>n.s.</i>                                                                                                                                                                    | <i>n.s.</i>    | <i>n.s.</i> |
| Mean connection duration                     | <i>n.s.</i>                                                                                                                                                                    | <i>n.s.</i>    | <i>n.s.</i> |
| $D_{max-c}$                                  | $\sqrt{D_{max-c}} = -18.61 + 3.70 (\text{non-perennial stream slope}) + 5.26 (\text{watershed relief}) + 1.51 (\log \text{ non-perennial stream length}) + 0.04 (\text{ksat})$ | 0.98           | < 0.001     |



**Fig. 7** 5-day antecedent rainfall totals when surface hydrologic connectivity (SHC) did and did not occur between forested ( $n=4$ ), restored ( $n=3$ ) and historical ( $n=4$ ) Delmarva bay wetlands and nearby perennial streams. Error bars are standard errors of the means. Paired Student's *t*-tests: \*  $p<0.05$ , \*\*  $p<0.01$

in turn altering wetland hydrology, including patterns of surface connectivity to nearby waters. Sharitz and Gresham (1998), for example, reported increased peak flow rates (up to three or four times that of undrained areas) and decreased flow durations in streams draining cultivated pocosin wetlands in North Carolina. We observed similar decreased flow duration in non-perennial streams connected to historical Delmarva bays relative to forested wetland-stream pairs. Additionally, active wetland infilling or infilling due to plowing or soil erosion may decrease surface water storage capacity in cultivated wetlands (Martin and Hartman 1987). Wetland cultivation can also result in increased soil compaction and bulk density (Braekke 1999), leading to decreased groundwater recharge and increased infiltration excess overland flow (Dunne and Leopold 1978). Together, decreased surface water storage capacity and increased soil compaction generate more ephemeral runoff to adjacent waters. Although rainfall-driven SHC occurred at both historical and restored sites (Fig. 7), two of three restored sites exhibited seasonally continuous SHC to nearby perennial streams similar to the groundwater-driven outflow patterns observed at forested Delmarva bays in this study (Fig. 5e, f).

Leibowitz et al. (2008) refer to geographically isolated wetlands and nearby waters as “integrated hydrological-ecological systems” with the degree of integration existing along a continuum from isolated to integrated (Leibowitz 2003). With regard to a continuum of surface hydrologic isolation, we found historical Delmarva bay wetlands to be connected to nearby perennial streams for a significantly lower cumulative duration than forested bays (Fig. 6a). In a wetland-stream connectivity mapping study in the same Tuckahoe Creek watershed, Lang et al. (2012) similarly found

farmed wetlands less likely than semi-natural wetlands to be connected to the perennial or intermittent stream network. They posit that farmed wetlands were less likely to be connected to streams, in part because small wetlands that are more isolated from nearby surface waters are easier to drain and convert to agriculture (Lang et al. 2012). Additionally, the small, ephemeral channels linking cultivated wetlands to nearby streams are rarely captured on available stream maps (Lang et al. 2012).

Surface hydrology, including patterns in duration and timing of flows, is a master variable controlling stream geomorphology, habitat suitability, thermal regulation, metabolism, biogeochemical cycling, and downstream fluxes of energy, matter, and biota (Poff et al. 1997). Hydrology is also a key factor with respect to the degree of ecological connectivity between a wetland and adjacent waters (Leibowitz et al. 2008). Differences in wetland-stream SHC along an agricultural alteration gradient may significantly influence the degree to which forested, historical, and restored wetlands impact the physical, chemical, and biological integrity of downstream waters.

Wetlands contribute to the integrity of downstream waters by supplying beneficial materials (*source function*), removing harmful materials (*sink function*), and/or preventing removal of beneficial materials (*refugia function*) (Leibowitz et al. 2008). From a source function perspective, more continuous SHC like that observed at native forested Delmarva bays supplies steady, seasonal subsidies of carbon, nutrients, and water necessary to support downstream communities (Leibowitz et al. 2008), while short-lived connections like those recorded at historical and restored bays provide only a pulsed, unpredictable delivery of resources (Ylla et al. 2011). Although historical wetlands and associated non-perennial streams are drier than native wetlands, from a sink perspective, they may still function as efficient nutrient processors (e.g., denitrification hotspots), particularly if more natural hydrology is restored (Ullah and Faulkner 2006).

With regard to refugia and habitat provision, the seasonally continuous SHC recorded between forested Delmarva bays and nearby streams are likely to provide more reliable dispersal corridors for migrating biota (Galatowitsch and van der Valk 1996, Babbitt and Tanner 2000) compared to the unpredictable and ephemeral connections typical of historical and restored bays (Hermoso et al. 2012). Wetlands more predictably connected to perennial stream networks can provide refugia for stream amphibians or habitat for fish spawning and rearing (*sensu* Dodds et al. 2004). Dispersal throughout temporarily connected networks may also support metapopulation persistence through genetic exchange (Semlitsch and Bodie 1998). Restoration of more natural Delmarva bay hydroperiod and SHC to nearby streams may mitigate detrimental impacts to native biotic communities.

## Regulatory Implications of Wetland-Stream Surface Hydrologic Connectivity

Records of wetland-stream SHC, along with a growing body of related wetland-stream connectivity research (Table 5), provide the science needed to help define jurisdictional waters of the U.S. following *SWANCC* (2001) and *Rapanos* (2006). State data loggers used in this study present a relatively inexpensive (~ \$90 USD per device at the time of publication) and simple means of capturing SHC patterns between wetlands and nearby waters (Fritz et al. 2006). Golden et al. (2014) stress the need for this kind of empirical connectivity data to advance current modeling approaches to best estimate connections between wetlands and nearby waters. Although based on a small sample size ( $n=11$ ) and a short period of record (i.e., one water year), the stepwise regression models we developed to describe controls on Delmarva bay wetland-stream SHC suggest remotely sensed data (e.g., digital elevation models) and existing maps (e.g., USDA soils data) may be used to predict ecologically and jurisdictionally critical connectivity metrics across the Delmarva region. Similar modeling efforts incorporating on-the-ground connectivity data should be explored in other regions across the country, particularly those with a high density of geographically isolated wetlands (e.g., South Atlantic Coastal Plain [pocosins, Carolina bays], Southern High Plains [playas], Upper Midwest [prairie potholes], Pacific Coast [west coast vernal pools]).

We acknowledge this study has several limitations, including a brief period of record, small sample size, and a lack of data describing groundwater flow paths connecting wetlands

and nearby waters. Firstly, because we only monitored SHC for one water year, and more importantly one of the wettest on record (90th percentile Palmer Drought Severity Index Maryland's Central Eastern Shore, date range 1895–2013; NOAA National Climate Data Center [<http://www.ncdc.noaa.gov>]), we are unable to make a statement regarding average Delmarva bay wetland-stream SHC patterns. In a 45-month long study of Texas Gulf Coast depressional wetland surface connectivity to a nearby perennial stream, Wilcox et al. (2011) found a complex of depressional wetlands was connected regularly during years with average and above average rainfall but exhibited no surface connections during a particularly dry year. A similar difference in Delmarva bay wetland-stream SHC undoubtedly occurs across a spectrum from dry to wet years. Secondly, our sample size for wetland-stream pairs was small ( $n=11$ ). While this is a common constraint in replicated ecosystem studies, particularly those conducted on private land, it nevertheless limited our statistical power to model relationships between wetland, watershed, and non-perennial stream physical properties and SHC metrics. Finally, while wetlands may be connected to nearby streams by both surface and subsurface flowpaths (Winter and LaBaugh 2003, Wilcox et al. 2011), this study only addresses surface flow timing, duration, and frequency. To best characterize wetland-stream connectivity, particularly in watersheds that fluctuate seasonally between discharge- and recharge-dominated systems, coupled surface and subsurface studies should be employed (Golden et al. 2014). Mass balance and tracer studies (e.g.,  $^{15}\text{N}$ , salt addition) could be used to calculate sources and magnitudes of hydrologic flux between wetlands and nearby waters (Golden et al. 2014).

**Table 5** Peer-reviewed studies that may be used to scientifically inform policy surrounding the jurisdictional scope of the U.S. Clean Water Act with respect to non-perennial streams and isolated wetlands

| Study                    | Location                                                                         | Scientific contribution to inform policy                                                                                                                                                              |
|--------------------------|----------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Caruso and Haynes (2011) | U.S. EPA Region 8 (Colorado, Montana, Utah, Wyoming, North Dakota, South Dakota) | Classifies stream hydrologic permanence and stream order in a semiarid region using National Hydrography Dataset Plus and suggests such data can aid in jurisdictional determinations                 |
| Wilcox et al. (2011)     | Texas gulf coast                                                                 | Quantifies non-perennial stream surface water discharge from isolated Texas Gulf Coast depressional wetlands                                                                                          |
| Lang et al. (2012)       | Delmarva Peninsula (Maryland)                                                    | Describes enhanced assessment of wetland–stream surface water connectivity using stream maps based on high resolution LiDAR-derived digital elevation models                                          |
| Lane et al. (2012)       | Southeastern & Mid-Atlantic US                                                   | Identifies extent, density, abundance, area, and expected condition of potential isolated wetlands using National Hydrography Dataset and National Wetland Inventory                                  |
| Golden et al. (2014)     | No specific location                                                             | Reviews potential models that could be used to better understand hydrologic connection between isolated wetlands and other surface waters and the impact of these connections on downstream hydrology |
| This study               | Delmarva Peninsula (Maryland)                                                    | Quantifies surface hydrologic connectivity in non-perennial streams connecting Delmarva bay wetlands to nearby perennial streams                                                                      |

## Conclusion

Surface hydrologic connectivity (SHC) represents an understudied but potentially significant ecological link between wetlands and nearby waters. From a regulatory standpoint, patterns of wetland–stream SHC may be helpful in determining wetland jurisdictional status within the U.S. (Leibowitz et al. 2008, Golden et al. 2014), particularly if the wetlands in question are traditionally considered to be geographically isolated. SHC patterns observed in this study reveal that not all native forested Delmarva bay wetlands are superficially hydrologically isolated from nearby perennial streams. Results indicate that cultivation of Delmarva bays can significantly alter patterns of wetland–stream SHC, but that hydrologic restoration can re-establish SHC that more closely resembles natural SHC. Restoration efforts should aim not only to mimic natural wetland hydrology, but also ecologically critical natural hydrologic connectivity to nearby waters. We suggest similar studies be conducted in areas of high geographically isolated wetland density to quantify the impact of these wetlands on downstream waters under varying human alteration scenarios.

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