Using Graph Networks to Quantify the Cumulative Importance of Riparian Wetlands within a Watershed

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Abstract

Wetlands provide many valuable ecosystem functions including nutrient cycling and retention, sediment capture, flood reduction, carbon storage, and habitat for water-dependent plant and wildlife species. The alteration of landscapes and the deterioration of upstream wetlands have been determined to be detrimental to downstream stream and watershed health. The position of the wetland in the landscape and its quality and size can significantly change the influence it has on stream condition. This research tests the efficacy of graphed networks created from the terrestrial-wetland-stream landscape to quantify the cumulative benefits of riparian wetlands within a watershed. We tested a combination of network parameters such as node degree, betweenness centrality, and the integral index of connectivity. Graphed networks are created by nodes that are connected by edges. Nodes were defined as stream reaches that extend out to the riparian landscape and edges as the stream confluences that connect them. Nodes were weighted by their capacity to perform ecosystem functions and the opportunity for such functions. We found that the network-based approach can quantify the impact of riparian wetland loss revealing that some riparian losses within the watershed were inherently worse than others at reducing connectivity and cumulative wetland function within the watershed. Incorporating these network metrics into wetland assessments can quantify the cumulative influence of geographic position, wetland function and size on overall wetland benefits within the watershed. This new approach can be applied to watershed planning efforts to assist managers with identifying wetlands for protection, enhancement, and re-establishment.

Introduction

Wetland ecosystems remaining on today's landscape are too often mere fragments of the area covered by these valued ecological systems before 1750 (Dahl and Allord 1996, Dahl 2011). Twenty-two states in the conterminous United States, including the Commonwealth of Pennsylvania, which lost 54%, have lost over half of their wetland areas, with six states losing >85%. Anthropogenic disturbances continue to affect many of the remaining wetlands and the most recent report to Congress shows that wetland losses continue to outpace wetland gains (Dahl and Allord 1996, Dahl 2011). The study conducted by Dahl (2011) makes clear that additional protections for wetlands are needed because under the current system, wetland losses continue despite the policy requiring avoidance, minimization, and/or mitigation of wetland impacts to maintain "no net loss" of all remaining functions and services (Federal Register 2008). In the last decade, efforts to re-establish former freshwater wetlands and create new ones from uplands and agricultural lands have been increasing (Dahl 2006, Dahl 2011). This increase, however, has been continually outpaced by losses (Dahl 2011). A significant body of research has reached a consensus that created freshwater wetlands do not match the functional potential of their naturally occurring counterparts (Gwin et al. 1990; Brown and Lant 1999; NRC 2001; Campbell et al. 2002; Robb 2002; Cole and Shaffer 2002; Morgan and Roberts 2003; Mack and Micacchion 2006; Hoeltje and Cole 2007; Kihslinger 2008; Bendor 2009; Gebo and Brooks 2012). More attention needs to be placed on how losses of natural wetlands, and underperformance of wetland creation and restoration projects have impacted landscape resilience or the ability of the landscape to assimilate pollution, store floodwaters, and support wetland-dependent species.

This paper presents a graph-theoretical approach that can be used to model hydrologic connections among riparian wetlands. This approach involves a graph-based view of the stream landscape that is both unique and non-traditional. Specifically, the graph-theoretical approach presents a framework for connectivity assessments that integrate terrestrial, stream, and riparian wetland landscapes to rank riparian wetlands by positional importance in network flows. By using this approach, a visual image of wetland functions that are important to water quality and other ecosystem services can be realized, and cumulative wetland loss based on positional importance within the watershed's network can be quantified.

The Use of Graph Theory in Landscape Ecology

Graph theory also known as network theory is focused entirely on connectivity (Urban et al. 2009). It comes as no surprise then that graph-based landscape ecological tools have become established as a means for exploring habitat connectivity and the complex spatial dynamics that occur across physical landscapes (Minor and Urban 2008; Urban et al. 2009; Zetterberg 2010). In this context, a graph consists of a set of *nodes* (also called vertices) that are connected by a series of *edges* (also called links, arc, or ties). Both nodes and edges can be assigned attribute data such as quality, size, distance, or geographic coordinates (Urban and Keitt 2001; Urban et al. 2009; Galpern et al. 2011). Edges can be binary (connected or not) and directed or undirected (Minor and Urban 2008). As a result of the wide and diverse variety of disciplines that use graph theory, a rich vocabulary has been developed with little uniformity (Minor and Urban 2008; Urban et al. 2009). This study adopts the convention defined by Minor and Urban (2008). As such, we will refer to the graph as the general structure of the data and the network as the topological relationships on the graph (Minor and Urban 2008). Stream ecologists also refer to the structure of streams within a watershed as a stream network. However, the term stream network within the context of this study refers to the relationship between nodes (stream reaches) within the graph.

Most, if not all, studies that have applied graph theory techniques to the riverine environment have focused on the dispersal of aquatic species. This study is unique in that it is not species dependent. Instead, it employs graph theory to quantify the positional importance of riparian wetlands based on their capacity to perform functions and the opportunity to support watershed health by existing within landscapes that are known to contribute watershed pollution. Riparia, the integrated collective of streams, rivers, floodplains, associated wetlands, and adjoining uplands, is inherently connected (Naiman et al. 2005; Brooks and Wardrop 2013), and as such, is easily transferable to a graph model. Riparian wetlands are distinct patches within the riverine landscape. At the site scale, these wetlands are extremely heterogeneous (Moon 2012; Moon and Wardrop 2013). A graph model, like any model, is a simplification of the stream corridor and the riparian wetland system. Graphs are context dependent and flexible enough to change as new information becomes available (Erős et al. 2012). In the most simplistic view, riparian wetlands are functionally connected to upstream and downstream ecosystems and are laterally connected to the terrestrial and other aquatic ecosystems (Mitsch and Gosselink 2000; USEPA 2015). An important indicator then of wetland functional capacity at the subwatershed scale (50 – 100 km^2) is the upland-riparian interface and the streambed-wetland interface (McClain et al. 2003). The functional capacity of a riparian wetland reveals its ability to perform a function independent of its surrounding landscape (Wainger et al. 2001).

Network Analysis

A network analysis uses connectivity metrics that are based in graph theory to model the focal ecosystem as a network of interconnected patches (Urban and Keitt 2001; Pascual-Hortal and Saura 2006; Minor and Urban 2007; Opsahl et al. 2010). In the example watershed, the graph model presented is created by nodes from stream reaches that include their riparian landscape and confluences as the edges that connect them (Figure 1).

Once the graph is formed, there are many metrics that can be used to establish the relationship among nodes and the importance of individual nodes to the connection and topology of the network. A metric should be consistently sensitive to the removal of all nodes within the network (results in a reduced value) whether the resulting loss contributes to change in connectivity or merely signifies the loss of habitat, or both (Pascual-Hortal and Saura 2006). Metrics that are sensitive enough to recognize that some changes to the network are inherently worse than others with respect to overall habitat condition (Pascual-Hortal and Saura 2006) or ecosystem function are suitable for quantifying the positional importance of nodes. Overall, when we examined the efficacy of individual metrics, we looked at that metric's ability to provide an index that quantifies the most important nodes in the landscape for maintaining overall connectivity of highly functioning riparian wetland patches. This study also examined the potential for these graph-based tools to target riparian wetlands for conservation and restoration as part of a strategy for restoring watershed health. This information can help inform conservation decisions and practices (Pascual-Horta and Saura 2006).

Methods

Study Area

This study focused on Shaver Creek watershed located in central Pennsylvania (Figure 1) to test the efficacy of network metrics to quantify geographic importance of individual riparian wetlands. Specifically, we examined a subcatchment within the northern portion known as Upper Shaver Creek subwatershed (herein referred to as the watershed), a United States Geological Survey (USGS) Hydrologic Unit Code (HUC) 11 and is in the Ridge and Valley Physiographic Province. The watershed is approximately 163 km^2 (63 mi^2) and is comprised of 71% forest, <1% urban, and 28% agriculture (Hychka 2010). Most of the agriculture is concentrated in the southwest region of the watershed along a limestone valley. The forested area is interspersed throughout the watershed, but is the dominant land cover type along the sandstone ridges. Small pockets of urban/residential areas are located mainly within the limestone and shale valleys.

Graphing Upper Shaver Creek Watershed

The streams and riparian landscape within upper Shaver Creek watershed were converted into a dendritic network with stream reaches and adjacent riparian landscape as nodes and stream confluences as the edges that connect them (Figure 1). Ground reconnaissance and extensive aerial image investigation enhanced the National Wetland Inventory (NWI) by adding 57 new wetlands totaling 22.9 ha (56.6 ac) and three NWI wetland extensions equaling 4.8 ha (11.9 ac) to the upper Shaver Creek wetland inventory. The mean area for the new inventory was 0.5 ha (1.2 acres) with a range in area from 0.004 ha (0.01 ac) to 5.2 ha (12.9 ac). After merging polygons to create contiguous areas and pruning polygons that were not headwater riparian wetlands from the NWI, the riparian wetland area in upper Shaver Creek subwatershed was increased by 69% over the existing NWI layer. The National Hydrography Dataset (NHD) also was enhanced adding 95 first and second order stream segments to the reported 72 stream segments, creating a 132% total increase in number of stream segments. Each stream segment identified within the watershed was digitized along flow accumulation lines that were derived from a submeter resolution digital elevation model (DEM). The riparian landscape that bordered the stream reaches varied by the proportion of wetlands contained, the quality of those wetlands as indicated by a rapid condition assessment, and the amount of agricultural land use within the contributing area. A series of network analyses were conducted with and without these parameters.

Connectivity Metrics: centrality measures, node importance, and component analysis

This network analysis used five connectivity metrics that are based in graph theory to model the focal ecosystem as a network of interconnected patches (Table 1) (Urban and Keitt 2001; Pascual-Hortal and Saura 2006; Minor and Urban 2007; Opsahl et al. 2010). Measures of centrality including node degree and betweenness centrality (BC) were calculated, as were node importance metrics described by Pascual-Hortal and Saura (2006). Components were analyzed to detect the influence of disturbance on riparian connectivity. Based on earlier hydropattern characterization (Tyrna 2015), highly disturbed wetlands are negatively correlated with the frequency (Pearson’s $r = -0.89$, $p < 0.001$) and duration (Pearson’s $r = -0.87$, $p = 0.020$) of hydrologic saturation (the presence of the water table in the root zone). The baseflow of these disturbed sites is well below the root zone for much of the year shortening the period of saturation (Tyrna 2015). Consequently, based on our definition of connectivity, riparian wetlands became functionally disconnected to the adjacent stream reach and to any downstream wetlands when the water table was below the root zone. Connected components for riparian wetlands were analyzed over two time-steps within the growing season to characterize the degree of network fragmentation resulting from wetland disturbance and the subsequent lowering of the water table. The two time-steps that were graphed were: 1) at the beginning of the growing season when the antecedent moisture condition was at its peak due to snowmelt, and 2) in the middle of the growing season when summer temperatures were high and evapotranspiration requirements were at the annual maximum. For connected component analysis, only stream reaches with corridors containing wetlands became nodes connected by stream confluences. In other words, two stream corridors containing wetlands could be connected if their adjacent stream reaches were connected and their baseflows were not impacted by onsite stressors as determined by a rapid assessment for condition.

Weighted Graph Model

All inventoried wetlands in the upper Shaver Creek watershed were rated by a rapid assessment described by Wardrop et al. (2007). The wetlands of upper Shaver Creek ranged from severely disturbed (condition score = 7.5) to high ecological integrity (condition score = 99.9), with a mean score in the lower range of the high condition category (mean = 59.0, ± 27.4). The rapid assessment score, and subsequently the weighting factor used in this study, has been determined by multiple intensive assessments of wetland condition to be significantly related to the functional capacity of wetlands (Brooks 2004; Brooks et al. 2006; Wardrop et al. 2007).

This study used the quality-weighted length of the wetland to stream interface to quantify a stream node's *capacity* to perform wetland functions and services. The greater the proportion of stream covered by a wetland with the least onsite stressors and the most intact buffer, the higher the capacity for that node to perform wetland functions such as nutrient cycling and pollution abatement. A second weighting factor represented *opportunity* and quantified the impact of the surrounding landscape (Adamus et al. 1987; King 1997). Opportunity was calculated by density of agricultural land within each stream reach's contributing area. We assumed that a higher density of agricultural land within a reach contributing area leads to a higher opportunity for nonpoint point sources of pollution entering the stream reach. Thus, the places in the watershed where high opportunity meets high capacity are perceived as the most important for maintaining watershed health. The graph model tracks the flow and connection of these important nodes and a Geographic Information System (GIS) was used to place them into a spatial context.

The graph model was created to highlight the places in the network where the highest capacity (large, high-quality wetlands) to perform ecosystem services overlapped with places of high opportunity (high percentage of agricultural land in the reach contributing area) to perform those services. This was achieved by altering the size of the nodes and the width of the edges. Larger nodes had higher capacity and thicker edges had higher opportunity. In this respect, the graph visually expressed the flow of potential wetland ecosystem services across the stream network.

Results

We found that graph metrics are effective at quantifying the positional importance of individual nodes. As a result, the network analysis was successful at identifying stream reach corridors that should be targeted for riparian wetland preservation, restoration, and/or re-establishment to improve watershed condition. The graph metrics were sensitive enough that individual riparian wetland loss and/or degradation were not uniformly ranked, but instead were ranked by the cumulative impact an individual wetland had on overall watershed connectivity.

Centrality Measures in a Weighted, Directed Network

By modeling node degree, the places in the graphed network with the highest local cumulative wetland influence were highlighted (Figure 2). Nodes associated with the longest and highest quality riparian wetland and were directly connected to neighbors with large, high-quality wetlands had the highest in-degree scores. For example, node 54 had the highest in-degree score because it had high quality wetlands covering 84% of its stream length and a first-order or directly connected neighbor that contained a high-quality wetland (Table 2). Node 149 had the second highest in-degree score. Node 149 contained 100% coverage of moderate-quality wetlands and had three first-order neighbors that were bounded by wetlands.

Betweenness centrality (BC) illustrated the places in the landscape that were critical to flow between nodes. The top 20 BC scores for streams of Shaver Creek are listed in Table 2. Nodes of the stream riparian landscape that made up Armond Run had the highest BC scores (Figure 3). These nodes had BC scores that ranged between 32 and 60. The stream landscape along Henry Run had the next highest BC scores ranging between 20 and 24. The 6 nodes with the highest BC scores had 73% of their stream length bounded by wetlands. The five nodes with the next highest BC scores had 48% of their length bounded by wetlands.

Node Importance and Geographic Position

According to the *dA* metric, 15 out of the 214 nodes in the network carried 40% of all the attribute weight (wetland rapid condition score multiplied by area) in the network. This calculation was not network dependent and could be calculated outside of any network analysis software. There were five stream reach corridors (nodes 85, 52, 78, 83, and 154) that were responsible for 20% of the total attribute weight in the watershed. When examining the spatial layout of these nodes, they were found scattered across the valley floor outside the influence of agriculture. Not surprisingly, all five stream reach corridors that carried 1/5 of the network attribute weight were in the Penn State Stone Valley Forest, a University-owned parcel with public access, and protection from most anthropogenic disturbances. Three out of the remaining 10 stream reach corridors that provided the other 20% of all the calculated attribute weight also were contained within protected areas such as state forest or university managed lands. The other seven stream reaches, however, are at risk of increased stress or alteration due to the lack of protection and potential for development in the reach contribution area.

The most important nodes according to the *dIIC* metric were either those with the highest betweenness scores, high quality-weighted stream length, nearly 100% of the stream length covered by riparian wetlands, or important stepping-stones for other nodes with high quality-weighted stream length. The results of the *dIIC* metric for capacity (a quality-weighted variable representing the proportion of stream corridor containing riparian wetlands) showed there are 5 nodes that rank high for both betweenness centrality and *dIIC* for capacity (Table 3 and Figure 4). This result highlights the cumulative benefit these riparian wetlands bring to the watershed in terms of quality, size, and geographic position. Furthermore, if maintaining wetland connectivity is a management goal, these wetlands should be targeted for protection. The *dIIC* metric for opportunity (nodes weighted by percent of agricultural land within the reach contribution area) shifted downstream toward the watershed outlet. Thus, the nodes with the highest opportunity for contributing nonpoint source pollution were highly connected to the watershed discharge point, and did not have a high pollution assimilative capacity (Figure 5). The persistence of this network topology without intervention can be a contributing factor to poor downstream water quality. Three of the highest scoring nodes for BC overlapped with the highest *dIIC* scores for capacity and the highest *dIIC* scores for opportunity. Arguably the three riparian wetlands corresponding to these nodes would be extremely important for protection as they are not only central to the flow of wetland services across the watershed as indicated by their BC scores, but also have the assimilative capacity and geographic position needed to perform such ecosystem services.

Another way to visualize *dIIC* scores for capacity and opportunity are to graph them. Figure 6 illustrates an enlarged portion of the graph model showing the *dIIC* scores for capacity and opportunity. Larger nodes have higher *dIIC* scores for capacity and thicker edges have higher *dIIC* scores for opportunity. Smaller nodes connected by thicker edges, such as those circled in Figure 6, should be targeted for restoration. Restoring nodes 155 and 130 would mean raising the *dIIC* scores for capacity or increasing the functional capacity of those wetlands to assimilate pollution leaving the agricultural landscape.

Network Components

In the wetland network there were 93 stream reach corridors that contained wetlands. When looking at the connectivity of the riparian wetlands within the stream corridor, 18 individual connected components appear (Figure 7). This means that many of the stream segments are not connected to other stream segments that contain riparian wetlands within the corridor. The largest number of connected riparian wetlands within upper Shaver Creek subwatershed, also known as the largest connected component (LCC), had 25 riparian wetlands connected by 39 stream corridors. Nine wetlands (14.7 ha) connected by 18 stream reach corridors in the LCC were in Penn State Stone Valley Forest. The remaining 16 wetlands (21.8 ha) in the LCC, connected by 22 stream corridors, were located on private lands. This analysis found that the largest number of connected riparian wetlands (the LCC) was vulnerable to fragmentation because of their location on private lands. In fact, the loss of just one wetland (node 155) on private land would fragment the LCC into three separate components resulting in a reduction in the cumulative benefits derived from connected wetlands.

A second component analysis was conducted to examine the change to the network during the dry summer months when highly disturbed wetlands have a long, deep drawdown of the water table. The network components in this second time-step were highly fragmented (Figure 8). The second time-step contained a total of 40 stream corridors and 13 components. The LCC had seven riparian wetlands (2.8 ha) connected by 10 stream corridors that shifted further upstream within Penn State Stone Valley Forest. Thus, the documented increase in human-induced wetland stressors as calculated by the rapid wetland assessment led to the fragmentation of the functional wetland network and a 72% reduction of the LCC from 25 connected riparian wetlands to seven.

Discussion And Conclusions

This study demonstrates the many uses of graph theory and network analysis on examining the potential for pollution assimilation by riparian wetlands at the watershed scale. First, observing node weighted in-degree and weighted BC was integral to illustrating the flow of wetland derived ecosystem services across the stream network. By examining wetland and stream ecosystems using these connectivity metrics, it was discovered that both weighted in-degree and weighted BC metrics could be adopted into a sampling framework that examines the impact of network topology on wetland water quality services. To do this, water chemistry samples should be collected at predetermined intervals from the confluence of streams that receive the highest local cumulative benefit (i.e., high in-degree). Similarly, other types of evidence could be gathered to compare the results of water chemistry tests among nodes with a range of BC scores.

Researchers have noted the disadvantages of BC in an unweighted network and cautioned the use of centrality metrics for dendritic networks analysis (Malvadkar et al. 2014). For many, BC scores have highlighted the middle of the watershed (Cote et al. 2009, Erős et al. 2011, VanLooy et al. 2013) and have negated the importance of headwaters and the streams immediately connected to headwaters (Malvadkar et al. 2014). As such, first order streams are given a score equal to zero despite the potential for high riparian wetland function. Yet in this study, calculating the BC score for nodes in a weighted network has overcome these disadvantages. Wetlands that are adjacent to first-order streams are important to the calculation of BC and if removed would significantly alter the ranking of stream reaches with the highest BC scores.   High quality riparian patches located on second order streams have BC scores that span the range of possible scores and are proportionate to their position in the path between other highly suitable riparian patches. Overall, weighted BC scores pinpoint the largest and highest quality wetlands that also are in the spatial position to intercept a high percentage of watershed flow, especially from land uses that are known to generate excess pollution. Wetlands in this spatial position are critical to improving water quality at the watershed scale (Woltemade 2000; Zedler 2003).

Malvadkar et al. (2014) compared structural connectivity using a series of metrics on two idealized watersheds and found, as many others have, that in a watershed with a clearly developed mainstem, and no limits on dispersal, the nodes in the middle of the watershed have the highest connectivity (Cote et al. 2009, Erős et al. 2011; VanLooy et al. 2013). Yet, when considering wetland function in addition to connectivity through the Integral Index of Connectivity (IIC) metric (Pascual-Hortal and Saura 2006), then the most important nodes shift from the middle of the basin to highlight the places in the network that are critical to the connectivity of the specified attribute (Cote et al. 2009; Erős et al. 2011; Van Looy et al. 2013).

The *dIIC* metric provided a list of nodes that if removed would cause the greatest cumulative impact to the watershed in terms of connectivity and wetland loss. These scores also were meaningfully reflective of wetland condition. Previous work in the Ridge and Valley ecoregion has shown a significant relationship between wetland condition and percent forest in the surrounding landscape (Brooks et al.

2006; Wardrop et al. 2007) and stream reaches found within densely forested landscapes are generally the least vulnerable to eutrophication from increased nutrients running off the landscape in the form of nonpoint source pollution (Gilliam 1994). The wetlands targeted by the *dIIC* metric had the highest capacity for ecosystem services (highest length of contact between high quality wetland and stream) and were adjacent to streams with the highest potential (due to landscape position) to transfer the most flow of water, materials, and organisms throughout the network. However, there is more to the flow of ecosystem services than mere capacity. For services to be rendered, opportunity must also be present.

Using both *dIIC* metric scores for capacity and opportunity two important groups of nodes were targeted for watershed management: 1) those that should be prioritized for riparian wetland protection, and 2) those that should be prioritized for riparian wetland restoration and re-establishment (Table 4). The graph model illustrating both *dIIC* metric scores for opportunity and capacity made these targets easily identifiable (Figure 6). Nodes that were the most essential for maintaining the connectivity between riparian corridors while simultaneously intersecting or buffering the agricultural landscape were considered priorities. Twenty-three nodes were identified as priorities for restoration, re-establishment, or protection given their spatial location within the watershed relative to other nodes and their surrounding land use.

The most influential nodes for wetland ecosystem functions, as calculated by the highest *dIIC* scores for capacity, are mostly upstream from the top 22 nodes presenting the highest opportunity or need for such functions. Johnston et al. (1990) found that downstream inputs of nutrients offset the detectable impact of nutrient retention by wetlands upstream. Seven stream reaches with only two riparian wetland patches located in highly disturbed landscape settings are hydrologically connected to the watershed's lowest pour point. These two wetlands are arguably the most important "hotspots" in upper Shaver Creek subwatershed, especially when considering the quality of water leaving the watershed. However, these two wetlands also were in the lowest wetland condition category. If the desired result is to increase the quality of water leaving the watershed, then efforts to restore these two sites should be made a priority. Similarly, if the scale of water quality improvements shifts to focus on individual stream reaches, then the upstream connected components should be scrutinized for potential restoration and protection efforts.

In conclusion, a quantitative assessment of cumulative benefits of riparian wetlands based on quality, size and landscape position was demonstrated. This type of calculation can be easily added to an analysis of the cumulative environmental impacts from permitted wetland losses. Similarly, this work establishes the value of using a network analysis to identify places in the watershed where the cumulative benefit of wetland re-creation, restoration, or enhancement would be equal (based on weighted in-degree, betweenness centrality and/or *dIIC* score) to the cumulative loss of the wetland permitted for development or removal meeting the requirement of no-net-loss of remaining wetland functions and acres. Finally, this study demonstrates the utility of graph visualization when investigating the spatial dynamics and potential consequences of multi-scale wetland disturbances on the connectedness, which when reduced increases the likelihood of diffuse sources of pollution moving through the watershed.

The 2008 final rule on the Compensatory Mitigation for Losses of Aquatic Resource (e.g., wetland mitigation) created a need for wetland management plans at the watershed scale (Federal Register 2008). Focusing on the watershed broadens the traditional site-by-site assessment approach for making wetland management decisions. This study establishes the ability of graph theory and network analysis to enhance a GIS analysis and integrate environmental realms that influence riparian wetland connectivity and watershed health. The importance of network topology (structure of the connected nodes) on the benefits received from riparian wetland functions has only been conceptualized. However, basic connectivity metrics such node in-degree and betweenness centrality create a sampling framework to test this theory.

Being able to configure and prioritize wetland restoration, re-establishment, and protection for mitigation projects to produce selected ecosystem services would highly increase our ability to manage watersheds (e.g., Zedler 2003; USEPA 2015). For many wetland ecosystem services, the desired configuration would be one with the highest connectivity of high-quality riparian areas. This study showcased the ability of the *dIIC* metric to highlight stream reaches in the watershed that maintain this desirable configuration and quantitatively identified the stream reaches that could be restored or enhanced to increase overall watershed health. García-Feced et al. (2011) adopted a two-step approach to effectively target agricultural landscapes that if reforested would be the most effective at increasing the connectivity of forested patches within predetermined dispersal distances.Using a similar two-step process, the results presented here show how the selection of certain stream reaches for restoration or re-establishment of riparian areas would not only enhance riparian wetland connectivity, but also buffer the agricultural landscape, which is critical for watershed rehabilitation.

Declarations

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Authors' contributions – **AT**: Conceptualization, methodology, formal analysis, investigation, resources, writing- original draft, visualization, project administration. **RB**: Supervision. **AT** and **RB**: Writing – review

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References

Adamus PR, Clairain EJ Jr, Smith RD, Young RE (1987) Wetland Evaluation Technique (WET); Volume II: Methodology. Operational Draft Technical Report Y-87-___. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, USA

Bendor T. (2009) A dynamic analysis of the wetland mitigation process and its effects on no net loss policy. Landscape and Urban Planning, 89:17-27

Brooks RP (ed.) (2004) Monitoring and Assessing Pennsylvania Wetlands. Final Report for Cooperative Agreement No. X-827157-01, between Penn State Cooperative Wetlands Center, Pennsylvania State University, University Park, PA and U.S. Environmental Protection Agency, Office of Wetlands, Oceans, and Watersheds, Washington, DC, USA

Brooks RP, Wardrop DH, Cole CA (2006) Inventorying and monitoring wetland condition and restoration potential on a watershed basis with examples from Spring Creek Watershed, Pennsylvania, USA. Environmental Management, 38:673-687

Brooks, RP, Wardrop DH, editors (2013) Mid-Atlantic Freshwater Wetlands: Advances in science, management, policy, and practice. Springer, New York

Brown PH, Lant CL (1999) The effect of wetland mitigation banking on the achievement of no-net-loss. Environmental management, 23:333-345

Campbell DA, Cole CA, Brooks RP (2002) A comparison of created and natural wetlands in Pennsylvania, USA. Wetlands Ecology and Management, 10:41-49

Cole CA, Shafer D (2002) Section 404 wetland mitigation and permit success criteria in Pennsylvania, USA, 1986–1999. Environmental Management, 30:508-515

Cote D, Kehler DG, Bourne C, Wiersma YF (2009) A new measure of longitudinal connectivity for stream networks. Landscape Ecology, 24:101-113

Dahl TE, Allord GJ (1996) History of wetlands in the conterminous United States, National Water Summary on Wetland Resources, U.S. Geological Survey Water Supply Paper, Washington, DC, USA

Dahl TE (2006) Status and trends of wetlands in the conterminous United States 1998 to 2004. U.S. Department of the Interior; Fish and Wildlife Service, Washington, DC, USA

Dahl TE (2011) Status and trends of wetlands in the conterminous United States 2004 to 2009. U.S. Department of the Interior, Fish and Wildlife Service, Washington, DC, USA

Erős T, Schmera D, Schick RS (2011) Network thinking in riverscape conservation–a graph-based approach. Biological Conservation, 144:184-192

Erős T, Olden JD, Schick RS, Schmera D, Fortin MJ (2012) Characterizing connectivity relationships in freshwaters using patch-based graphs. Landscape ecology, 27:303-317

ESRI (2009) ArcGIS Desktop: Release 9.3. Environmental Systems Research Institute, Redlands, CA

Federal Register (2008) Compensatory Mitigation for Losses of Aquatic Resources, Final Rule. 73:19594-19705

García-Feced C, Saura S, Elena-Rosselló R (2011) Improving landscape connectivity in forest districts: A two-stage process for prioritizing agricultural patches for reforestation. Forest ecology and management, 261:154-161

Gebo NA, Brooks RP (2012) Hydrogeomorphic (HGM) assessments of mitigation sites compared to natural reference wetlands in Pennsylvania. Wetlands, 32:321-331

Galpern P, Manseau M, Fall A (2011) Patch-based graphs of landscape connectivity: a guide to construction, analysis and application for conservation. Biological Conservation, 144:44-55

Gilliam JW (1994) Riparian Wetlands and Water Quality. Journal of Environmental Quality, 23:886-900

Gwin SE, Kentula ME, Shaffer PW (1999) Evaluating the effects of wetland regulation through hydrogeomorphic classification and landscape profiles. Wetlands, 19:477-489

Hoeltje SM, Cole CA (2007) Losing function through wetland mitigation in central Pennsylvania, USA. Environmental Management, 39:385-402

Hychka KC (2010) Characterizing Hydrologic Settings and Hydrologic Regimes of Headwater Riparian Wetlands in the Ridge and Valley of Pennsylvania. Dissertation, Pennsylvania State University

Johnston CA, Detenbeck NE, Niemi GJ (1990) The cumulative effect of wetlands on stream water quality and quantity. A landscape approach. Biogeochemistry, 10:105-141

Kihslinger RL (2008) Success of wetland mitigation projects. National Wetlands Newsletter, 30:14-16

King DM (1997) Valuing Wetlands for Watershed Planning. National Wetland Newsletter, 19:5-10

Mack JJ, Micacchion M (2006) An Ecological Assessment of Ohio Mitigation Banks: Vegetation, Amphibians, Hydrology, and Soils. Environmental Protection Agency, Division of Surface Water, Wetland Ecology Group, Columbus, OH, USA

Malvadkar U, Scatena F, Leon M (2014) A Comparison of Connectivity Metrics on Watersheds and Implications for Water Management. River Research and Applications, 1535-1467

McClain ME, Boyer EW, Dent CL, Gergel SE, Grimm NB, Groffman PM, Hart SC, Harvey JW, Johnston CA, Mayorga E, McDowell WH, Pinay G (2003). Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems. Ecosystems, 6:301-312

Minor ES, Urban DL (2007) Graph theory as a proxy for spatially explicit population models in conservation planning. Ecological Applications, 17:1771-1782

Minor ES, Urban DL (2008) A graph-theory framework for evaluating landscape connectivity and conservation planning. Conservation biology, 22:297-307

Mitsch WJ, Gosselink JG (2000) Wetlands, 3rd ed. John Wiley & Sons, New York

Moon JB (2012) Edaphic Properties, Their Heterogeneity, and Associated Microbial Communities in Headwater Wetland Complexes of the Ridge and Valley Region, Pennsylvania. Dissertation, Pennsylvania State University

Moon JB, Wardrop DH (2013) Linking Landscape to Wetland Condition: Case Study of Eight Headwaters. In: Brooks RP, Wardrop DH (ed) Mid-Atlantic Freshwater Wetlands: Advances in science, management, policy, and practice. Springer, pp 61-108

Morgan KL, Roberts TH (2003) Characterization of wetland mitigation projects in Tennessee, USA. Wetlands, 23:65-69

Naiman RJ, Decamps H, McClain ME (2005) Riparia: ecology, conservation, and management of streamside communities. Elsevier Academic Press, Amsterdam

NRC (2001) Compensating for Wetland Losses Under the Clean Water Act. National Academy Press, Washington, DC

Osborne LL, Kovacic DA (1993) Riparian vegetated buffer strips in water-quality restoration and stream management. Freshwater biology, 29:243-258

Opsahl T, Agneessens F, Skvoretz J (2010) Node centrality in weighted networks: Generalizing degree and shortest paths. Social Networks, 32:245-251

Pascual-Hortal L, Saura S (2006) Comparison and development of new graph-based landscape connectivity indices: towards the priorization of habitat patches and corridors for conservation. Landscape Ecology, 21:959-967

PMAP (2014) Program Land Cover for Pennsylvania 2005. http://www.pasda.psu.edu/uci/MetadataDisplay.aspx?entry=PASDA&file=palanduse05utm18nad83.xml&dataset=1100. Accessed 21 September 2014

Robb JT (2002) Assessing wetland compensatory mitigation sites to aid in establishing mitigation ratios. Wetlands, 22:435-440

Saura S, Pascual-Hortal L (2007) Conefor Sensinode 2.2 User's Manual: Software for quantifying the importance of habitat patches for maintaining landscape connectivity through graphs and habitat availability indices. University of Lleida, Spain. www.conefor.org. Accessed 24 January 2015

Saura S, Torné J (2009) Conefor Sensinode 2.2: a software package for quantifying the importance of habitat patches for landscape connectivity. Environmental Modeling & Software 24: 135-139

Saura S, Pascual-Hortal L (2007) A new habitat availability index to integrate connectivity in landscape conservation planning: comparison with existing indices and application to a case study. Landscape and Urban Planning, 83:91-103

Sifneos JC, Cake EW, Kentula ME (1992) Effects of Section 404 permitting on freshwater wetlands in Louisiana, Alabama, and Mississippi. Wetlands, 12:28-36

Tyrna A (2015) Characterizing the Network Structure of Headwater Riparian Wetlands in the Ridge and Valley Region, Pennsylvania. Dissertation, Pennsylvania State University

Urban D, Keitt T (2001) Landscape connectivity: a graph-theoretic perspective. Ecology, 82:1205-1218

Urban DL, Minor ES, Treml EA, Schick RS (2009) Graph models of habitat mosaics. Ecology letters, 12:260-273

USEPA (2015) Connectivity of streams and wetlands to downstream waters: a review & synthesis of the Science. EPA/600/R-14/475F, Office of Research and Development, U.S. Environmental Protection Agency, Washington DC, USA

Van Looy K, Cavillon C, Tormos T, Piffady J, Landry P, Souchon Y (2013) A scale-sensitive connectivity analysis to identify ecological networks and conservation value in river networks. Landscape ecology, 28:1239-1249

Wainger LA, King D, Salzman J, Boyd J (2001) Wetland value indicators for scoring mitigation trades. Stan. Envtl. LJ, 20:413

Wardrop DH, Kentula ME, Stevens DL Jr, Rubbo JM, Hychka K, Brooks RP (2007) Assessment of wetlands in the Upper Juniata watershed in Pennsylvania, U.S.A using the hydrogeomorphic approach. Wetlands. 27:432-445

Woltemade CJ (2000) Ability of restored wetlands to reduce nitrogen and phosphorus concentrations in agricultural drainage water. Journal of Soil and Water Conservation, 55:303-309 yWorks GmbH, the diagramming company (2004-2014). Tubingen, Germany. docs.yworks.com/yfiles/doc/developers-guide/. Accessed 2 December 2014

Zedler JB (2003) Wetlands at your service: reducing impacts of agriculture at the watershed scale. Frontiers in Ecology and the Environment, 1:65-72

Zetterberg A, Mörtberg UM, Balfors B (2010) Making graph theory operational for landscape ecological assessments, planning, and design. Landscape and Urban Planning, 95:181-191

Table

Metric Type	**Metric Name**	**Metric Description**	**Metric Formula**	**Software Program**	**Citation**
Centrality	Weighted node in-degree with α=1	The sum of the quality weighted stream length entering the node with the number of edges negligible.	In-degree (ks_c^{in}), where s is the weighted in-degree	t-net in R	Opsahl et al. 2010
Centrality	Weighted betweenness centrality (BC) with α=1	Sum of the shortest weighted path between nodes or the frequency of the focal node falling between two other nodes in the network.	BC for node k equals all shortest paths between nodes i and j divided by how many pass-through node k.	t-net in R	Opsahl et al. 2010
Node Importance	*dA*	Total percentage of habitat attribute contributed by the focus node.	where a_i is the attribute value for node *i* and A_C is that totally attribute value for all nodes within the network.	Confor 2.6	Pascual-Hortal and Saura 2006, Saura and Torné 2009
Node Importance	Integral index of connectivity *(IIC)*	The attribute of each habitat patch was calculated using the capacity of nodes i through j to perform riparian wetland functions and services and the opportunity of nodes i through j to perform such services. Wetland condition and size were surrogates for wetland function and services. Agricultural land use density was a surrogate for opportunity to perform services.	where *ai* is the area or any attribute of each habitat patch and nl_{ij} is the number of links in the shortest path (topological distance) between patches i and j	Confor 2.6	Pascual-Hortal and Saura 2006, Saura and Torné 2009
Component analysis	Largest connected component (LCC)	The largest set of nodes that are connected to each other.		Cytoscape 2.7	Minor and Urban 2008

Table 1. List of network metrics tested in this study.

Table 2. Node weighted in-degree and weighted BC scores for the top 20 scoring nodes. The highest scores for node in-degree, a measure of local benefit, do not track with the highest scores of BC, a network-wide measure.

	Measures of Centrality		
Node	**Percent Wetland**	**Weighted In-degree** $\alpha=1$	**Weighted BC** $\alpha=1$
149	0.72	714	60
151	1.00	345	60
152	1.00	340	56
154	1.00	370	48
145	0.41	363	42
155	0.85	591	42
182	0.43	545	33
143	0.76	210	32
167	0.79	5	25
166	1.00	242	24
173	0.44	162	24
174	0.02	104	24
176	0.69	373	20
44	0.07	335	18
137	1.00	242	18
52	1.00	56	16
148	1.00	383	14
164	0.66	224	14
54	0.83	783	10
130	0.40	40	9

Table 3 The top 20% of *dIIC* scores for stream reach nodes in Shaver Creek subwatershed. The percent of the stream length covered by wetlands is also listed for reference.

Node	Percent Wetland	*dICC*
155	0.41	39.56
154	1.00	30.17
124	0.32	28.25
130	0.40	25.93
182	0.43	25.69
128	0.50	24.61
90	0.00	24.36
151	0.72	24.29
152	1.00	24.21
119	1.00	22.36
115	0.62	22.23
123	0.86	21.77
149	1.00	20.96
113	0.00	20.60
85	0.96	17.25
87	0.00	16.96
54	0.83	15.42
89	0.00	15.06
176	0.69	14.93
52	1.00	14.84
183	0.00	14.57
86	0.24	14.55

Table 4. The 23 stream reaches identified as priorities for riparian wetland restoration, re-establishment or protection based on two *dIIC* metric scores. Targeted stream reaches are not only essential for maintaining the connectivity of high quality-weighted riparian areas, but also for disrupting the connected agricultural landscape.

Priority Stream Reaches Targeted for Watershed Management

Node ID	To Node	Percent Ag	Percent Wetland	Wetland Condition Score	Type of Prioritization
18	223	57.5	20.0	35.6	restoration
124	128	66.8	32.0	49.6	restoration
128	130	25.7	50.0	45.3	restoration
130	155	49.5	40.0	52.0	restoration
151	152	1.0	72.0	70.0	protection
152	154	7.7	100.0	84.1	protection
154	155	1.7	100.0	71.4	protection
155	182	32.8	41.0	52.4	restoration
167	173	26.3	79.0	42.0	restoration
173	174	14.0	43.8	42.5	restoration
174	176	44.5	100.0	42.5	restoration
176	182	13.6	69.3	43.0	restoration
181	183	74.8	55.0	20.9	restoration
182	183	35.2	43.0	23.1	restoration
183	209	59.7	0.0	0.0	re-establishment
205	207	73.9	0.0	0.0	re-establishment
207	208	69.2	0.0	0.0	re-establishment
208	209	84.2	8.0	19.7	restoration
209	211	81.3	64.8	26.2	restoration
211	223	49.5	5.6	26.2	restoration
214	216	66.7	0.0	0.0	re-establishment
216	223	79.1	0.0	0.0	re-establishment
217	223	72.7	0.0	0.0	re-establishment
223					outlet

Figures

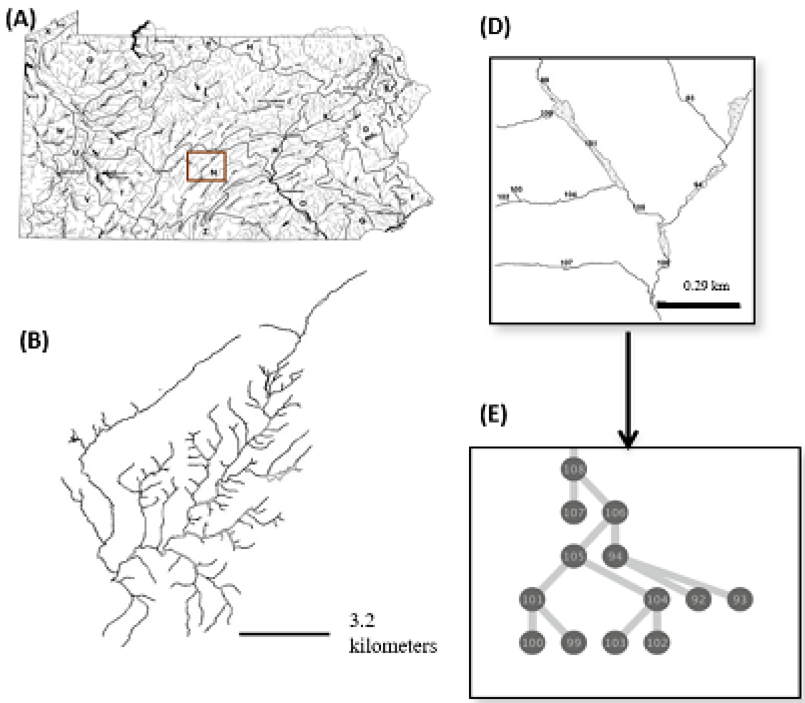

Figure 1

(A) Location of Shaver Creek watershed on the Pennsylvania Gazetteer of Streams (25 Pa. Code). Shaver Creek watershed is located within the dark red box. (B) The streams (black) and riparian wetlands (gray) of Shaver Creek subwatershed. (C) Graph model representation of the streams reaches in Shaver Creek subwatershed. (D) Zoomed region of Shaver Creek subwatershed with stream reaches labeled with node IDs. (E) Graph model representation of the zoomed in region pictured in (D). Stream reaches become nodes connected by confluences (edges).

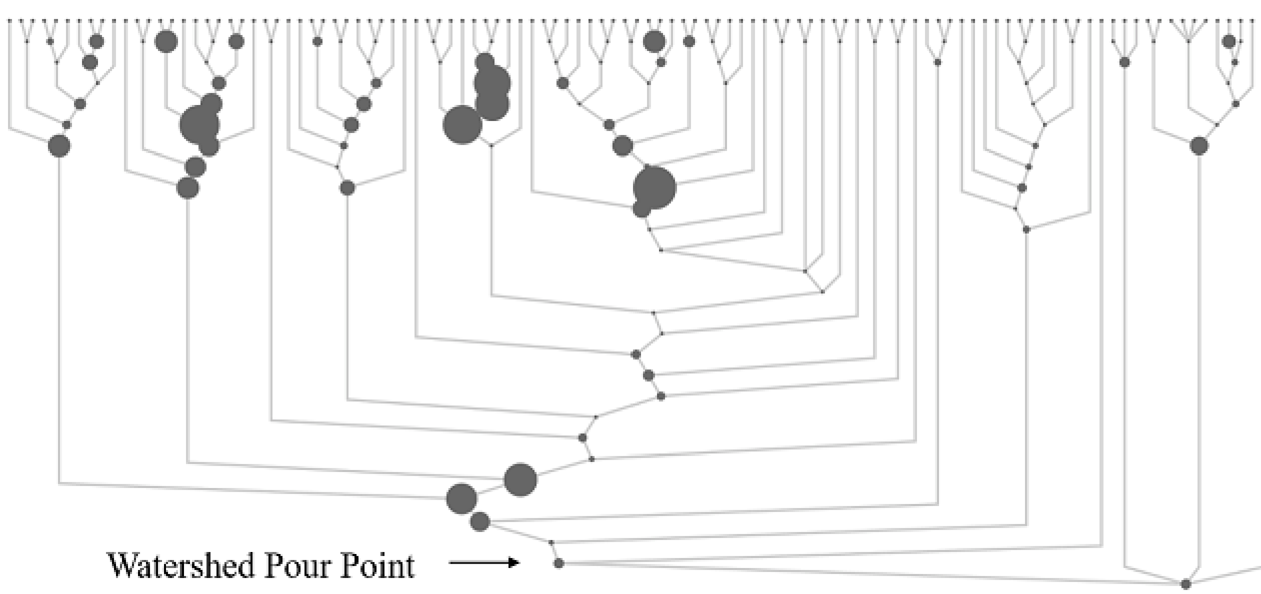

Figure 2

Hierarchal graph model of the stream network. Nodes are sized by weighted in-degree with the largest nodes having the highest in-degree. This illustration of the stream network also portrays the places in the watershed receiving the greatest local benefit from neighboring riparian wetlands because the weights were calculated from wetland attributes (size and condition).

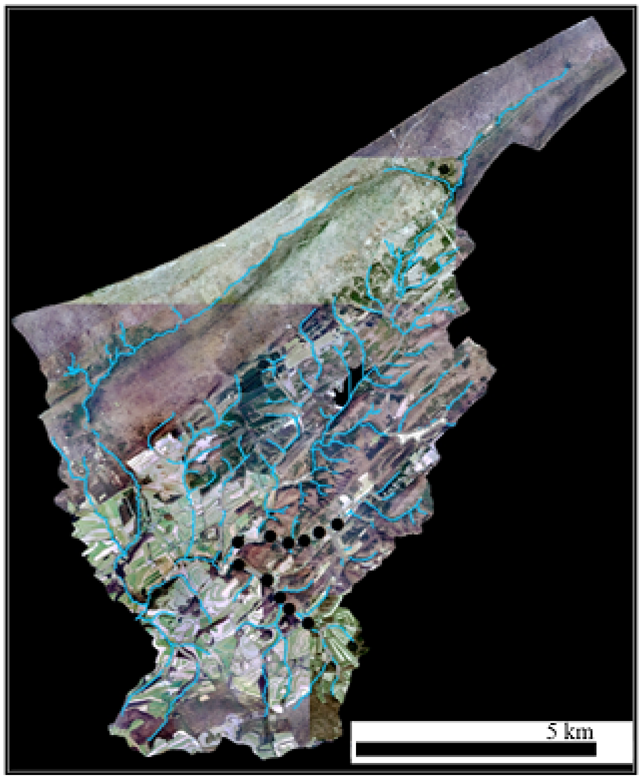

Figure 3

Nodes with the highest BC scores are symbolized by black dots and the streams are symbolized by blue lines. The black dots are the 11 most frequently traveled stream reaches for water, materials, organisms, or energy moving between riparian corridors.

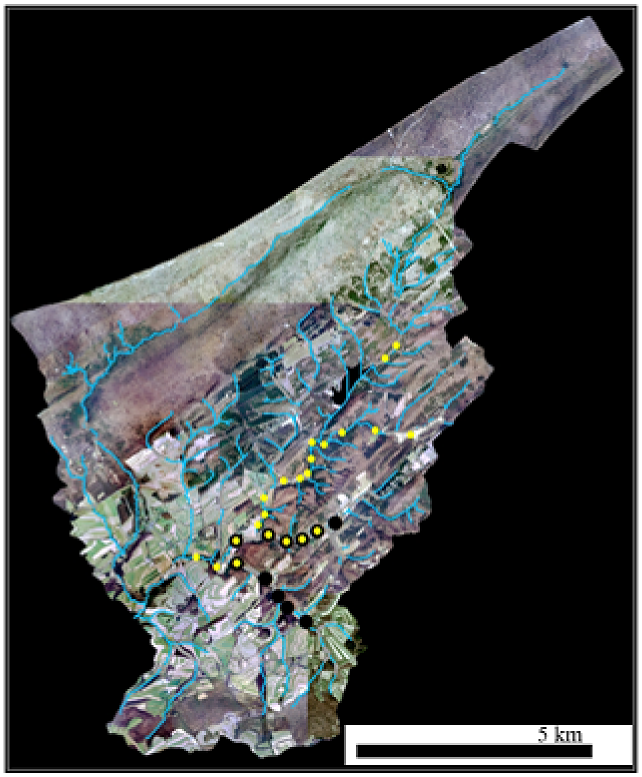

Figure 4

Nodes with highest BC scores (black dots) overlaid with the highest dIIC scores for capacity (yellow dots). dIIC scores for capacity calculate node importance for wetland function by including measures of centrality with attributes. Despite the clear distinction between the two metrics, there are 5 nodes that rank high for both (yellow dots with black border).

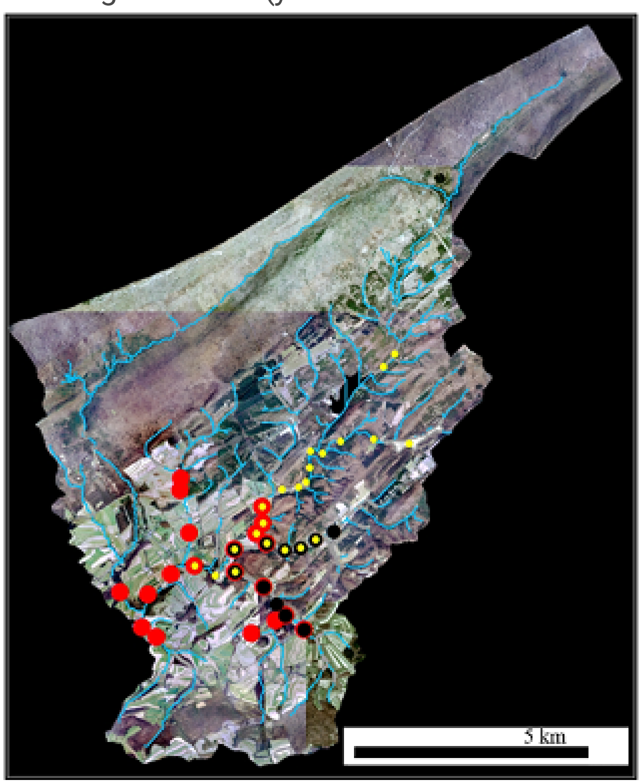

Figure 5

Nodes with highest BC scores (black dots) overlaid with the highest dIIC scores for capacity (yellow dots) and the highest opportunity (red dots). dIIC scores for opportunity calculate the stream reaches with the highest potential for carrying nonpoint source pollution by including measures of centrality with density of agricultural land within each reach contribution area. The nodes with the highest opportunity included the watershed pour point. Three nodes rank high for all three metrics (yellow dots with black and red borders).

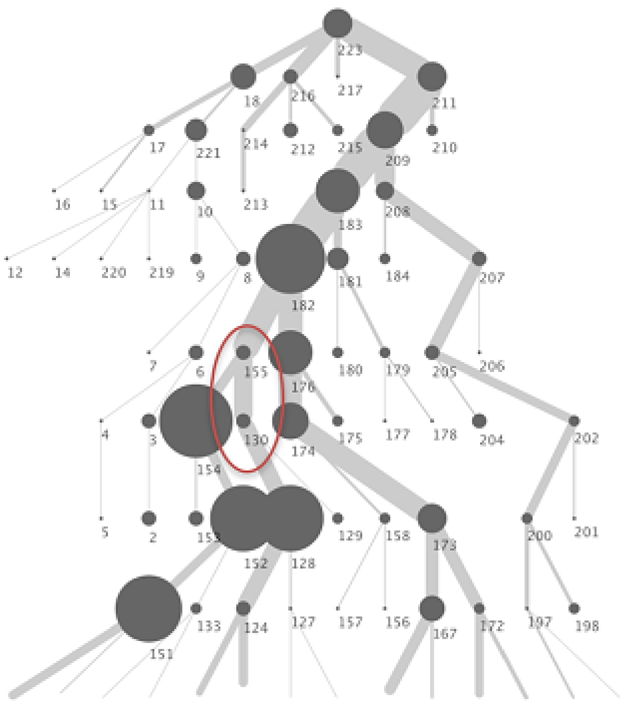

Figure 6

An enlarged view of a portion of the graph model illustrating the dIIC scores for capacity and opportunity. Larger nodes have higher dIIC scores for capacity. dIIC scores for opportunity are symbolized using edge width. The thicker the edge the higher the opportunity dIIC score. Restoring the two nodes within the circle (nodes 155 and 130) would mean raising the dIIC capacity scores and result in a disruption to the flow of pollution leaving the agricultural landscape.

Figure 7

A graph model of the wetland network containing 93 stream reach corridors containing riparian wetlands. The network contains 18 individual wetland connected components. The largest number of connected riparian wetlands within the upper Shaver Creek subwatershed also known as the largest connected component (LCC, pictured on the far left) had 39 stream corridors. Eight riparian wetlands were not connected to other riparian wetlands within watershed.

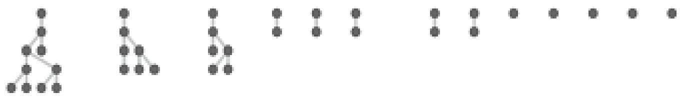

Figure 8

A graph model of the connected wetland network after removing nodes that would be no longer functionally connected to adjacent streams because of having deep water tables during the summer months. This new graph contains 40 stream reach corridors containing riparian wetlands. The network is severely fragmented with 13 individual connected components. The LCC contains 10 stream corridors with connected riparian wetlands (pictured on the far left). Five riparian wetlands are not connected to other wetlands within the watershed.