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Geographically isolated wetlands are part of the hydrological landscape

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Introduction

Since the US Supreme Court's 2001 *SWANCC* case (531 US 159), there has been significant focus on whether Clean Water Act (CWA) protections should be extended to so-called geographically isolated wetlands (GIWs); wetlands that are surrounded by uplands and lack readily apparent surface water connections to downgradient waters (Downing *et al*., 2003; Leibowitz and Nadeau, 2003; Tiner, 2003a, b; see Mushet *et al*. (2015) for a history and critique of this term). Following the US Supreme Court's 2006 *Rapanos* case (547 US 715), interest in GIWs increased, with a more recent emphasis on the roles surface and subsurface hydrological flows might play in connecting GIWs to downgradient waters at the landscape scale (Downing *et al*., 2007; Nadeau and Rains, 2007; Leibowitz *et al*., 2008). One key outcome from *Rapanos* comes from the opinion penned by Justice Anthony Kennedy, which states that non-adjacent wetlands, including non-adjacent GIWs, can be waters of the USA (WOUS) subject to regulation under the CWA if they, either individually or cumulatively, have a 'significant nexus' with the chemical, physical, and/or biological integrity of other, more traditionally defined WOUS (e.g. navigable waters). In other words, a GIW is a WOUS if it is connected to a downgradient WOUS, and this connection substantively contributes to the chemical, physical, and/or biological integrity of that downgradient WOUS.

The US Environmental Protection Agency recently completed a review of peer-reviewed literature, seeking to synthesize existing scientific understanding of how wetlands and streams, individually or in aggregate, affect the chemical, physical, and biological integrities of downstream waters (US Environmental Protection Agency, 2015). The report concludes that all wetlands located on floodplains and/or within riparian areas have significant chemical, physical, and/or biological connections with downgradient WOUS. The report is more equivocal about those other wetlands, including the vast majority of GIWs, which are not located on floodplains and/or riparian areas. Instead, the report concludes that these wetlands occur along a continuum of connectivity, with a great deal of spatial heterogeneity and temporal variability, and that a lack of knowledge makes any generalization difficult. The report cites more than 1200 peer-reviewed papers, suggesting that the problem is not a lack of general knowledge about wetlands and waters but, rather, a lack of specific knowledge on the roles that GIWs might play in controlling the chemical, physical, and/or biological integrities of downgradient WOUS. Therefore, the report concludes that additional research focused on the frequency, magnitude, timing, duration, and rate of fluxes from GIWs to downgradient waters is needed to improve the US Environmental

Protection Agency's abilities to 'identify waters of national importance and maintain the long-term sustainability and resiliency of valued water resources'. Towards these ends, a broad range of research is needed, from field and numerical modelling studies that evaluate connectivity and better elucidate functional relationships between GIWs and downgradient waters to the development of new conceptual frameworks that can be used to generate hypotheses regarding how these systems vary over space and time. The latter is the focus of this commentary, with a specific focus on the effects of GIWs on flows in downgradient waters.

GIWs as Nodes in Hydrologic Networks

Hydrological flowpaths connect landscapes in four dimensions – longitudinal, lateral, vertical, and through time. This four-dimensional hydrological connectivity, operating at local to landscape scales, is a basic tenet of freshwater ecology (Ward, 1989). Hydrological flowpaths are extensive and dynamic, connecting landscapes within watersheds (McDonnell, 2013) and across watershed divides (see Sun *et al.*, 1997 and references therein). Fluxes of water along these hydrological flowpaths occur at varying frequencies, magnitudes, timings, durations, and rates, which are primarily determined by climate, geology, and topography (Winter, 2001; Wolock *et al.*, 2004; Devito *et al.*, 2005; Wigington *et al.*, 2013; Park *et al.*, 2014) and collectively control the physical integrity of downgradient waters (Nadeau and Rains, 2007). GIWs distributed throughout the landscape intercept and interact with water that flows along these flowpaths, and these GIWs are therefore integrally connected to uplands, other wetlands, and downgradient waters.

Conceptually, this hydrological landscape is a network, with GIWs as nodes – receiving, storing, and sending water – and flowpaths as edges – transmitting water (Figure 1). In the GIWs, flows are modulated by the performance of lag, sink, and source functions (Table I; Leibowitz *et al.*, 2008; US Environmental Protection Agency, 2015). Lag functions delay the flow of water to downgradient waters and include local surface water and groundwater storage (Haag *et al.*, 2005; Gleason *et al.*, 2007; Lane and D'Amico, 2010) and exchange (Min *et al.*, 2010; Nilsson *et al.*, 2013; McLaughlin *et al.*, 2014), with the latter regulating water tables and enhancing or reducing surface water and groundwater storage depending on the direction of the exchange. Sink functions reduce the flow of water to downgradient waters and include evapotranspiration (Sun *et al.*, 2002; Towler *et al.*, 2004; Hammersmark *et al.*, 2010) and deep groundwater recharge (Sinclair, 1977; Wood and Sanford, 1995; Rains, 2011). Lag and sink functions can act in concert to more greatly affect wetland response to variable precipitation (Rosenberry and Winter, 1997). Collectively, these lag and sink functions modulate the source function that can contribute flow to downgradient waters by surface water and shallow groundwater outflow (Leibowitz and Vining, 2003; Rains *et al.*, 2006; Sass and Creed, 2008; Wilcox *et al.*, 2011; Golden *et al.*, 2015). Along the flowpaths, flows are further altered by interactions among flowpath length, gradient, resistance or conductance (e.g. hydraulic conductivity and surface roughness), and leakage (e.g. evapotranspiration and deep recharge). As water flows through this network, the frequency, magnitude, timing, duration, and rate of flows are all modulated by myriad interactions occurring in GIWs and along flowpaths.

Network-Scale Effects of GIWs on Flow Generation

While an individual GIW can affect local-scale hydrology, its effect on landscape-scale hydrology is likely negligible. However, the cumulative effect of many GIWs can play an important role in landscape-scale hydrology by regulating the frequency, magnitude, timing, duration, and rate of flows to downgradient waters (Ogawa and Male, 1986; Hey and Philippi, 1995; Cohen and Brown, 2007; Golden *et al.*, 2015). This cumulative effect emerges from lag, sink, and source functions resulting in time-varying flows being directed towards downgradient waters along overland (Leibowitz and Vining, 2003; Wilcox *et al.*, 2011), shallow subsurface (Rains *et al.*, 2006; van der Kamp and Hayashi, 2009), and deep groundwater (Winter, 1999; Rains, 2011) flowpaths.

The GIWs and the flowpaths that connect them to downgradient waters exist along a hydrologically dynamic continuum (Euliss *et al.*, 2004; Cohen *et al.*, In Review). Geology and topography are spatially heterogeneous but temporally fixed. However, climate is variable, and its effects vary annually, seasonally, and episodically. Therefore, the degree to which lag, sink, and source functions are performed and the flowpaths along which water is directed to downgradient waters are strongly dependent on both current and antecedent conditions (Rains *et al.*, 2006; Pyzoha *et al.*, 2008). When lag and sink functions dominate and/or water is directed from GIWs to downgradient waters along shallow subsurface or deep groundwater flowpaths, then downgradient flows might be delayed or diminished. In contrast, when source functions dominate and/or water is directed from GIWs to downgradient waters along overland flowpaths, then downgradient flows might be hastened or enhanced. Therefore,

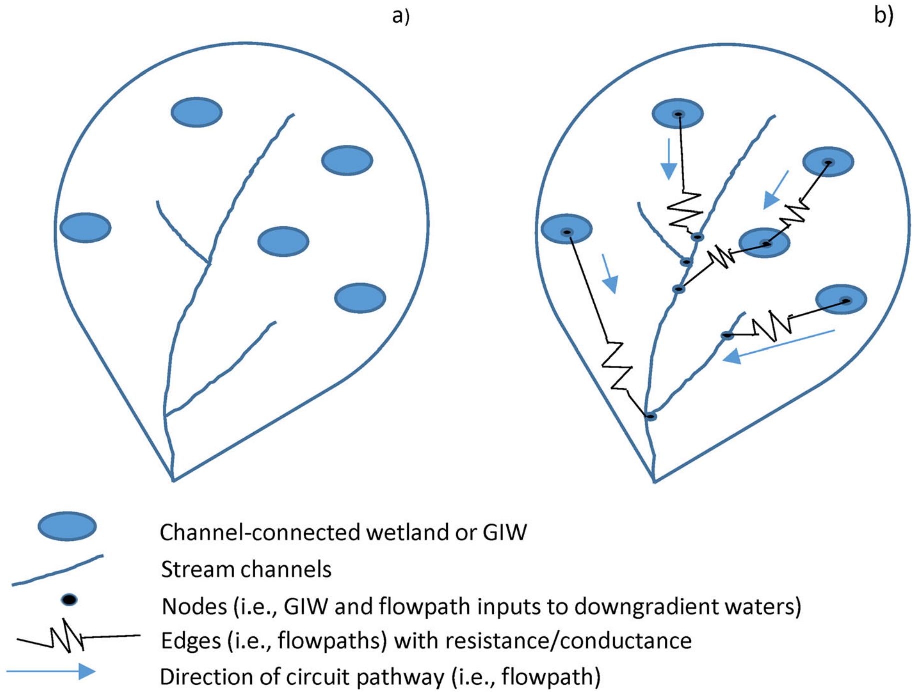

Figure 1. (a) A watershed with GIWs and other waterbodies conceptualized as (b) a network with GIWs and other waterbodies as nodes – receiving, storing, and sending water – and flowpaths as edges – transmitting water. GIW, geographically isolated wetland

Table I. Hydrologic functions of geographically isolated wetlands

Function	Type	Description
Storage	Lag	Storage of surface water and/or shallow groundwater. Partially controls other hydrologic functions. Especially pronounced in depressional GIWs.
Exchange	Lag	Exchange of surface water and groundwater, thereby regulating water table variation because of bidirectional exchanges (recharge and discharge) at local scales.
Evapotranspiration	Sink	Enhanced evapotranspiration because of prolonged presence of surface water and/or shallow groundwater. Potentially an important watershed-scale loss of water.
Deep recharge	Sink	Enhanced deep groundwater recharge because of local topographic lows that hold surface water and/or shallow groundwater. Potentially an important watershed-scale loss of water. Especially pronounced in depressional GIWs.
Flow generation	Source	Alteration of the frequency, magnitude, timing, duration, and rate of outflows to downgradient wetlands and waters because of the combined effects of the lag and sink functions.

GIW, geographically isolated wetland

antecedent conditions exert a substantial control on travel times, with water entering a GIW being directed along slow subsurface flowpaths, rapid surface flowpaths, to or from adjacent shallow groundwater, or to the atmosphere or deep groundwater storage depending upon those antecedent conditions.

The cumulative effect results from water flowing from many GIWs to downgradient waters along a continuum of travel lengths and times, varying by GIW and over time. At a given moment in time, there might be no flow from some GIWs, relatively slow subsurface flow from other GIWs, and relatively rapid surface flow from still other GIWs. The cumulative effect of the many GIWs on downgradient streamflows emerges from the convolution of these travel times (Cohen *et al.*, In Review; Figure 2). In this convolution, time-varying flows – or the lack thereof – from each GIW cumulatively contribute to the maintenance of the natural flow regime (Poff *et al.*,

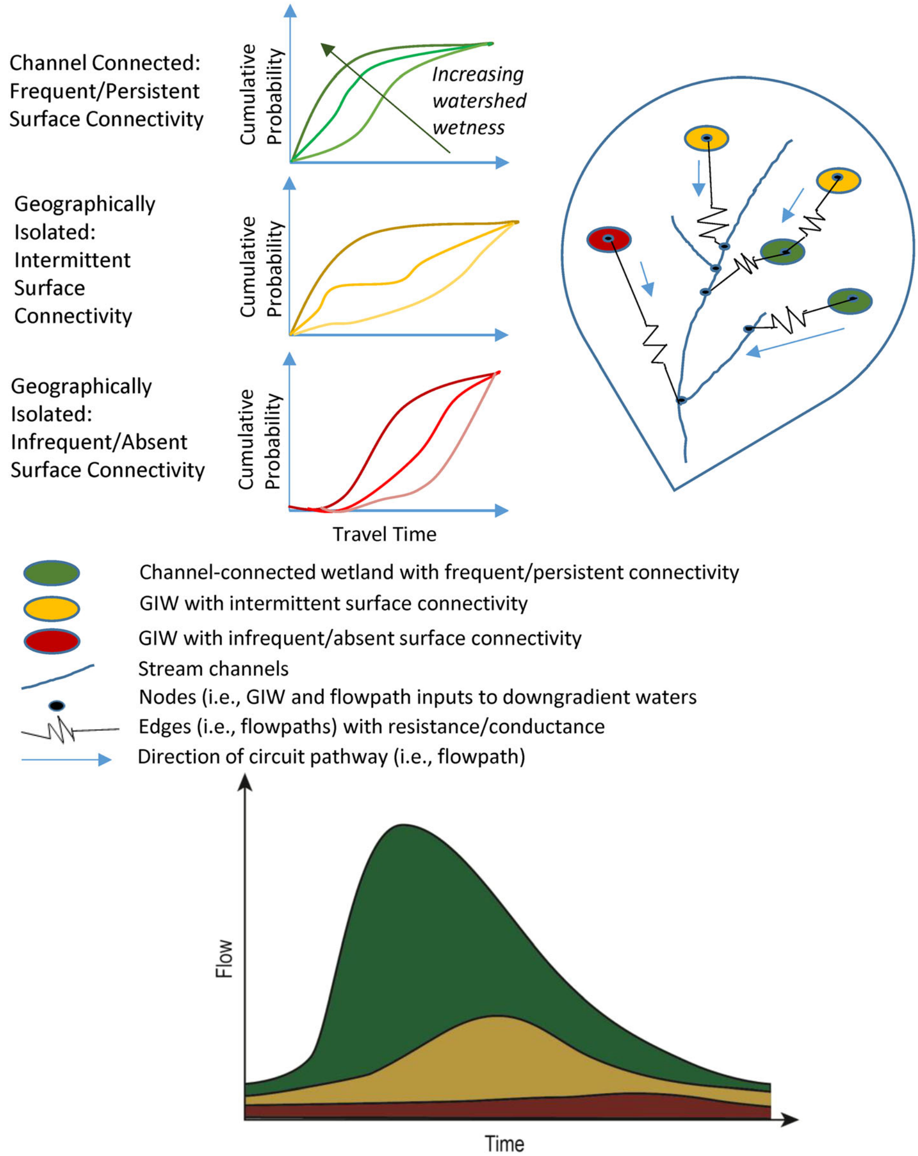

Figure 2. At a given moment in time, the effects of GIWs on downgradient hydrographs emerge from the convolution of the continuum of travel times between the portfolio of GIWs in the network and the downgradient water. The result is a component of the hydrograph composed of the time-varying contributions from each GIW in the network, which could collectively play important roles in maintaining the natural flow regime. Modified from Cohen *et al*. (In Review). GIW, geographically isolated wetland

1997). Because these flows are time varying, the effect on downgradient hydrographs is not fully realized until all GIWs have gone through complete annual and inter-annual cycles of connectivity (Phillips *et al*., 2011), so altering any component of the convolved hydrological response could change the natural flow regime, with potential impacts to downgradient waters.

Human Alterations to GIWs

Human alterations to GIWs can affect lag, sink, and source functions, thereby altering the convolved, watershed-scale hydrologic response. For example, sediments can be deposited in GIWs – either by direct placement or indirect sediment-laden discharge from the contributing basin – reducing storage capacity, sometimes by as much as 100% (Luo *et al*., 1997, 1999; Fenstermacher *et al*., 2014). Direct drainage of GIWs can result in the disproportionate loss of small GIWs and those distant from the stream network at the landscape scale (Lang *et al*., 2012), which can increase the runoff efficiency between the remaining wetlands and downgradient waters (Van Meter and Basu, 2015). Direct drainage also can alter the hydraulic gradients that arise between GIWs and adjacent uplands, thereby altering the surface water and groundwater exchange between GIWs and adjacent uplands (McLaughlin and Cohen, 2013). Regional groundwater pumping can lower hydraulic heads, resulting in enhanced groundwater recharge from overlying GIWs (Haag *et al*., 2005; Lee *et al*., 2009; Haag and Pfeiffer, 2012).

Human alterations to flowpaths also can affect the convolved hydrologic response. Ditching and tiling (e.g. for agricultural purposes) increase drainage efficiency, with the result commonly being that water is quickly routed into and/or out of GIWs (Randall *et al*., 1997; Min *et al*., 2010; Boland-Brien *et al*., 2014). This often more directly links otherwise remote GIWs to stream systems (Gamble *et al*., 2007) and has a significant effect on downgradient streamflows (Cohen and Brown, 2007; Babbar-Sebens *et al*., 2013). Even in the absence of direct ditching or tiling, changes in land use and/or land cover can alter flowpath dynamics, as the mechanical destruction of soil structure and the homogenization of microtopography in agricultural settings can increase runoff efficiency into and out of GIWs (Euliss and Mushet, 1996; van der Kamp *et al*., 2003; Pyke and Marty, 2005; Tsai *et al*., 2007; McDonough *et al*., 2014), and preferential surface water flowpaths can be established through animal-mediated soil compaction along trails often terminating at GIWs (e.g. Tanner *et al*., 1984; van der Kamp *et al*., 2003; Franzluebbers *et al*., 2012). In addition, increases in impervious surfaces in urban settings may also increase runoff efficiency, thereby contributing to downstream hydrograph 'flashiness' (Walsh *et al*., 2012; Faulkner, 2004). Conversely, the restoration of GIWs may moderate flows (McDonough *et al*., 2014).

Implications for Future Research and Policy

The extensive and dynamic hydrological flowpaths connect landscapes in four dimensions is well known as regards to stream networks (Ward, 1989; Nadeau and Rains, 2007; McDonnell, 2013). More poorly known and understood is the role that GIW nodes and related flowpath edges play in the functioning of the broader hydrological network, including the stream network. This represents a critical knowledge gap, especially in archetypal GIW-dominated landscapes (e.g. vernal pools, prairie potholes, and Carolina bays) where the number of these GIW nodes and related flowpath edges is large (Semlitsch and Bodie, 1998).

Does recognition of GIWs as nodes within the hydrological network mean that there is a significant nexus between the nodes and the chemical, physical, and/or biological integrities of downgradient waters? Whether this constitutes a significant nexus is a policy decision that we do not purport to advance here; nevertheless, GIWs certainly perform lag, sink, and source functions that can influence the chemical, physical, and/or biological integrities of downgradient waters, especially when considered in aggregate (Ogawa and Male, 1986; Hey and Philippi, 1995; Bullock and Acreman, 2003; Cohen and Brown, 2007; US Environmental Protection Agency, 2015). But few studies have sought to discern the specific effects of GIWs on downgradient waters (McLaughlin *et al*., 2014; Golden *et al*., 2015). Therefore, there remains a lack of general agreement on the roles that GIWs play in landscape-scale hydrology (US Environmental Protection Agency, 2015). Understanding the emergent properties of GIWs at the landscape-scale requires that we consider more than just the typical behaviour of a GIW or given class of GIW. Rather, it requires that we focus instead on the aggregate effects of a portfolio of functions and behaviours expressed by a network of GIWs and GIW complexes (Figure 2; Cohen *et al*., In Review).

An initial step towards improving our understanding of the aggregate effects of GIWs is the development of a classification system that can be used to define regions or conditions under which GIWs have expected behaviours that can be studied in aggregate, much like the concept of hydrological landscapes (Winter, 2001; Wolock *et al*., 2004; Wigington *et al*., 2013), although defined at scales and including factors more appropriate for the study of GIWs (Rains *et al*., 2008). The next step is to place an increasing emphasis on regional-scale data collection, including both field data and remote-sensing data. As regards to the latter, improvements in the sensitivity and temporal resolution of commonly available datasets might be necessary to map GIWs and related flowpaths, given that remote-sensing datasets traditionally used to map aquatic resources (e.g. aerial photographs) may have significant limitations when applied to GIWs (Lang *et al*., 2012; Yang and Chu, 2012; Lang *et al*., 2013). The final step is improving the sensitivity and accessibility of modelling and analytical tools that can be used to evaluate the aggregate effects of the portfolio of GIWs that emerge at the watershed scale. This might require the development of new model approaches with an explicit focus on the roles that GIWs play at the network scale (e.g. McLaughlin *et al*., 2014). Alternatively, this might instead only require the adaptation of existing models to better describe the fine-scale surface–subsurface interactions that characterize connectivity between GIWs and the broader hydrological landscape (Golden *et al*., 2014).

A concerted effort such as this could transform our understanding of watershed-scale hydrology, facilitating a better understanding of the roles played by GIWs and how these roles change depending upon spatial heterogeneity and temporal variability. A concerted effort such as this also would be timely given the ongoing debate about the geographic extent of the CWA, particularly as it relates to non-navigable, intrastate waters, including

GIWs. Under the current rule, non-adjacent wetlands, including non-adjacent GIWs, require case-by-case determinations of significant nexus if they are members of five subcategories (e.g. western vernal pools, prairie potholes, Delmarva Bays, Carolina Bays, or pocosins) or are within 1219 m of the ordinary high water mark or high tide line (US Army Corps of Engineers/US Environmental Protection Agency, 2015). A concerted effort such as this would improve upon the scientific understanding underlying the policy (e.g. US Environmental Protection Agency, 2015) and facilitate the development of improved policy and/or regulatory guidance (e.g. 80 FR 37054), better enabling decision-making regarding the geographic extent of WOUS subject to regulation under the CWA.

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