Integrating geographically isolated wetlands into land management decisions

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Wetlands across the globe provide extensive ecosystem services. However, many wetlands – especially those surrounded by uplands, often referred to as geographically isolated wetlands (GIWs) – remain poorly protected. Protection and restoration of wetlands frequently requires information on their hydrologic connectivity to other surface waters, and their cumulative watershed-scale effects. The integration of measurements and models can supply this information. However, the types of measurements and models that should be integrated are dependent on management questions and information compatibility. We summarize the importance of GIWs in watersheds and discuss what wetland connectivity means in both science and management contexts. We then describe the latest tools available to quantify GIW connectivity and explore crucial next steps to enhancing and integrating such tools. These advancements will ensure that appropriate tools are used in GIW decision making and maintaining the important ecosystem services that these wetlands support.

Wetlands perform hydrologic, biogeochemical, and biological functions that provide ecosystem services linked to human health and well-being (Junk *et al.* 2013). Despite considerable global policy attention toward improving their conservation in recent years, many wetlands remain poorly protected (Figure 1). At particular

In a nutshell:

- Wetlands in general receive insufficient protection and this is particularly true for geographically isolated wetlands (GIWs), which are completely surrounded by upland areas
- GIWs have recently gained policy attention because they provide important ecosystem services, but like most wetlands, their loss and degradation continues
- Knowledge of the hydrologic connections of GIWs to downstream waters is necessary for their management, particularly under US federal law
- We synthesize data and modeling tools to quantify GIW connectivity and assess consequent individual and cumulative effects on downstream waters
- The most defensible management decisions are based on knowledge from a combination of measured, modeled, and hypothesized GIW connections

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risk are so-called geographically isolated wetlands (GIWs) (Tiner 2003; Mushet *et al.* 2015; Leibowitz 2015), which are completely surrounded by uplands and lack apparent surface water connections to downstream waters.

GIWs exhibit wide spatial and temporal variations in their hydrologic connections to downstream waters. It is through the variability of these hydrologic connections and disconnections (ie their isolation) that GIWs support numerous watershed and ecosystem functions, including hydrologic regulation (Rains *et al.* 2016), nutrient retention (Marton *et al.* 2015), and provision of habitat or refugia for many organisms (EPA 2015; Cohen *et al.* 2016). GIWs are also important in the decision-making context because of their limited, and often case-by-case jurisdictional, protection (Creed *et al.* 2017). To help prioritize GIW protection and restoration, natural resource agency personnel around the world need better tools to quantify the hydrologic connectivity of these wetlands. For example, for management purposes, recent federal US policies require a clear demonstration of GIW connectivity to, and their individual and cumulative effects on, downstream waters (Alexander 2015).

At present, management objectives to protect and restore GIWs are often applied at the landscape scale and are meant to counteract adverse impacts on ecosystems and human health. In these cases, currently available tools (ie measurements and models) are insufficient if used singularly or incorrectly. For instance, it is not possible to make management decisions for the existing 8.3 million GIWs across the conterminous US (Lane and D'Amico 2016) based on individual data collection and analyses alone. This is also true for the potentially large number of GIWs that make up the remaining global
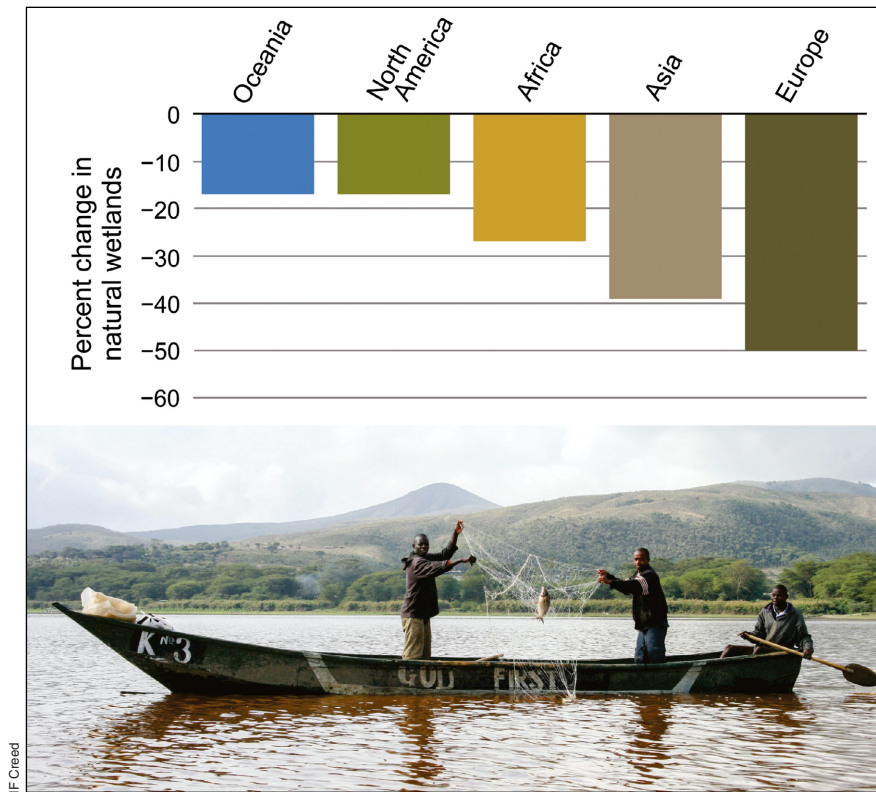
Figure 1. *The average global loss of wetlands – many of which are GIWs – is estimated at 31% since 1970 (Dixon et al. 2016). These losses have major societal consequences, including increased floods, impaired water supplies, impoverished biodiversity, and degraded fisheries. International policies (eg the Ramsar Convention on Wetlands) have sought to curb wetland loss with varying degrees of success. Although slowing in some parts of the world (eg North America), rates of wetland loss elsewhere (eg Europe) remain high. The photograph depicts Lake Naivasha, Kenya, a Ramsar Wetland of International Importance.*

arguments in the public sphere are commonly local and contextual, focusing more on reacting to public comments than on analysis of data (Depew and Lyne 2013). For example, public discourse led to a decrease in vaccinations for preventable diseases even though the data indicated the validity and success of such vaccines for individual and public health (Kata 2009). For GIW management, a measurement (ie the data) may demonstrate that water from a GIW flows into another water body, but a counterargument in the public sphere might be that the measurement only represents a specific outcome at one point in time. Adding models that verify measurements and confirm how GIWs connect to and functionally affect other water bodies under a wide range of plausible environmental conditions can further support science-based decision making.

Natural resource managers can therefore improve their effectiveness by integrating and adding new approaches to make decisions based on converging evidence (ie a set of similar conclusions derived from diverse independent sources). This may include an "ensemble approach" – combining multiple measurements and models. For GIW management, the most scientifically defensible information for decision making is based on a proportional mix of knowledge derived from measured, modeled, and hypothesized (often via models, data, and professional judgement) connections to other water bodies (Figure 2). Often, however, only a portion of that knowledge mix is available to managers, so that information frequently trends toward the vertices in Figure 2 (eg 100% hypothesized connections). Recognizing the challenges that managers face, we have attempted to show that novel measurements combined with models can assist in decision making by providing multiple lines of, or convergent, scientific evidence.

wetland extent. Therefore, scientists need to advance the integration of existing and new tools to efficiently gather evidence on these systems. This supportive science could then be used by natural resource managers, who make challenging and multifaceted local, state, provincial and national land management decisions.

Here we address the real-world challenge of protecting, conserving, restoring, and otherwise managing wetlands across the globe by: (1) discussing the need for GIW management tools, (2) describing the concept of GIW connectivity, (3) synthesizing current knowledge on the integration of GIW connectivity into measurements and models, (4) providing guidance for selecting tools to characterize GIW connectivity, and (5) identifying future advancements toward integrating GIWs into the next generation of hydrologic data and models.

■ Integrating GIWs into science and management

Evidence-based natural resource management is crucial for water stewardship, particularly for the protection and restoration of GIWs. Unfortunately, successful

■ Defining GIW connectivity

A factor that contributes to disagreements regarding how to approach GIW management is the ambiguity associated with the phrase "hydrologic connectivity" (Ali and Roy 2009; WebTable 1). There are many definitions of hydrologic connectivity, which, broadly speaking, can be grouped into structural and functional

connectivity. The former describes the spatial relationships between landscape elements (eg a GIW, a stream) to infer potential water movement, while the latter quantifies the actual movement of water across the landscape (Bracken *et al.* 2013; Okin *et al.* 2015).

We define GIW connectivity as the degree to which GIWs are linked to each other and to other landscape elements by surface-water flows (across the land surface), shallow subsurface-water flows (just below the land surface), and deep groundwater flows (over long distances and through large underground formations) – or a combination of the three (Figure 3a; Rains *et al.* 2016). These flows can vary temporally in their frequency, magnitude, duration, and direction (Figure 3b; Rains *et al.* 2016) and result from watershed properties relating to climate, geology and soils, topography, and land cover/land use (WebTable 2). Likewise, these flows may demonstrate spatial variation, such as through localized effects of individual GIWs on water movement (eg to groundwater), wetland-to-wetland water transfers within groups of GIWs, or cumulative effects of GIWs at the watershed scale.

Despite connectivity concepts being central to hydrology, the discipline has made only small contributions to decision making (Bracken *et al.* 2013), particularly with respect to GIWs. The variety of definitions of connectivity – together with the complexity of the connections over time and space – has led to the adoption of a wide assortment of measurement and modeling approaches. A synthesis of information to guide the selection of emerging tools to measure and model GIW connectivity has – until now – been absent.

■ Characterizing GIW connectivity

On the ground (in situ) and remotely sensed (satellite or aircraft) measurements can be used independently, in combination with other measurements, and in support of modeling efforts to characterize GIW hydrologic connectivity (WebTable 2). Measurements provide evidence that supports the development of a conceptual model of GIW connectivity in a specific system. Modeling, in turn, reduces the uncertainty of this conceptualization by corroborating measurements and also by projecting data beyond their original temporal and spatial boundaries. Therefore, the integration of measurements and models can improve and facilitate our understanding of the connectivity of GIWs, their downstream cumulative effects, and their functions at a broad range of spatial and temporal scales (Golden *et al.* 2014).

Measurements

Measured data (ie data derived from direct measurements) can be collected to produce GIW connectivity information that is implicit, quasi-explicit, or explicit with regard to its spatial detail or resolution (Figure 3c). We define *implicit connectivity* information as that which is
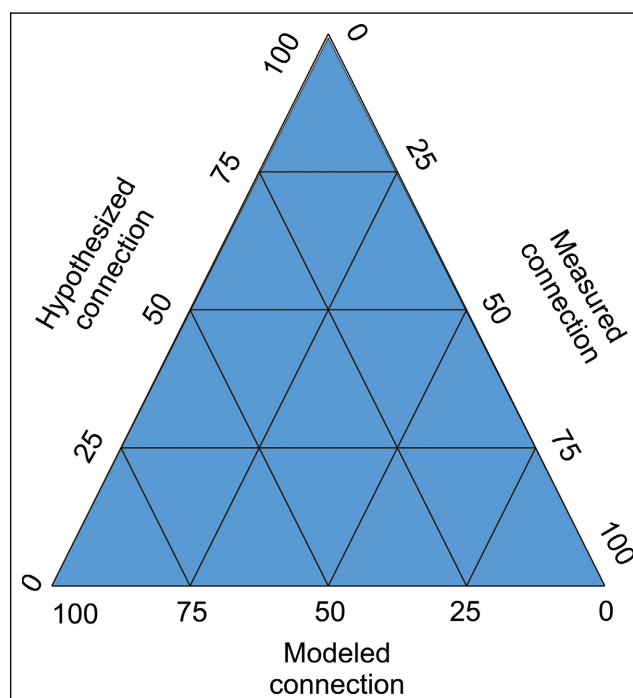

Figure 2. Knowledge regarding GIW connectivity for a particular management objective is a balance between hypotheses, model outputs, and measured data. Any point within the figure (a ternary diagram) represents the relative percent of connectivity knowledge from each source, which will add to 100%. For example, the vertex at the top of the figure represents a 100% hypothesized connection. A point in the middle of the diagram may represent connectivity knowledge from all three sources (eg 25% measured, 25% modeled, and 50% hypothesized connections).

estimated from data without spatial or locational detail. For example, the percent of GIWs in a watershed that potentially connect to other wetlands after a long rainfall event would be considered implicit connectivity information. *Quasi-explicit connectivity* information is produced when GIW connectivity is measured, and considered similar within smaller subsections of a larger system. In such a case, the measured length of time that one GIW within a subwatershed is hydrologically connected to another during the year may be assumed to represent that of all GIWs across that particular subwatershed. *Explicit connectivity* information is developed when each GIW and its individual flowpaths are separately measured across the entire area of interest. For instance, measurements of the frequency of water moving out of each GIW within a watershed would yield explicit information on the timing of its connectivity.

In situ approaches such as sensors and tracers (eg chemical compounds or isotopes used to track flowpaths) are particularly useful for assessing functional GIW connectivity. They can do so implicitly, quasi-explicitly, or explicitly (Figure 4), and at different temporal scales. Sensors can be used to infer GIW flow rates, flowpaths, and downstream
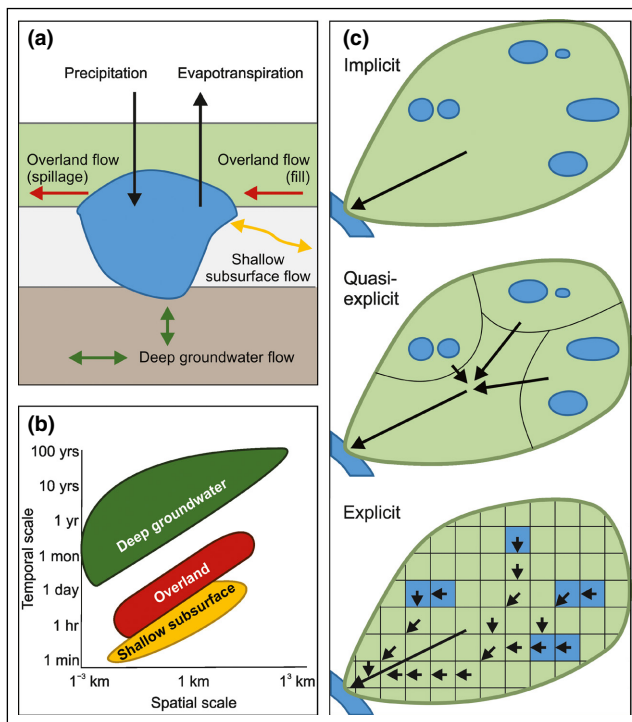
Figure 3. *Measuring, modeling, and representing GIW connectivity: critical needs for science and management. (a) Important flowpaths for GIWs, including precipitation and evapotranspiration as major wetland water inputs/outputs. (b) Generalized spatial and temporal scales of different GIW flowpaths (adapted from Blöschl and Sivapalan [1995]). (c) Types of GIW connectivity information provided by different spatial representations of connectivity: implicit (connectivity is assumed similar at the watershed scale, which is often associated with spatially lumped models), quasi-explicit (connectivity is assumed to be similar for portions of the watershed area, which is often associated with semi-distributed models), and explicit (each GIW's connectivity flowpath is measured or modeled individually, which is often associated with fully distributed models).*

connections. Examples include water-level recorders to calculate groundwater flows to and from wetlands at high temporal resolutions (McLaughlin and Cohen 2013), data loggers to mark the presence or absence of GIW surface water connections (McDonough *et al.* 2014), soil moisture or water table sensors to assess the spatial and temporal patterns of flowpaths (Jencso *et al.* 2009), and stream discharge measurements to correlate GIW inundation and downstream dynamics (Vanderhoof *et al.* 2016). Conservative tracers (ie chemicals, such as chloride, that undergo limited reactive processes while in transport) can provide direct evidence of connections by linking source and receiving waters (Rains *et al.* 2006).

Remote sensing, combined with Geographic Information Systems (GIS), can produce explicit information concerning both structural and functional GIW connectivity. The former type of connectivity is often quantified using the relationship between mapped wetlands (eg US Fish and Wildlife Service [USFWS] National Wetland Inventory Geospatial Data Layer) and streams (US Geological Survey [USGS] National Hydrography Dataset). Structural GIW connectivity also can be estimated from land elevation information, particularly from digital terrain models (DTMs) and the remote-sensing data used to produce them. DTMs are three-dimensional representations of surface terrain that can help to estimate volume of water or elevation thresholds above which connectivity occurs – both potentially key model parameters. Functional connectivity can be characterized using a wide variety of sensor types (eg various instruments on *Landsat*, *Sentinel-1*, *Radarsat-1* and *-2* satellites). With these sensors, scientists can assess functional GIW connectivity through the detection of GIW inundation and soil moisture changes over space and time (Lang *et al.* 2008, 2012; Huang *et al.* 2014; Vanderhoof *et al.* 2016). The spatial and temporal resolutions of remotely sensed data are important considerations for detecting GIW connectivity. The required resolution depends on management goals and landscape and climate characteristics.

Models

A suite of models are available to estimate GIW connectivity (WebFigure 1; WebTable 3) and, similar to measurements, provide implicit, quasi-explicit, and explicit connectivity information (Figure 3c). Few models were specifically developed for estimating GIW connectivity; however, many can be repurposed to do so (Golden *et al.* 2014). Prior to selecting a specific model, the following questions need to be answered:

(1) What are the dominant GIW flowpaths (eg surface water, groundwater, or both) for the management area?;
(2) How should these GIW flowpaths be represented across the landscape? (eg is the GIW connectivity information needed implicit, quasi-explicit, or explicit?); and
(3) How should thresholds that determine GIW connections and isolation be represented in the model?

Flowpaths can vary in time and among landscape types. The dominant flowpaths across a network of wetlands or within a watershed guide the selection of the GIW modeling approach. Surface flowpaths can be determined through a broad range of approaches including graph theory and simulations. Graph theory approaches are mathematical ways of representing a landscape through the relationship between points (such as wetlands) and lines (such as flowpaths; eg Larsen *et al.* 2012). Alternatively, some methods can simulate the full spatial and temporal range of surface-water routing from and into wetlands (eg Chu *et al.* 2013).

Groundwater flowpaths are relatively more complex but can be estimated through groundwater models (eg Harbaugh 2005) or models that couple surface and groundwater flow (eg Therrien *et al*. 2008).

Representations of GIW connectivity in models across the landscape are classified into three general groups, based on the type of GIW connectivity information they provide (WebFigure 1; WebTable 3). Spatially lumped models have no spatial detail and supply implicit GIW connectivity information (eg Liu and Schwartz 2011). Semi-distributed models break the watershed into subdivisions and produce information on quasi-explicit GIW connectivity (eg Evenson *et al*. 2016). Fully distributed models represent each point within the watershed and yield explicit GIW connectivity (eg Therrien *et al*. 2008; Ameli and Creed 2017).

Thresholds in connectivity modeling are values or equations that provide a switch to indicate when and where in the landscape GIWs transition from being isolated to being connected, or vice versa. Connectivity thresholds are used in models in different ways, producing either structural or functional connectivity. Otherwise, a model may rely on structural connectivity (eg land elevation across the landscape) as an input threshold and produce functional connectivity (eg the actual movement of water) as an output (WebFigure 1; WebTable 3). These thresholds can be modeled with empirically or process-based modeling approaches.

Empirically based models of GIW connectivity are primarily statistical or conceptual, requiring direct observations of connections to develop correlations between measured properties (eg wetland saturated area and streamflow; Creed *et al*. 2003). In contrast, process-based models simulate GIW connectivity processes. These models rely on rule-based thresholds above which the GIWs connect. For instance, connections may occur once a simulated maximum wetland water depth is reached and water spills out of the wetland. Alternately, they may allow connections to emerge in the landscape based on process laws (Bracken *et al*. 2013), such as the conservation of mass and momentum. Process-based models are generally more computationally and resource intensive than empirically based models.

◼ Selecting tools for GIW management

Model trade-offs

Model selection is one of the most formidable challenges when assessing the appropriate tools for extensive or complex GIW protection or restoration management projects. The model selection process involves trade-offs that balance the fidelity and complexity required and the resources – such as the skill, data, time, and money – available for a particular management objective (Figure 5). Model fidelity is the degree to which a model faithfully represents the actual attributes and
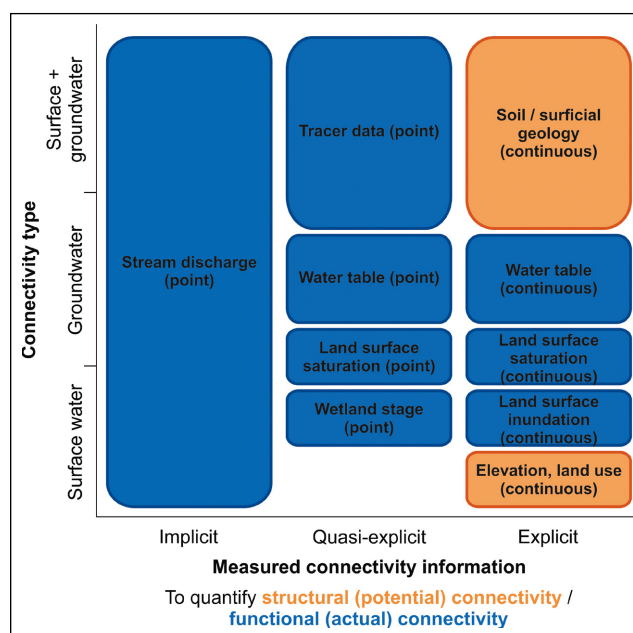

Figure 4. The presence or absence of GIW connectivity can be demonstrated by data to varying degrees, ranging in spatial detail from implicit (*no connectivity represented*) to explicit (*each GIW's connectivity flowpath is measured individually*). Examples of existing connectivity information derived from measured data are included here (detailed in WebTable 2). Point measurements are taken at specific locations and are often sparse. Continuous measurements are taken at regularly spaced intervals across the landscape, which allows continuous mapped surfaces to be produced from the measurements.

processes of the system (eg a wetland or watershed) being modeled. Model complexity refers to the number of factors (parameters, variables) and fluxes (eg the movement of water), and the degree to which physical processes of the system are represented in the model (Clark *et al*. 2015). In general, models with higher fidelity are also more complex.

As the need for model fidelity increases, so too does the necessity for resources (Figure 5a). In most cases, fewer resources are required to reach the potential fidelity of a spatially lumped model (which provides implicit connectivity information) compared to that of a fully distributed model (which produces explicit connectivity information). However, potential fidelity is often higher in the latter. Ultimately, selecting the lowest fidelity model needed to answer a given question is the best choice to minimize resource expenditures.

The information required for a management objective should influence the level of model complexity necessary to evaluate GIW connectivity. If limited resources are available, or if only implicit information is needed on GIW connectivity, a model with low levels of fidelity and complexity could be used (Figure 5b; eg an empirically based model such as that of Rains *et al*. [2006]). Alternately, in some situations, modeling skills and data
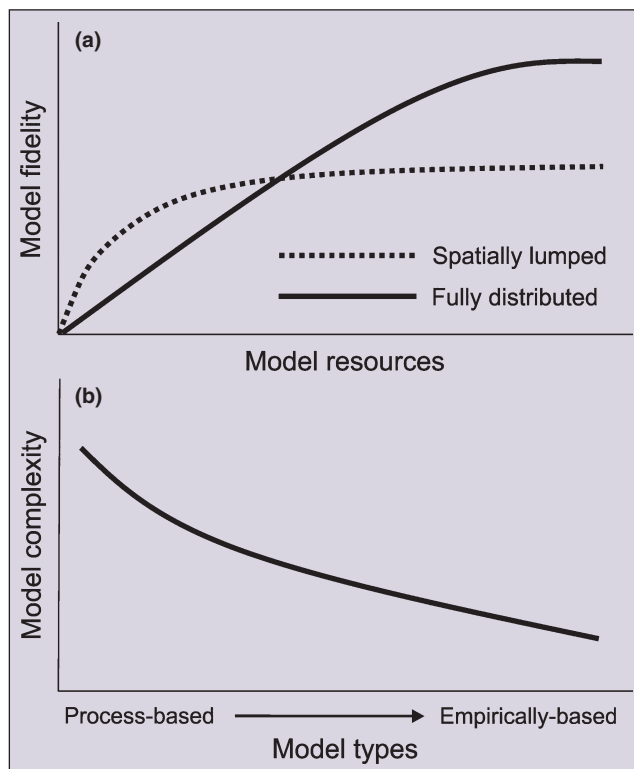
Figure 5. *A manager's guide to modeling GIW connectivity. (a) Trade-offs between* model fidelity *(the degree to which a model faithfully represents wetland or watershed attributes and processes) and resources are required for model selection. This hypothesized curve is modified by how connectivity is represented in the model, from* spatially lumped *(no spatial detail, providing* implicit connectivity *information) to* fully distributed *(represents each point within the watershed, providing* explicit connectivity *information). (b) Changes in* model complexity *(the number of model factors and fluxes, and the degree to which wetland and watershed physical processes are represented) occur along a process-based (simulated GIW connectivity) to empirically based (statistically or conceptually represented GIW connectivity) model gradient.*

on GIW connectivity are more abundant, or quasi-explicit or explicit connectivity information about GIWs is needed. These instances require models with greater fidelity and complexity, primarily process-based models. Such models may simulate a wide range of GIW flowpath dynamics (eg Min *et al.* 2010; Ameli and Creed 2017) and can provide greater support for data-driven decision making regarding GIW connectivity.

An effective and efficient science–policy interface

Scientists and managers need to collaborate and communicate to ensure that the most important GIW connectivity information is derived from models and measurements that will lead to optimal decision making. We argue that the primary issue for GIW protection

and management targets is selecting the "right" set of tools, not the "best" single tool. This is because different management questions regarding GIWs require different types of information. For example, predicting how a 10% reduction in GIWs within a basin will affect total nutrient runoff requires information regarding implicit connectivity; details regarding the spatial placement of GIWs on the landscape are not relevant to this question. Employing spatially lumped models and complementary measurements are most efficient in terms of resources expended for the knowledge gained. In contrast, predicting which particular GIWs most affect nutrient runoff requires explicit connectivity information, in which case details regarding the spatial placement of the GIWs on the landscape are highly relevant. Here, employing fully distributed models and complementary measurements is most efficient. Irrespective of which management question is posed, it is important that concordance among the different estimates be sought; that is, simple to complex approaches should all converge on the same answer.

The potential for such complementary use of measurements and models can be illustrated in the management of the Lake Winnipeg Watershed of North America (Panel 1). In recent years, the frequency and magnitude of eutrophication events has increased, leading to the 2013 listing of Lake Winnipeg as the most threatened lake in the world (Global Nature Fund 2013). The integration of measurements and models will play an important role in mitigating nutrient runoff by designing GIW restoration strategies to maximize retention of nutrients.

◼ Integrating tools for GIW connectivity

Scientists have reached a pivotal junction in the development of tools for quantifying GIW connectivity. The adoption of multiple measurements and models (ie an "ensemble approach") will be at the forefront of future developments. Convergence of these measurements and models will lead to greater certainty in evidence, less reliance on hypothesized connections (Figure 2), and therefore increased progress toward an integrated approach to decision making.

Measurements obtained from novel or advanced technology provide not only the measured data (ie "hard" data) but also sets of qualitative knowledge interpreted from them (ie "soft" data). This interpreted knowledge does not include exact numbers but enables insights about how a system works (Seibert and McDonnell 2002). In some cases, interpreted knowledge derived from measured data can be more helpful for modeling than the measured data themselves. For example, Vaché and McDonnell (2006) relied on measurements of surface flowpath distances (the measured data) to estimate variations in how long water is stored across a watershed (the interpreted knowledge). The interpreted knowledge was more effective as input to their watershed model.

Panel 1. Science to meet management needs – a spotlight on eutrophication

The financial cost of sound GIW management can be optimized by clearly defining the management question, understanding what information is required to answer that question, and using the appropriate type and combination of models and measurements.

For example, modifications to the Prairie Pothole Region (PPR) landscape of North America (Figure 6, a and b) have led to substantial GIW loss in the Lake Winnipeg Watershed

(Figure 6c). The removal of GIWs in the watershed is known to decrease the capacity of the landscape to sequester nutrient runoff, facilitating phosphorus (P) inputs from agricultural areas to surface waters and contributing to severe algal blooms in Lake Winnipeg (Ulrich *et al.* 2016). As a result, Lake Winnipeg was designated as the 2013 "Threatened Lake of the Year" (Global Nature Fund 2013). Restoration of GIWs to reduce P loads to Lake Winnipeg is one management strategy being considered.

A range of management questions are relevant to this issue. Each is associated with information at different spatial resolutions and requires different models and measurements, including:

(1) What are the cumulative effects of current drivers (eg agriculture) and pressures (eg loss of GIWs) on P loads to Lake Winnipeg?;

(2) What wetland restoration targets will help to lower P loading to the point where the risk of eutrophication events is reduced to acceptable levels?; and

(3) Where within the watershed should wetland restoration be prioritized?

As a manager goes from question 1 to question 3, the necessary knowledge about connectivity shifts from implicit to explicit, and the most efficient measurement and modeling approaches shift from spatially lumped to fully distributed.
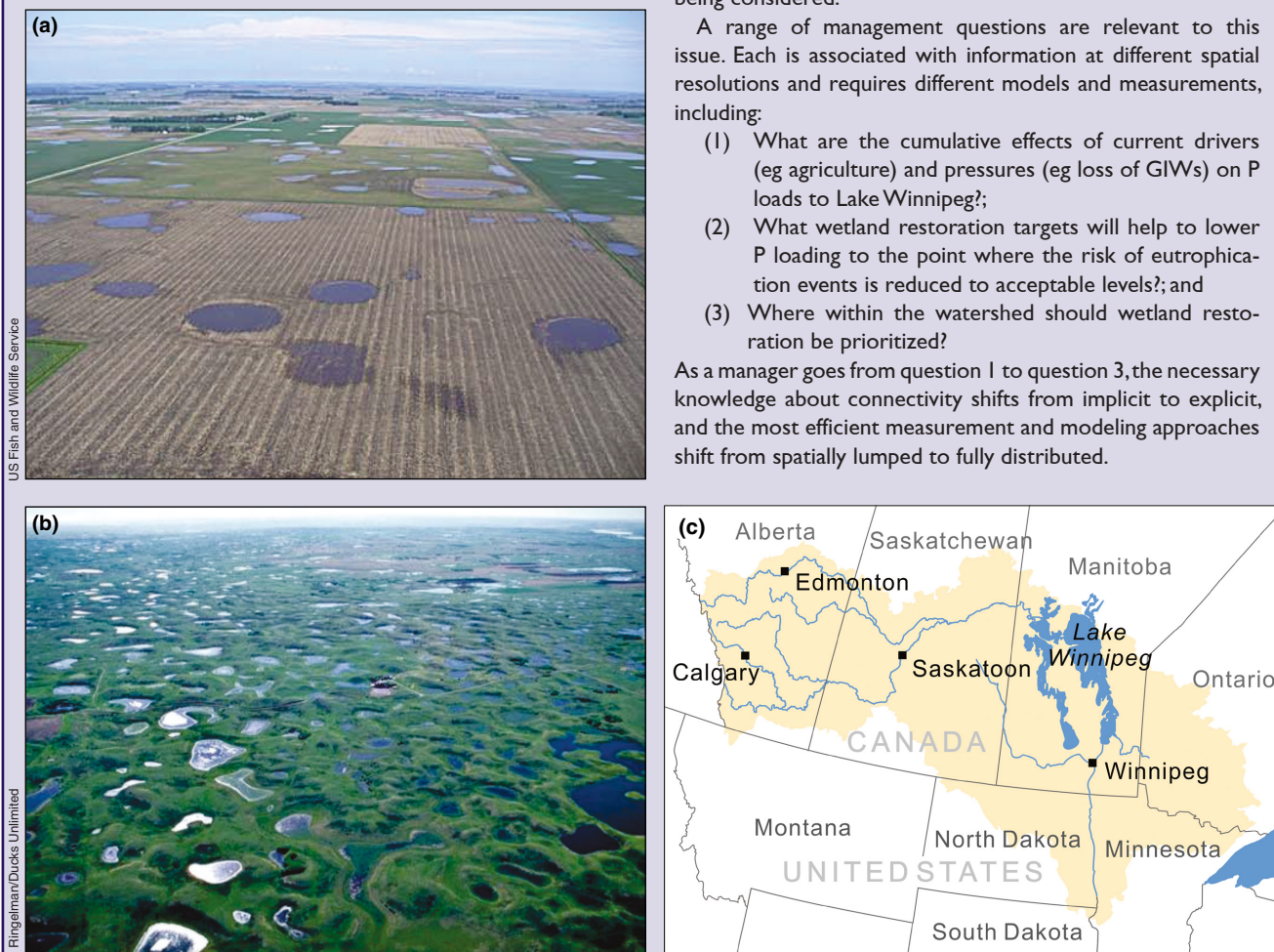
Figure 6. (a) GIWs in an agricultural landscape versus (b) the "original" distributions of GIWs in a landscape prior to human modification; (c) Lake Winnipeg Watershed.

Scientists who collect measurements and those who develop models must therefore be willing to consider both the direct use of measured data and the knowledge interpreted from them. The former can empirically demonstrate GIW connectivity, and the latter can provide insights on how to conceptualize GIW connectivity processes.

Modelers must become increasingly adaptable in terms of (1) modifying their models to better align with data produced by GIW connectivity measurements, and (2)

incorporating potential feedbacks as new data become available. Model advances should also follow the principle of Occam's razor where appropriate – meaning that models should have just as much complexity as needed to capture GIW connectivity for the targeted management question and context. At the same time, scientists should focus on developing interfaces for managers that interpret outputs of complex models.

Integrated measurement and modeling tools can also help to estimate and quantify how GIW connectivity

varies in space and time. For instance, Horton's scaling laws, such as those that scale small streams to river networks (Leopold *et al.* 1964), are used to develop simple models of water flowpaths and nitrogen transport (eg Gomez-Velez *et al.* 2015). Similar approaches could be developed to scale measurements at individual GIWs to multiple GIWs connecting across a landscape. Furthermore, better assessment of GIW dynamics – including expanding, contracting, and merging of GIWs based on climatic and landscape conditions – is needed. Such information can be obtained from remotely sensed data and extrapolated to other domains through modeling. Literature that describes approaches for estimating temporally varying connections of ephemeral streams (eg Czuba and Foufoula-Georgiou 2015) could inform methods for temporally varying connections in GIWs – both among GIWs and between GIWs and streams.

■ Conclusions

GIWs are frequently excluded from policy and management directives because evidence of their connections to, and consequent effects on, downstream waters is lacking. Recent recognition of extensive GIW declines combined with the growing importance of protecting wetlands equates to a crucial issue: scientists and natural resource managers alike are increasingly challenged to develop and select efficient tools to demonstrate GIW connectivity in the landscape. Scientists and managers must therefore collaborate to design appropriate models, standardize model input, and then translate model output into evidence.

Quantifying GIW connectivity through measurements is useful for developing conceptual models of hydrologic functions among groups of GIWs or within a watershed. However, measurements alone are resource intensive and often cost-prohibitive to collect, may not be comprehensive enough to provide the necessary evidence, and could contribute to misunderstandings about watershed systems. Models, combined with measurements, can reduce uncertainty (by reproducing measured data) and increase generalizability (by simulating GIW connections or isolation across a range of spatial and temporal scales). Integrating measurements with models will help to provide converging evidence of GIW connectivity, which is essential for improved decision making.

■ Acknowledgements

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■ Supporting Information

Additional, web-only material may be found in the online version of this article at http://onlinelibrary.wiley.com/doi/10.1002/fee.1504/suppinfo

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