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Review

Hydrologic connectivity between geographically isolated wetlands and surface water systems: A review of select modeling methods

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ABSTRACT

Geographically isolated wetlands (GIW), depressional landscape features entirely surrounded by upland areas, provide a wide range of ecological functions and ecosystem services for human well-being. Current and future ecosystem management and decision-making rely on a solid scientific understanding of how hydrologic processes affect these important GIW services and functions, and in turn on how GIWs affect downstream surface water systems. Consequently, quantifying the hydrologic connectivity of GIWs to other surface water systems (including streams, rivers, lakes, and other navigable waters) and the processes governing hydrologic connectivity of GIWs at a variety of watershed scales has become an important topic for the scientific and decision-making communities. We review examples of potential mechanistic modeling tools that could be applied to further advance scientific understanding concerning: (1) The extent to which hydrologic connections between GIWs and other surface waters exist, and (2) How these connections affect downstream hydrology at the scale of watersheds. Different modeling approaches involve a variety of domain and process conceptualizations, and numerical approximations for GIW-related questions. We describe select models that require only limited modifications to model the interaction of GIWs and other surface waters. We suggest that coupled surface–subsurface approaches exhibit the most promise for characterizing GIW connectivity under a variety of flow conditions, though we note their complexity and the high level of modeling expertise required to produce reasonable results. We also highlight empirical techniques that will inform mechanistic models that estimate hydrologic connectivity of GIWs for research, policy, and management purposes. Developments in the related disciplines of remote sensing, hillslope and wetland hydrology, empirical modeling, and tracer studies will assist in advancing current mechanistic modeling approaches to most accurately elucidate connectivity of GIWs to other surface waters and the effects of GIWs on downstream systems at the watershed scale.

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1. Introduction

Wetlands provide a wide range of ecosystem services important to human well-being, including flood regulation, fish and fiber production, contributions to water supplies, coastal protection, water purification, and recreational activities (Millennium Ecosystem Assessment, 2005). Geographically isolated wetlands (GIWs) are a specific subset of wetland systems and are characterized as depressional wetland areas on the landscape that are completely surrounded by uplands (e.g., prairie potholes, seasonal vernal pools, and cypress domes/flatwoods ponds Brinson, 1988; Tiner, 2003). GIWs are traditionally considered "isolated" because they often exhibit unmeasurable or limited hydrological connectivity to surface waters; therefore, any wetland systems with these characteristics can be considered "isolated". While GIWs operate at the periphery of aquatic ecosystems, these features provide a wide array of ecological and watershed values and functions, including the enhancement of watershed biodiversity, modification of

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watershed biogeochemical cycling, and the storage and recharge of water supplies (Leibowitz, 2003). In watersheds with a sufficiently dense distribution of GIWs, the hydrologic functions they provide could have important implications for flood regulation and mitigation of the future effects of climate and land use change. Further, garnering a clearer scientific understanding of the functions of GIWs-such as the extent to which GIWs are hydrologically connected to downstream surface waters-is also important for policy and decision-making, especially in areas with high GIW densities. For example, in 2001 the Solid Waste Agency of Northern Cook County (SWANCC) vs. the United States (US) Army Corps of Engineers ruling by the US Supreme Court invalidated the Clean Water Act's (CWA) Migratory Bird Rule that provided protection of GIWs (see Downing et al., 2003). This decision limited the scope of the United States Army Corps of Engineers CWA regulatory permitting program as it applied to isolated waters of the US. A subsequent 2006 US Supreme Court decision (*Rapanos v United States 547 U.S.__(2006)*) suggested that GIWs as a class could be afforded CWA protection if a *significant nexus* (e.g., a hydrologic connection) could be identified between GIWs and navigable downstream waters (Leibowitz et al., 2008).

As a result of the important policy implications for GIW protection and the human health and ecosystem services GIWs provide, scientists and decision makers face a critical challenge, namely the development of methods to: (1) Assess the extent to which GIWs are measurably connected to other surface waters via surface and/or groundwater connections and (2) Estimate the effects of GIWs on downstream hydrology. Such research includes characterizing mechanisms behind these hydrologic connections and quantifying how the aggregated impacts of GIWs within a watershed can alter downstream flows. This task, however, is particularly challenging. Surface water–groundwater connections are variable across spatial and temporal scales, physiographic settings, and ecoregions. Moreover, connections between GIWs and surface waters can occur via multiple pathways, including but not limited to overland flow (Wilcox et al., 2011), groundwater (Winter and LaBaugh, 2003), perched groundwater discharge (Brunner et al., 2009; Rains et al., 2006), or through horizontal near-surface flow (Pyzoha et al., 2008; Sun et al., 1996). Thus, tailored approaches to understanding connectivity will be necessary for specific physiographic settings, wetland types, and ecoregions. Also, few long-term data sets exist that can sufficiently elucidate these connections across seasonal, annual, and multi-year cycles (e.g., Cook and Hauer, 2007; Wilcox et al., 2011), and findings from these data typically apply only to the boundaries of the study site or watershed.

Models are therefore valuable tools with which to complement limited existing data on hydrologic connectivity between GIWs and other surface water systems. Mechanistic modeling approaches in particular also contribute to potential insights into the hydrologic and hydraulic dynamics driving these connections. However, while models that simulate wetland hydroperiods (the seasonal patterns of water levels in wetlands) and hydrodynamics (e.g., Dai et al., 2010; Mansell et al., 2000; Zhang and Mitsch, 2005), connections among non-isolated wetlands at the plot to field scale (e.g., Johnson et al., 2010; Voldseth et al., 2007; Yang et al., 2010; Zhang et al., 2009a), connectivity between floodplain wetlands and surface waters (Amatya et al., 1995; Karim et al., 2011; Min et al., 2010), and general groundwater–surface water interactions at broad spatial scales (e.g., Frei and Fleckenstein, 2014; Gilfedder et al., 2012; Rassam et al., 2013) exist, modeling approaches that explicitly simulate hydrologic connectivity between GIWs and other surface water systems, including streams, rivers, lakes, and other navigable waters at the watershed scale are limited and have only recently begun to emerge (e.g., Yang et al., 2010). Thus, the identification and development of such approaches is imperative for future guidance on managing GIW systems.

The goals of this paper are twofold. Our first objective is to review and describe examples of existing mechanistic modeling approaches that could be applied with minimal modifications (e.g., via parameter modifications or links to a separate model) to further advance scientific understanding concerning: (1) The extent to which hydrologic and hydraulic connections exist between GIWs and other surface water systems and (2) How these connections affect downstream hydrology at the watershed scale. Our goal is not to comprehensively review every potential modeling method available. Rather, we describe a subsample of select models with potential applications toward meeting our objectives and highlight their advantages and limitations. Models were chosen, in part, based upon their prospective adaptability for GIW hydrologic connectivity simulations and their documented use in answering questions related to hydrologic transport in watersheds of various scales. We consider the watershed scale to include multiple drainage areas ranging across various orders of magnitude (e.g., 0.1 km^2–1000 km^2). While temporal scales are not explicitly discussed, they are intrinsically associated with the time step the modeler selects to solve the governing equations of each respective model (e.g., typically–though not always–daily, if considering a watershed model or annually for the transient groundwater flow equation). Our second objective is to discuss empirical methodologies that could potentially improve the accuracy of these mechanistic models (e.g., statistical models, tracer studies, and remote sensing techniques) and summarize recommendations for model selection.

We recommend coupled surface–subsurface flow models (termed from Furman, 2008) in the majority of situations; however, watershed and groundwater models are robust and hold promise in systems dominated by a specific GIW flow regime (e.g., surface runoff versus groundwater flows). Moreover, coupled surface–subsurface flow models are very complex mechanistic models and require high level modeling expertise to set up and run. Each modeling type is therefore given similar weight in our review of potential modeling approaches. Detailing the potential modeling approaches described herein fills a fundamental gap toward advancing the science of GIW hydrologic connectivity modeling and the development of approaches to support future watershed scale decision making for ecosystem management.

2. Approaches for modeling hydrologic connectivity of GIWs in diverse watersheds

Debate exists regarding the term "connectivity" to describe dynamics such as the hydraulic connection between surface water and groundwater systems (Brunner et al., 2011). In this paper, we use the term hydrologic connectivity to describe the multiple transport means by which water directly issuing from a GIW connects with a surface water system, via groundwater flow (shallow aquifer or deep aquifer), surface runoff, or shallow subsurface flows. A general approach for assessing the degree of hydrologic connectivity of GIW systems using the model types described herein will, at minimum, involve the model selection process (detailed below), parameterization and calibration of the model, the development and implementation of scenarios that characterize GIW presence/absence, non-GIW presence/absence, and diverse spatial arrangements of these wetland systems throughout the watershed, and assessment of changes in streamflow at the model assessment point(s) in response to these scenarios. This general approach should provide insights to the extent to which GIWs influence downstream hydrology. Fig. 1 provides an example distribution of GIWs and (here, navigable) surface waters on the

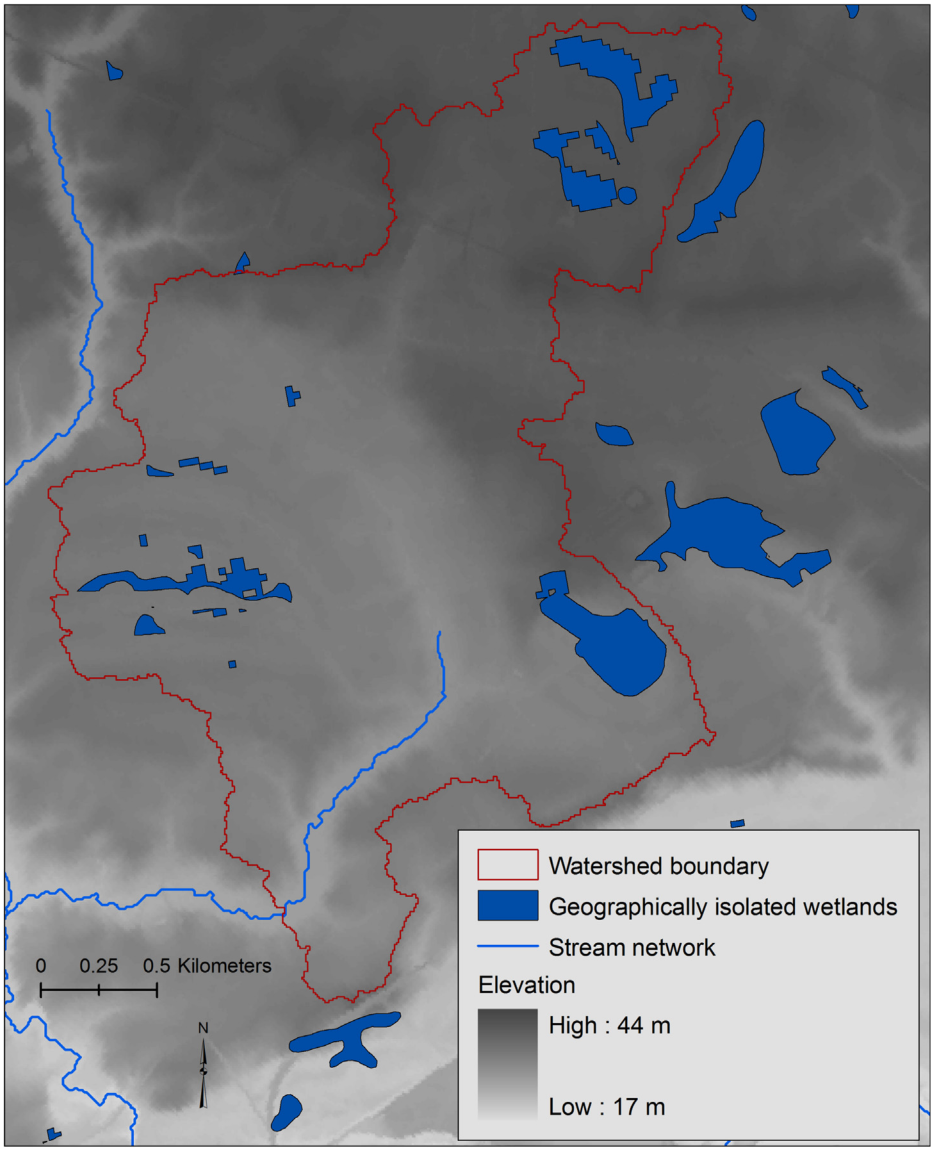

Fig. 1. An example distribution of GIWs on the landscape within a watershed boundary (Lower Neuse River Basin) in the coastal plain of North Carolina, USA; GIWs were delineated based on a distance-to-water body buffering methodology from Reif et al. (2009) and Frohn et al. (2009). Base wetland data are from the North Carolina Coastal Region Evaluation of Wetland Significance (NC CREWS) data set (Sutter, 1999). The stream network represents a simplified example of a navigable waterway. Note: non-isolated wetlands (e.g., riparian wetlands) and surface waters can also co-exist with GIWs on the landscape and within watershed boundaries. The GIWs and navigable stream network in this figure are for illustrative purposes only.

landscape within a watershed boundary for the context of future discussions.

The model selection process for assessing the degree of GIW hydrologic connectivity within a watershed initially involves the development of a conceptual model that characterizes GIW and watershed hydrologic and hydraulic processes based on site-specific or regional long-term monitoring data, remotely sensed data, past modeling efforts in the system, previous literature, professional judgment, or a combination thereof. As part of the model selection process the location and types of wetlands in the study watershed are identified (Lang et al., 2013, 2012) and the extent of surface waters (navigable or non-navigable) are evaluated to determine the spatial scale of the analysis. Model selection also includes consideration of data requirements (e.g., types and quality of data) for candidate models. Most model types require an accurate digital elevation model (DEM) to characterize connectivity gradients, in addition to spatial layers that map the locations of streams, wetlands, and other surface water features. Measured and long-term monitoring data (e.g., streamflow, wetland stage levels and variations in the areal extent of wetlands, hydraulic conductivity) are also an important requirement for each model type for calibration procedures, though some data requirements may vary by model type (e.g., pumping well and observation well locations for most groundwater models; accurate precipitation data for watershed models). Further, evaluating the model requirements (e.g., set up and implementation times) for spin-up, calibration, and uncertainty analyses is necessary. However, model selection must also consider the costs associated with minimizing model uncertainty via the increased computational intensity and data collection requirements of sophisticated models with the benefits of using simpler model approaches, potentially using the decision analysis framework detailed by Freeze et al. (1990). Finally, most models simulate mass balances within a collection of discretized units, such as regularly spaced grids or hydrologic response units.

Therefore, the size of the GIWs in the study area compared to the scale at which they can be represented in the model is an important consideration so that water storage and water fluxes can be accurately simulated.

GIWs are connected to landscape hydrodynamics in multiple ways (Winter and LaBaugh, 2003). The complex hydrodynamics of GIWs can be generalized as recharge, discharge, or flow-through systems (Euliss et al., 2004; Sun et al., 1995). GIWs are typically depressions on the landscape and thus receive overland and interstitial flow from surrounding portions of the "wetland watershed" (e.g., O'Driscoll and Parizek, 2003). Waters that move downslope to the wetland and from the wetland percolate downwards to an underlying aquifer are considered recharge systems. Discharge systems occur when groundwater levels are sufficiently high to fill the wetland system. Flow-through systems reflect high groundwater levels and water transport through the wetland along a hydrologic gradient (Crownover et al., 1995; Leibowitz and Vining, 2003; Sun et al., 1995; Winter and LaBaugh, 2003). A given GIW may exist along a continuum (Euliss et al., 2004) and express all three simplified states in any given year or season depending on phreatic and climatic conditions (Dempster et al., 2006; Hayashi et al., 1998; Pyzoha et al., 2008). It is also possible that GIWs within an integrated system are hydrologically disconnected from other surface waters during part or all of the year. For example, a GIW could be underlain by a confining layer and lose much of its standing water to evapotranspiration without generating overland flow.

For the purposes of this paper, we classify GIWs into two conceptual flow regimes: multi-directional flow systems or bidirectional flow systems (Figs. 2 and 3). A multi-directional flow system involves water entering a GIW via multiple flow paths, including overland, shallow subsurface (and sometime via return flow back to the surface), and/or groundwater discharge (Fig. 2). Water can also flow through or out of the system in any of multiple flow path directions, including spillover from the wetland (resulting in overland flow), shallow subsurface flow, saturated subsurface flow, and/or recharge to deep groundwater. These systems are inherently complex and seasonally variable (e.g., Sun et al., 1995). GIWs with bidirectional flow systems have impermeable layers beneath the surface soils (e.g. clays, fragipans), and are therefore relatively disconnected from the groundwater. Hydrologic connections of bidirectional flow GIWs are therefore likely only through overland or shallow subsurface flow (Fig. 3). We focus on representing both flow regimes and their effects at the watershed scale, ranging across several orders of magnitude, e.g., 0.1 km^2–1000 km^2, using mechanistic modeling approaches; however, we also explore emerging approaches including empirical modeling, tracer methods, and the application of light detecting and ranging (LiDAR) data in Section 3.

For the clarity of this discussion, we divide potential mechanistic approaches for modeling the hydrologic connectivity of GIWs into three categories: (1) Watershed models, (2) Groundwater models, and (3) Coupled surface–subsurface flow models (all defined in subsequent sections). Each model within these categories relies on hydrologic conceptualizations and mathematical structures that are particular to the hydrologic component of interest (e.g., surface water, shallow subsurface water, groundwater, surface water–groundwater interactions). Time steps for each model vary based on the user's choice of available temporal options for solving the model's governing equations. While we recommend the use of coupled surface–subsurface flow models in watersheds where GIW flow is dominated by multiple flow regimes (e.g., surface water and groundwater flows), a discussion of each modeling approach is critical. This is particularly true because each modeling approach and type offers alternative conceptualizations for GIW connectivity and in some systems, watershed or groundwater modeling applications are the most practical choice for scientific, policy, and/or resource purposes. Further, we recognize that some methods discussed herein can be considered modeling platforms that use a particular modeling method (e.g., MODFLOW, MIKE-SHE). However, for the purposes of this paper we describe all mechanistic modeling approaches, software, and platforms as "models".

2.1. Watershed modeling approaches

Watershed models are physically-based simulation tools that describe rainfall–runoff processes and often include an associated biogeochemical or pollutant fate and transport module that routes point and non-point source pollutants from the landscape to the stream. Hydrology modules within watershed models use topographically defined watersheds as boundaries and focus strongly on surface water runoff, and often shallow subsurface, processes. Therefore, even though most watershed models include percolation to deep groundwater systems as part of their mass balances, they are distinguishable from coupled surface–subsurface flow models because the groundwater flow equation is not explicitly solved (i.e., the deep groundwater system is considered a sink).

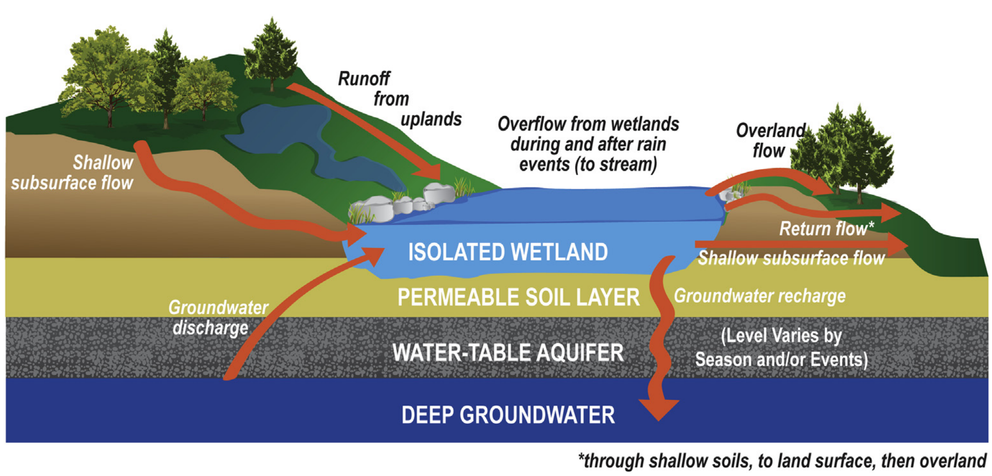

Fig. 2. Conceptual model of how GIWs are connected hydrologically to surface water systems where a permeable soil layer exists beneath the GIW (i.e., multi-directional flow systems).

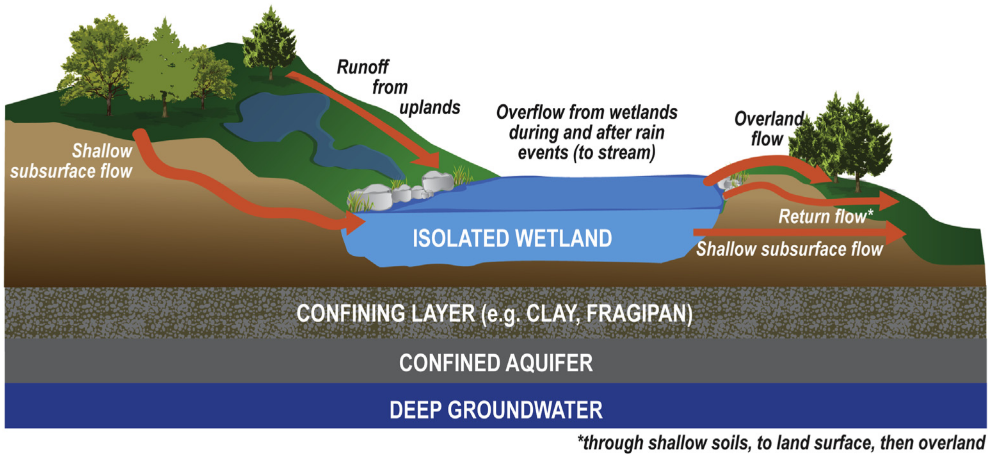

Fig. 3. Conceptual model of how GIWs are connected hydrologically to surface water systems where an impermeable soil layer (e.g., clay, fragipan) exists beneath the GIW (i.e., bidirectional flow systems).

Watershed models provide a mechanistic framework from which to pose questions concerning whether GIWs are measurably connected to other surface water systems, particularly via surface and shallow subsurface flows, and the effect of GIWs on the downstream hydrology of streams, rivers, and lakes at the watershed scale. The application of existing watershed models to answer such questions is limited (e.g., Yang et al., 2010); however, a wide array are adaptable for these purposes primarily because (1) many GIW systems exhibit potential (e.g., based on physiographic setting) for surface and shallow subsurface hydrologic connectivity to other water bodies and (2) watershed models are structured to dynamically link landscape features to downstream hydrologic and biogeochemical processes. Because multiple watershed models that address specific hydrological and/or fate and transport processes exist, discussions of watershed models comprise a considerable portion of this paper in comparison to those of groundwater and surface water–groundwater interaction models. Here we discuss a subset of watershed models readily adaptable to address GIW connectivity questions at a wide variety of spatial scales (e.g., up to and greater than 1000 km^2), including the Soil and Water Assessment Tool (SWAT), the Hydrological Simulation Program-FORTRAN (HSPF) model, the DRAINmod for WATershed model (DRAINWAT), TOPMODEL, the Grid Based Mercury Model (GBMM), and the Visualizing Ecosystems for Land Management Assessments (VELMA) model (Table 1).

2.1.1. *The Soil and Water Assessment Tool (SWAT)*

The Soil and Water Assessment Tool (SWAT) model is a popular semi-distributed mechanistic watershed model that is used to evaluate the effects of land management and agriculture on water, sediment, and chemical fluxes across a wide range of watershed sizes, land uses, and physiographic provinces (Neitsch et al., 2005). Recent applications of SWAT include evaluating the effects of climate change on watershed hydrology (Gül and Rosbjerg, 2010; Schilling et al., 2008; Shrestha et al., 2012; Wu and Johnston, 2007), assessing variations in nutrient fluxes arising from different land management practices (Du et al., 2006; Kemanian et al., 2011), and assessing the hydrology and nutrient fluxes of karst (Amatya et al., 2011; Buffaut and Benson, 2009) and low-gradient forested watersheds (Amatya and Jha, 2011). The SWAT hydrology submodule includes subbasin, reservoir, and channel flow routing. Within the subbasin structure, SWAT simulates a multidirectional flow regime using a modified curve number approach and includes surface runoff, percolation, lateral subsurface flow, groundwater flow, evapotranspiration, and transmission losses. SWAT divides each subbasin within a watershed into hydrologic response units (HRUs), which have similar land cover, soil moisture, and slope classifications. Uniform parameter values are assigned to HRUs of the same land/soil/slope classifications throughout a subbasin. SWAT can be run at multiple time steps (e.g., daily, sub-daily).

Recent advancements in SWAT applications involve the use of model parameters to calibrate the potential storage volumes of GIWs in a variety of subbasins, linking these volumes through periodic overland and groundwater transport to downstream surface waters [Wanhong Yang, University of Guelph, *personal communication*, 2011]. For example, SWAT allows parameterization of only one wetland and one pond per subbasin of which runoff is treated separately from the HRUs. In response to this, Wang et al. (2008) developed a method using SWAT called a hydrologic wetland equivalent (HEW) concept. The HEW concept describes a collection of wetlands within a subbasin using five key parameters: (1) The fraction of the subbasin area that drains to the HEW, (2) Surface area of the HEW at “average” water levels, (3) The volume of water stored in the HEW when filled to the “average” water level, (4) The surface area of the HEW at maximum water levels, and (5) The volume of water stored in the HEW when filled to its maximum water level (Wang et al., 2008). Each HEW is parameterized to perform the identical hydrologic functions as its component wetlands. This affords a means to incorporate GIWs into SWAT without compromising the rainfall-runoff representation in the model (i.e. because the concept uses existing model parameters). Other connected wetlands in the system (e.g, riparian wetlands) could be parameterized using the “pond” option so that hydrologic processes between the two wetland types would be simulated differently (though both would still be modeled as point sources to the stream). For example, Yang et al. (2010) utilized the SWAT model and the HEW concept in the prairie pothole region to simulate the influence of wetland restoration in western Manitoba, Canada, on streamflow and sediment fluxes at the watershed scale. Further, recent versions of SWAT allow “potholes” (i.e., ponded areas with detention storage) to be placed within each HRU (Neitsch et al., 2011), which could assist in simulating GIW hydrologic dynamics and contributions to streamflow. The HEW and pothole methods require further testing in diverse watershed settings and sizes but both are promising for systems in which GIWs exhibit primarily surface and shallow subsurface flow dynamics.

Table 1
Example watershed models that could be readily adapted to answer questions concerning geographically isolated wetland hydrologic connectivity.

Model	Hydrologic approach	Primary advantages for GIW research	Primary limitations for GIW research	Model files publically accessible	Available online user manual
Example Watershed Models					
Soil and Water Assessment Tool (SWAT)[a]	Modified curve number using semi-distributed hydrologic response units (HRUs)	Ability to characterize GIWs with parameters already built into the model using the HEW approach	Limited applicability in GIW groundwater-dominated systems; wetland parameters lumped for each subbasin; location of wetland within subbasin not considered.	Yes	Yes
The Hydrologic Simulation Program-FORTRAN (HSPF)[b]	Semi-distributed primarily infiltration excess runoff approach	Ability to characterize GIWs with parameters already built into the RCHRES model with limited modification	Limited applicability in GIW groundwater-dominated systems	Yes	Yes
DRAINMOD for Watershed (DRAINWAT)[c]	DRAINMOD-based flow; instantaneous unit hydrograph for overland flow	Ability to characterize parameters already built into DRAINWAT fields, or subcatchments, with limited modification	Limited applicability in GIW groundwater-dominated systems	No	No
TOPMODEL[d]	Semi-distributed variable source area rainfall-runoff approach	Capacity to assist in spatially identifying and simulating dynamics of standing water bodies such as GIWs	Limited applicability in GIW groundwater-dominated systems	Yes	Yes
Grid Based Mercury Model (GBMM)[e]	Spatially-distributed modified curve number approach	Could serve as a coupled surface water-groundwater model with GIW to GIW transport, with link to WhAEM	Wetlands placeholder in module needs to be developed and coded	No	No
Visualizing Ecosystems for Land Management Assessment (VELMA)[f]	Spatially-distributed approach using simple logistics functio based on soil saturation levels	Ability to simulate multiple subsurface dynamics of GIWs	Requires estimates of hydraulic conductivities for each GIW or GIW complex; lengthy computational time	No	No

[a] Neitsch et al., 2005; Wang et al., 2008.
[b] Bicknell et al., 2001.
[c] Skaggs, 1978; Amatya, 1993; Amatya et al., 1997.
[d] Beven and Kirkby, 1979.
[e] Dai et al., 2005; Tetra Tech, 2006.
[f] Abdelnour et al., 2011.

2.1.2. The Hydrological Simulation Program-FORTRAN (HSPF)

The Hydrological Simulation Program-FORTRAN (HSPF) is a semi-distributed watershed hydrologic and water quality model developed by the US Environmental Protection Agency (US EPA) to simulate water quantity and water quality processes using stream hydraulics and physical and empirical formulations (Bicknell et al., 2001). The HSPF model has successfully been applied on many watersheds of various sizes and terrains to assess the impact of sediment and nutrient transport on streams and groundwater (Anne and Uchrin, 2007; Chin et al., 2009; Liu et al., 2008). It simulates peak and low flows, nutrients, sediments, and user-defined constituents at hourly time steps. The model is primarily an infiltration excess model that separates precipitation into infiltration and non-infiltration parts, and comprises four main modules that control processes on the pervious surface (PERLND), the impervious surface (IMPLND), the stream and reservoir reaches (RCHRES), and the best management practices (BMP). The classification of land into pervious and impervious categories is based on land use, soil type, and surface geology. The hydrologic component for the land phase includes three flow types: surface runoff, interflow, and groundwater discharge, which are determined by processes of infiltration, loss to deeper groundwater, and storage in the upper and lower soil layers. Detailed description of each HSPF module and the physical and empirical formulations are found in Bicknell et al. (2001).

Most modifications of HSPF to model the behavior of specific hydrologic features such as constructed wetlands and different BMPs are implemented using the RCHRES module (Mohamoud et al., 2008; Nath et al., 1995; Nichols and Timpe, 1985; Said et al., 2007; Zhang and Ross, 2012; Zhang et al., 2009b). This is done by customizing the stage or depth, surface area, volume, and flow relationships expressed by a hydraulic function table (F-table). The RCHRES module in HSPF has been used to represent three watershed hydraulic components. The first component is the riparian wetland which is represented as a connected reach that directly discharges downstream, the second component is the geographically isolated wetland which is represented as a conditionally connected reach that is not directly connected downstream but discharges downstream only during conditions of very high water stage, and the third component is the stream channel network which is represented as a routing reach that receives water from the connected and the conditionally connected reaches and transports it to downstream sub-watersheds (Guerink et al., 2006; Zhang et al., 2012). The upland runoff is partitioned to connected, conditionally connected, and routing reaches based on the percent areal coverage of each reach type. The percentages are determined using GIS overlay operations. The above representations are fully implemented in the Integrated Hydrologic Model (IHM) which combines HSPF and MODFLOW (Guerink et al., 2006). Therefore, GIWs can be modeled in HSPF as storage-attenuation systems using the RCHRES module, which enables stage dependent flow from each GIW and the interaction of flow per unit area from groundwater systems to the GIW. Each GIW can be represented by a storage attenuation reach whose site-specific cross-section area is generated from wetland survey data or a digital elevation model (DEM), including LIDAR-based mapping (Lang et al., 2013; Lang and McCarty, 2009), while the depth-volume and depth-discharge relationships may be generated from models of Nilsson et al. (2008) and Mueses et al. (2007) or from HSPF model calibration. Such implementations include studies by Said et al. (2007) and Zhang et al. (2009b). Said et al. (2007) used the RCHRES module in HSPF to model shallow interconnected and isolated wetlands in Charlotte Harbor in Florida, while Zhang et al. (2009b) used RCHRES to model shallow interconnected and isolated wetlands in the Peace River watershed in Florida.

2.1.3. DRAINmod for WATershed (DRAINWAT)

The DRAINWAT (DRAINmod for WATershed) hydrology model (Amatya, 1993; Amatya et al., 1997) is a watershed-scale version of the DRAINage MODel (DRAINMOD) (Skaggs, 1978), an agricultural water management model originally developed to simulate the performance of drainage and related water management systems at a field scale on poorly drained soils with flat topography (Skaggs, 1978; Skaggs and Chescheir, 1999; Skaggs et al., 1991). DRAINWAT couples two DRAINMOD-based models: a field scale forestry version DRAINLOB (McCarthy et al., 1992) modified for forest hydrology and an agricultural watershed-scale version FLD&STRM (Konyha and Skaggs, 1992). DRAINWAT has been tested and modified to simulate the hydrologic balance and nutrient loading from agricultural, forested, and mixed land use watersheds over 100 km^2 (Amatya et al., 2003, 2004). However, DRAINMOD-based models such as DRAINWAT are limited to poorly drained high water table soils in low-gradient landscapes. DRAINWAT can be run at multiple time steps (e.g., daily, sub-daily).

DRAINWAT first combines outflow from each field with that of other fields that drain into the collector ditch of the subcatchment. An instantaneous unit hydrograph with a time of concentration concept is used to route the overland flow and ditch flow to the subcatchment outlet (Amatya et al., 2003, 1997). The simulated outflow from all subcatchments (fields) provides lateral inflow to the main channel network. The lateral inflow obtained after an iterative water balance with the ditch/canal reach is then routed through the channel system to the watershed outlet (Amatya et al., 2003). Details of the DRAINWAT modeling procedure including a sensitivity analysis of the parameters are described elsewhere (Amatya, 1993; Amatya et al., 1997; Kim et al., 2012; Konyha and Skaggs, 1992).

Based on the Amatya et al. (1995) application of DRAINWAT and the structure of model, there are two potential ways of specifically incorporating the hydrologic effects of GIWs into the model. First, DRAINWAT can treat up to approximately 200 fields (subcatchments) with land areas of 0.002 km^2 to approximately 1 km^2. These "fields" can represent different land cover types, including depressional wetlands (e.g., GIWs, Fig. 1). For example, a non-geographically isolated wetland (approximately 1.4 km^2) was simulated by Chescheir et al. (1994) as a subcatchment with multiple fields including overland and channel routing. Alternatively, the same wetland was simulated as one of 40 subcatchments in watershed-scale modeling in other studies in the North Carolina Coastal Plain (Amatya et al., 2004; Amatya and Skaggs, 2001; Kim et al., 2012). Within these fields/subcatchments, important parameters to consider in the model for GIW research include those related to depressional surface storage, drainage design, and physical soil properties (e.g., hydraulic properties, root depth), many of which can be derived from measurement data or spatial databases (e.g., SSURGO soils data (USDA-NRCS, 2013)). Both the daily overland surface runoff and subsurface drainage (simulated by DRAINMOD) from the ditches in each field are routed to the field outlet at the collector channel and/or stream for further transport downstream (capturing a maximum area of 200 km^2) in the channel/stream.

Second, the user of DRAINWAT could incorporate the hydrologic effects of GIWs by assigning depressions as small as 0.002 km^2 (e.g., a GIW) a high average effective surface depression parameter (STMAX, which describes microtopographical surface storage and controls on runoff following rainfall events) in the field containing the GIWs. This presents an alternative to representing each individual GIW as a stand-alone field, an approach that is limited by the number of fields a watershed-scale model can represent and the time requirements for parameterization and computation. The field with a GIW could be assigned as much as 20–30 cm effective STMAX (depending upon the size and depth), higher than that of other land cover types (Amatya and Skaggs, 2001; Amoah et al., 2012; Dai et al., 2008; Harder et al., 2006; Skaggs, 1980; Skaggs et al., 1991; Tian et al., 2012). This may result in a standing predicted water table on the surface during periods of rainfall and low evapotranspiration rates. While in theory this approach should work for integrating GIWs into DRAINWAT, further tests to apply this STMAX concept for GIW simulations in the model are needed.

2.1.4. TOPMODEL

TOPMODEL is a widely used physically-based watershed hydrologic model (Beven and Kirkby, 1979) that simulates multi-directional transport of precipitation through a watershed to its final endpoint as streamflow. TOPMODEL is a flexible mass balance modeling tool that has gone through numerous iterations (Beven, 1997a), as it can be adapted for individual research questions and linked to biogeochemical models for use in watersheds of a variety of sizes (e.g., 1 km^2–1000 km^2). The primary concept underpinning TOPMODEL's hydrologic structure is that the water table typically follows variations in topography. Therefore, TOPMODEL has often been applied in systems with highly variable elevations and steep terrain. Hydrologic simulations in TOPMODEL are driven by variable source area dynamics (saturated overland flow) and shallow saturated subsurface flows. Water balance accounting in the model is conducted by tracking the saturation deficit, or the amount of water needed in soil to bring the water table to the soil surface. A water balance is computed for each "reservoir" within the watershed, e.g., the soil reservoir and the interception reservoir. To route water through the watershed, the water balance from the multiple reservoirs are linked and a routing equation is computed. The model is considered semi-distributed because areas within the watershed that exhibit similar hydrologic responses to precipitation events are simulated with the same flow characteristics. These clusters of hydrologically similar response areas are based on a topographic wetness index (TWI) in which TWI = ln (a/tan β), where a is the area of the upslope drainage and tan β is the slope of the grid cell. TOPMODEL can be applied at variable time steps (e.g., daily, sub-daily) (Beven, 1997b).

TOPMODEL's potential application to simulate hydrologic connectivity of GIWs is system-dependent. In watersheds where a perched water table or shallow soils exist (Fig. 3), TOPMODEL has the potential to capture GIW dynamics and connectivity using the *qsrip* flow component. Within this flow component precipitation that falls on water bodies will either directly create surface runoff or gradually infiltrate to the shallow subsurface. Water stored in the shallow subsurface is assumed to move downslope toward the stream channel. TOPMODEL's TWI could also provide insights into mapping and delineating GIWs (Lang et al., 2013; See Section 3.). For example, high TWIs indicate areas where saturation-excess runoff is likely to occur on the landscape; these areas also point to potential groundwater discharge areas. Such high TWI locations may therefore correlate with wetland areas on the landscape (Lang et al., 2013). Tracking the spatial distribution of TWIs in the study watershed also provides insights to potential overland routes of GIW hydrologic transport by assessing the gradient of high TWIs to lower TWIs in the watershed. One key caveat for using TOPMODEL in the detection of GIW connectivity is that all standing water bodies (e.g., lakes, ponds, other wetland types) are considered hydrologically similar. Therefore, TOPMODEL would work best in systems dominated by similar GIW types and where a limited number of other lentic systems exist in order to discern the specific hydrologic effects of GIWs at the watershed scale.

2.1.5. Grid Based Mercury Model (GBMM)

GBMM is spatially-distributed grid-based watershed mercury (Hg) model that computes daily mass balances for water, sediment, and mercury within each GIS raster grid cell (GBMM v2.0, Dai et al., 2005; Tetra Tech, 2006). Recent applications of GBMM have been conducted in the Southeastern US in terrain with moderately varying relief and specifically focusing on hydrologic applications (Feaster et al., 2010; Golden et al., 2010), questions relating to mercury fate and transport (Golden et al., 2012), or a combination of multiple stressors (e.g., multiple land cover change scenarios) in the environment (Golden and Knightes, 2011) in watersheds ranging from less than 100 km^2 to greater than 3000 km^2. Within GBMM's hydrology module, daily fluxes from each grid cell are routed through watersheds to tributary networks and assessment points along stream channels. The selected resolution of each grid cell is dependent on the catchment size and the objectives of research or management questions. GBMM implements a simple water balance per grid cell on pervious surfaces to compute available soil water in the unsaturated zone when levels are greater or equal to wilting point. Runoff is computed using a spatially explicit modified Natural Resources Conservation Service (NRCS) curve number (CN) approach (NRCS-CN) (Neitsch et al., 2005). The modified NRCS-CN method varies the curve number calculations daily based on five day antecedent moisture conditions. Kim and Lee (2008) provide a detailed explanation of the modified NRCS-CN methods, and details of GBMM equations can be found in Golden et al. (2010).

GBMM has a placeholder (an area of the model coded to link to a future module) to incorporate wetland components though this remains an undeveloped area of the model. Because the model is spatially explicit and each grid cell has its own simulated daily mass balance, multiple GIWs in different spatial locations of the watershed could be assessed with further enhancement of the wetlands placeholder. Similar to the functioning within SWAT's wetland parameterization scheme, GIWs in GBMM could be modeled as point sources of flow to the stream network. Because the model focuses in most detail on surface runoff, GBMM would be best applied where bidirectional overland flow is the dominant hydrologic pathway connecting GIWs to surface waters (see Fig. 3). However, during the model set-up process in GBMM, the user can select whether the model should connect to the Wellhead Analytic Element Model (WhAEM) (Kraemer et al., 2007), which would link percolated groundwater and elevations along the stream into the GBMM simulations. The WhAEM model uses the analytic element method (discussed in Section 2.2) to represent regional groundwater flow systems and groundwater–surface water interactions. This option increases model set-up and computational time considerably. However, the linked watershed (GBMM) and groundwater model (WhAEM) could potentially be used to capture the connections between GIWs and downstream surface waters regardless of whether the GIWs were multi-directional or bidirectional flow dominated. With the current wetlands placeholder in the watershed model and additional tests linking GBMM to WhAEM, GBMM offers potential for evaluating the downstream effects of GIWs within the framework of a watershed-scale model. Such developments are ongoing (Christopher Knightes, US EPA, *personal communication*, 2013).

2.1.6. Visualizing Ecosystems for Land Management Assessment (VELMA)

VELMA is a spatially-distributed eco-hydrological model that simulates daily soil water infiltration and redistribution, evapotranspiration, surface and subsurface runoff, carbon (C) and nitrogen (N) cycling in plants and soils, and the transport of dissolved organic carbon, dissolved inorganic nitrogen, and dissolved organic nitrogen from the terrestrial landscape to streams (Abdelnour et al., 2011). VELMA has most recently been applied in widely varying terrains including a 0.1 km^2 forested catchment in the Pacific Northwest of the US (Abdelnour et al., 2011) and an approximately 80 km^2 watershed in the Coastal Plain of South Carolina, USA (Feaster et al., 2010; Golden et al., 2012). VELMA uses a distributed soil column framework to simulate the lateral and vertical movement of water, energy, and nutrients within the soil. The multidirectional modeling domain of VELMA covers the topographical surface (x-y) and four soil layers (z). The resolution of the soil system's grid cells is user-defined and based on the DEM resolution. The depth and thickness of each soil layer is also determined by the user. The soil column model consists of three coupled sub-models: 1) A hydrological model that calculates a water balance for each layer and simulates vertical and lateral movement of water within the soil, including a variable source area flow component similar to TOPMODEL (Wolock, 1993) and losses of water from the soil and vegetation to the atmosphere, 2) A soil temperature model that simulates daily ground soil layer temperatures from surface air temperature and snow depth, and 3) A biogeochemistry model that simulates C, N, and Hg dynamics. The soil column model is placed within a catchment framework to create a spatially distributed model applicable to watersheds and landscapes. The governing equations within the hydrological model of VELMA include a simple logistics function which is based on the degree of saturation within the four-layered soil column. Adjacent soil columns interact with each other through the downslope lateral transport of water. Surface and subsurface lateral flow are routed using a multiple flow direction method. A DEM is used to determine flow direction and compute flow contribution area.

The rate of the vertical and horizontal movement of water within and between grid cells is determined by the vertical and horizontal hydraulic conductivity parameters for each soil layer. Within VELMA, hydraulic conductivity can be modified based on land cover type within each grid cell (e.g., grid cells with GIWs could have different hydraulic conductivities based land cover type). This feature will also be available for different soil types within a forthcoming version of VELMA (Allen Brooks, US EPA, *personal communication*, 2012). Thus, hydraulic conductivity for each soil type in grid cells containing GIWs could be parameterized based upon the physical properties or measured values for that particular soil (i.e. the hydraulic conductivity values in soils underlying GIWs and other initial conditions in the model that represent soil moisture storage and hydrologic transport would be based on the soil type). The model would simulate groundwater and surface water connections from these cells containing GIWs to the stream network if the simulated daily soil saturation and calibrated hydraulic conductivity values are conducive to the initiation of flow from GIW grid cells. If multiple GIWs occur within a grid cell, lumped values (e.g., averaged hydraulic conductivity of soils beneath GIWs) could be specified for those GIWs, and the aggregated cumulative flows at the watershed outlet could be assessed with the incorporation of GIWs. Therefore, VELMA's multi-layer soil structure (and hydrologic transport mechanisms) would lend to the evaluation of multiple types of GIW connections via surface water connections and shallow groundwater flow because the simulated mass balances from VELMA indicate the flow contribution from each of the four soil layers.

2.2. Groundwater modeling approaches

Groundwater models focus on the movement of subsurface flows through saturated porous media. Traditional regional groundwater modeling approaches estimate the movement of infiltrated precipitation through regional groundwater flow networks using Darcy's flow equation (i.e., the groundwater flow equation), which considers the relationship among hydraulic conductivity, hydraulic gradient, area of the model domain, and fluid flow rates. Groundwater models can receive inputs from rainfall-runoff models. Therefore, associated surfaces water features, such as streams, rivers, lakes, ponds, and wetlands are considered boundary conditions to groundwater models and are not treated explicitly inflow simulations. Inflow, outflows, and water levels in GIWs across several physiographic regions in the US (e.g., parts of the Prairie Pothole Region) are dominated by complex groundwater flow dynamics. In these areas, interaction with the water table largely regulates GIW stage levels, and outflow from GIWs occurs primarily via groundwater flow (e.g., Euliss et al., 2004). Thus, groundwater model approaches would be appropriate for such systems.

While hydrologic connections between GIWs and local and regional groundwater dynamics can be simulated using groundwater modeling methods, the capacity to model connections via surface runoff and at the watershed scale depend on the selected modeling tool. Although multiple groundwater modeling approaches exist, we focus on two specifically: a popular model using the finite difference approach to solving the groundwater flow equation (MODFLOW Wetlands Package and a modification therein) and the analytic element method, an approach integrated into several software packages, for modeling hydrologic connectivity of GIWs and the effect of GIWs on hydrology at the watershed scale (Table 2).

2.2.1. MODFLOW

MODFLOW is the quasi-industry standard for simulating groundwater flow and originated in the 1980s from the US Geological Survey (McDonald and Harbaugh, 1984). MODFLOW is a finite difference model that simulates flow in three dimensions via a series of independent modules, where each module represents a different process. Finite difference approaches typically apply a regularly-spaced rectangular grid, and spatial derivatives are approximated based on the difference between variables (e.g., groundwater head) at neighboring nodes and the spatial distance between the nodes. Therefore, the model domain is discretized into rectangular blocks, and the values for potentiometric head in all the blocks are found based on a water balance for each block. The groundwater flow can then be reconstructed based on the potentiometric heads. MODFLOW is most suited for multidirectional wetland types where the water table is shallow yet resides below the surface for much of the year and flow of water is through the subsurface. MODFLOW can be simulated in time steps (transient flow) or as a steady state solution. Here we refer to MODFLOW as a groundwater model and specifically address its capabilities for modeling the connectivity of GIWs with groundwater flow systems. However numerous packages exist in which MODFLOW functions as a coupled surface–subsurface flow model, which we discuss in Section 2.3.1.

Restrepo et al. (1998) developed a wetlands simulation package linked to MODFLOW (MODFLOW wetlands package), which was calibrated and validated across a gridded region of greater than 26,000 km^2. The additions to the MODFLOW model include surface flows into and out of wetlands, wetland-aquifer flow interactions, evapotranspiration from wetlands, wetting and drying of wetlands, and sheet flow through dense vegetation and channel flow through sloughs. The wetlands package also includes variations in the wetland surface and subsurface water levels throughout the year. Based on these developments, Wilsnack et al. (2001) found that under relatively low hydraulic head gradients, solutions to the model's flow equation were highly sensitive to wetland transmissivity and were often not obtained because of the limited flow resistance in the wetlands. Gusyev and Haitjema (2011) increased the numerical stability of the finite difference solutions in the MODFLOW wetlands package by modifying calculations of the total discharge vector, including discharge from wetlands and aquifers.

Although recent studies describe some limitations of MODFLOW in respect to its simplified conceptualization of surface water bodies and associated boundary conditions (e.g., a river is either fully connected or fully disconnected (Brunner et al., 2010); the use of grid-based criteria for simulating stream–aquifer interactions is generalized (Mehl and Hill, 2010)), the MODFLOW wetlands package and modifications therein are useful tools to begin advancing current understanding of the hydrologic connectivity of GIWs with multidirectional flow, especially where groundwater is the dominant flow pathway. This is particularly true in low gradient physiographic settings such as the Florida Everglades (Gusyev and Haitjema, 2011; Wilsnack et al., 2001). However, further modifications to the MODFLOW wetlands package for quantification of GIW connectivity at the watershed scale are needed. These modifications include (1) Discretization and parameterization of the model so that water issuing from GIW complexes can be distinguished from other water body types and (2) Linkages between

Table 2
Example groundwater approaches that could be readily adapted to answer questions concerning geographically isolated wetland hydrologic connectivity.

Model	Hydrologic approach	Primary advantages for GIW research	Primary limitations for GIW research	Model files publically accessible	Available online user manual
Example Groundwater Models					
MODFLOW Wetlands Package[a]	Finite difference approach	Appropriate for GIW groundwater-dominated systems	Requires linked rainfall-runoff model watershed approach; limited applicability in GIW surface runoff dominated systems; solutions sensitive to wetland transmissivity values	No	Yes
Analytic Element Method (AEM)[b]	Analytic element approach	Flows accurate across broad spatial scales; models surface waters as linear features; appropriate for GIW groundwater-dominated systems	Requires linked rainfall-runoff model watershed approach; applicable to regional-scale watershed only; limited applicability in GIW surface runoff dominated systems	N/A	N/A

[a] McDonald and Harbaugh, 1984; Restrepo et al., 1998; Wilsnack et al., 2001.
[b] Strack, 1989, 1999; Haitjema, 1995; Fitts, 2002.

flows simulated by the MODFLOW wetlands package (i.e., groundwater-GIW flow and surface water flows into and out of the GIWs) and upland flows moving into and out of the GIWs. For example, Kim et al. (2008) integrated the SWAT watershed model with MODFLOW by linking SWAT HRUs to grid cells in MODFLOW. This approach allows simulations of the interaction between surface runoff, channel reaches, and saturated aquifer flow. Linking groundwater models such as the MODFLOW wetlands package with rainfall-runoff models might therefore include a simple approach where runoff simulated by a watershed model is manually provided by the user as a boundary condition for the MODFLOW wetlands package or via a distinct coupled surface–subsurface flow model system such as those in Section 2.3.

2.2.2. Analytic Element Method

The Analytic Element Method (AEM) (Fitts, 2002; Haitjema, 1995; Strack, 1989, 1999) creates a model domain that is discretized into hydrogeologic features, such as rivers, wells, and recharge zones, an approach that differs from other grid-based methods. This allows groundwater flow to be modeled over very large spatial domains (i.e., regional scale). The impact of each hydrogeologic feature (termed element) on the groundwater flow field is represented by an analytic function in terms of the discharge potential. The impacts of all the elements are superimposed to find the flow field. Spatial approximations of derivatives are not required in AEM; therefore, the flow field is not dependent upon specific spatial scales. Consequently, a single model can be used to investigate local (e.g., infiltration from a river due a pumping well) and watershed-scale water balance effects.

One of the main assumptions in AEM is that the resistance to groundwater flow in the vertical direction can be neglected so that flow is essentially horizontal (i.e., the Dupuit-Forchheimer assumption), a valid assumption for most groundwater models because the thickness of aquifers is usually small compared to the lateral extents of interest. For cases with significant vertical variations in the hydraulic conductivity, several two-dimensional layers can be "stacked" above each other, leading to a multiple-layered approach (Bakker, 2006). AEM also assumes that the aquifer is horizontal and that all aquifer parameters (e.g., hydraulic conductivity and porosity) are piecewise constant (i.e., constant over a specific area), although they are allowed to vary for different sections of the domain. In general AEM assumes steady-state flow (i.e., storage effects are neglected), although periodically-varying infiltration rates and time-varying impacts due to wells have been assessed in various applications (Bakker, 2010a; Bakker and Kuhlman, 2011; Furman and Neuman, 2003). AEM has been implemented into several software packages, ranging from commercial packages (e.g., GFLOW (Haitjema Software, 2007)), to open source projects (e.g., TimML (Bakker, 2010b)), and research codes (e.g., SPLIT (Bandilla et al., 2005)), each with its strengths and weaknesses.

The inputs to an AEM model for investigation of GIWs would include location, water level, and bed type (direct contact or flow resistance) of the GIWs and other surface water features (navigable or not); thickness, conductivity and porosity of any aquifers of interest; location, pumping rates and screened intervals of groundwater wells; and infiltration rates from precipitation. GIWs and surface water features (i.e., streams, ponds, lakes) can be modeled as constant head conditions if they are in direct hydraulic contact with the groundwater; otherwise a flow resistance can be assigned to the river bed (Bakker, 2007). Infiltration due to precipitation can be modeled through areal recharge rates (piecewise constant). For cases where seasonal changes in water levels and/or precipitation are important, a set of steady-state models (e.g., a model for the dry season and a model for the wet season) can be used to incorporate the seasonal change in boundary conditions. Once the groundwater flow field has been calculated, numerical particle tracking can be used to determine if water from a GIW reaches a surface water system (Barnes and Jankovic, 1999). Particle tracking is more accurate than just visualizing flowlines as particle tracks may pass under smaller streams (Bandilla et al., 2009), especially in a multiple-layer model.

AEM shows considerable potential for investigating the connectivity of GIWs to other surface waters, because modeling domains of large spatial extent (e.g., regional watersheds) is one of its strengths. At these large spatial-scales features of interest (i.e., the surface water system) can be considered linear features and the impacts of small-scale variations in aquifer properties become negligible, and thus a representation of piecewise constant aquifer properties should be appropriate. Due to AEM's ability to produce accurate solutions over a wide range of spatial scales (via a grid-free approach), fine-scale features (e.g., highly reactive zone along stream banks or flow obstructions such as sheet pile) can be included in a regional-scale model without significantly increasing the computational cost.

2.3. Coupled surface–subsurface flow models

The complexity of surface water–groundwater interactions has led to a traditional separation of the two domains; however, this artificial separation between surface water and groundwater process modeling has been diminishing with the development of new coupled surface–subsurface flow models within the past two decades (Brunner and Simmons, 2012; Kazezyilmaz-Alhan et al., 2007; Markstrom et al., 2008; Sun et al., 1996, 1998; Thompson et al., 2004). Coupled surface water–groundwater models are those which either simultaneously solve governing equations of surface and subsurface flows (e.g., Konyha and Skaggs, 1992; Panday and Huyakorn, 2004) or divide surface and subsurface flow into flow "regions" and subsequently couple governing equations describing flow in each region using iterative solution methods (e.g., Markstrom et al., 2008). These models either represent a coded, simulated link between existing surface water and groundwater models or are single models housing multiple modules that simulate transient or steady state transfer of water between surface water and groundwater domains. These integrated models or modeling systems are important for assessing complex watershed scale questions because they consider feedbacks among the various water balance components (e.g., evapotranspiration, surface runoff, groundwater flows). They may, therefore, be the most robust of the three modeling approaches discussed herein for answering questions related to GIW hydrologic connectivity in systems where multiple flow regimes are dominant. Consequently, coupled surface–subsurface flow models are often the most computationally intense and complex to set up and run, as these models require a high level of modeling expertise (e.g., to discretize and parameterize the system) and extensive field data to produce meaningful results. We provide an overview of two select coupled surface–subsurface flow models (GSFLOW and MIKE-SHE) and their potential for simulating hydrologic connectivity of GIWs and the influence of GIWs on downstream hydrology (Table 3), recognizing that a number of other models e.g., HydroGeoSphere (Brunner and Simmons, 2012) and ParFlow (Ashby and Falgout, 1996; Jones and Woodward, 2001; Kollet and Maxwell, 2006) in addition to recent methodological developments (e.g., Partington et al., 2011, 2012) could also provide promising contributions to GIW connectivity research.

2.3.1. GSFLOW

GSFLOW is a coupled surface–subsurface flow model that simulates multidirectional hydrologic processes across an entire

Table 3
Example coupled surface–subsurface flow models that could be readily adapted to answer questions concerning geographically isolated wetland hydrologic connectivity.

Model	Hydrologic approach	Primary advantages for GIW research	Primary limitations for GIW research	Model files publically accessible	Available online user manual
Example Coupled Surface Water–Groundwater Models					
GSFLOW[a]	MODFLOW (finite difference approach) for groundwater; Precipitation-Runoff Modeling System (PRMS) which uses a semi-distributed Hydrologic Response Unit (HRU) soil moisture accounting, continuous surface runoff approach	Models interaction of surface water and groundwater such that GIWs exhibiting complex flow patterns are potentially captured.	PRMS and MODFLOW linked with minimal changes to underlying code, so effort must be taken to parameterize GIW storage and transport differently than other wetlands types; high-level model expertise required for use	Yes	Yes
Coupled MIKE SHE[b]	Spatially-distributed physically-based MIKE-SHE rainfall-runoff hydrology using a uniform grid cell network and the MIKE 11 hydrodynamic simulation model	Models interaction of surface water and groundwater such that GIWs exhibiting complex flow patterns are potentially captured.	Complex, highly parameterized modeling approach; high-level model expertise required for use	No	Yes

[a] Markstrom et al., 2008.
[b] Refsgaard and Storm, 1995.

watershed (Markstrom et al., 2008), setting the stage for assessment of GIW hydrologic connectivity at the watershed scale. GSFLOW couples the 2005 version of the groundwater flow model MODFLOW (Harbaugh, 2005) with the US Geological Survey's Precipitation-Runoff Modeling System (PRMS; Leavesly et al., 1983, 2005). MODFLOW-2005 is a similar version of the finite-difference, three-dimensional MODFLOW groundwater flow model discussed in Section 2.2.1 (McDonald and Harbaugh, 1984). PRMS is a semi-distributed watershed model that simulates watershed hydrologic processes, including surface runoff that responds to a soil infiltration-excess gradient. Hydrologic simulations within PRMS are discretized into Hydrologic Response Units (HRUs), which are assumed to be homogenous in particular physical and hydrologic characteristics (e.g., land use/land cover, soil morphology, slope, distribution of precipitation) and in hydrologic response to precipitation events. PRMS has a modular design that allows selection of different rainfall–runoff process algorithms. Vining (2002) demonstrated the applicability of PRMS to questions related to wetland hydrology by simulating wetland storage and streamflow dynamics in an approximately 800 km^2 subbasin. MODFLOW and PRMS are spatially coupled so that flow is routed between PRMS' HRUs to MODFLOW's finite difference cells. PRMS simulates hydrologic processes from the plant canopy to the bottom of the soil boundaries and MODFLOW simulates hydrologic processes in streams, lakes, and the subsurface region below the soil zone.

GSFLOW is a promising approach for conducting investigations related to hydrologic connectivity of GIWs at the watershed scale, particularly in systems with highly variable flow dynamics (i.e., where surface, shallow subsurface, and groundwater flow dynamics contribute to GIW hydrologic behavior). However, such applications of GSFLOW have not yet been conducted (Steven Markstrom, US Geological Survey, *personal communication*, 2013). Because GSFLOW was developed with minimal modifications to the underlying codes of PRMS or MODFLOW, alterations to the way both models are parameterized would therefore be needed. Such modifications would include integrating the detention storage function in PRMS' HRUs (Viger et al., 2010) for use in GIW parameterization and either recoding or parameterizing the model such that hydrologic transport processes and connectivity dynamics similar to those measured, estimated, conceptualized, and a combination thereof for GIWs in the study watershed are represented. For example, because PRMS affords relative flexibility for selecting the hydrologic and physical characteristics that define HRUs in the study watershed, the user could categorize HRUs to correspond with different wetland types. HRUs containing GIWs could be characterized using a specific set of parameters (e.g., detention storage volumes, distribution of precipitation, temperature, solar radiation, plant type and cover) that influence HRU water balances and runoff, and riparian/non-GIW wetlands would be assigned a separate set of parameter values. Alternatively, MODFLOW finite difference cells could be parameterized to reflect the hydrologic conditions of component GIWs. Finally, a more rigorous approach would include coupling (and recoding) linkages of PRMS with the MODFLOW wetlands package described previously (Restrepo et al., 1998; Wilsnack et al., 2001) and making the modifications suggested for that package as well.

2.3.2. Coupled MIKE-SHE

MIKE-SHE is a physically-based, fully distributed, deterministic hydrological modeling system (Refsgaard and Storm, 1995) from which several additional modules have been developed that can be considered conceptual and semi-distributed approaches (e.g., Refsgaard et al., 2010; Thompson et al., 2013). MIKE-SHE simulates six key processes of the hydrologic cycle within a watershed system including overland flow and channel flow, unsaturated zone flow, saturated flow, interception and evaporation, snowmelt, and exchanges between aquifers and rivers. Watersheds are discretized into a uniform finite difference grid cell network within which parameter values (i.e., watershed characteristics such as soils, land cover, elevation, precipitation) are spatially distributed. User-defined soil and hydrogeological parameters can also vary with depth within each grid cell. Overland and saturated subsurface flow can occur between grid squares. Horizontal flow in the unsaturated zone is assumed to be negligible; therefore, only vertical flow in the unsaturated zone is considered. Early work that applied MIKE-SHE in watersheds with abundant wetland systems revealed limitations with the channel flow component of MIKE-SHE (see Al-Khudhairy et al., 1999; Thompson et al., 2004). Dynamically coupling MIKE-SHE with a more sophisticated MIKE-11 hydraulic modeling system, which can represent structures such as weirs and culverts in addition to processes such as river-aquifer exchange in wide channels and floodplains, has helped to overcome these limitations. This coupling of MIKE-SHE and MIKE-11 is dynamic in that water levels from coupled reaches are fed into the MIKE-SHE river system, MIKE-SHE simulates overland flow to MIKE-11, and feedbacks between the two models can then take place with each subsequent time step. Coupled versions of MIKE-SHE have been applied to small catchments (Thompson et al., 2009, 2004), mid-sized watersheds (e.g., Huang et al., 2010; Singh et al., 2011), and large basins (e.g, Andersen et al., 2001; Stisen et al., 2008; Thompson et al., 2013).

Coupling MIKE-SHE and MIKE-11 offers a spatially explicit comprehensive surface water–subsurface water modeling system to explore the effect of GIWs on downstream surface water systems, though applications of the coupled MIKE-SHE system in watersheds of varying sizes with abundant GIWs are limited. In a related approach, however, Dai et al. (2010) first calibrated and validated the MIKE-SHE model with measured daily flows and water table depths for a 1.6 km^2 forested wetland watershed and then linked MIKE-SHE with the DeNitrification-DeComposition (DNDC) model to assess the greenhouse gas emissions from the watershed, including those from wetlands on the landscape (Dai et al., 2011). The coupled MIKE-SHE system could be similarly applied in multiple ways to ask important GIW connectivity questions, where GIW hydrologic transport vectors including discharge, recharge, overland flow, and shallow subsurface flow could be simulated. First, a small watershed system could potentially be discretized so that single GIWs fall within single grid cells. Parameters contributing to GIW storage and hydrologic transport (i.e., those included in the governing equations for these processes, such as surface detention storage and horizontal and vertical hydraulic conductivity) could be adjusted based on measured values such as water levels from well and piezometer data, spatial databases that detail soil physical characteristics (e.g., SSURGO data (USDA-NRCS, 2013)), a conceptual model of the storage and flow characteristics of watershed GIWs, or a combination thereof. The degree of hydrologic connectivity of watershed GIWs would then be assessed by comparing streamflow generated by a calibrated model that considers GIW storage and transport parameterization explicitly and one that does not. However, the approach of discretizing the system by GIWs would be complex in larger systems with many small GIWs or in systems with a variety of GIW sizes, i.e., the number of grid cells would become far too abundant for efficient computation.

Another approach for assessing the influence of GIWs on downstream flows using coupled MIKE-SHE would therefore include discretizing the system such that multiple GIWs fall within the grid cells and the grid cells would be parameterized based on lumped (e.g., averaged) values for all collective GIWs within that cell. Floodplain and otherwise "connected" wetlands would require different parameterization. For data-intensive models such as coupled MIKE-SHE, decisions concerning the most sensitive parameters for which accurate initial parameter values must be ensured and those that can be calibrated within a range of literature values would be based on the conceptual model of wetlands within the watershed and, potentially, a sensitivity analysis (e.g., using the autocalibration module Autocal within MIKE Zero, the common interface to most MIKE-SHE models) in the initial stages of the modeling effort. This is particularly important because coupled MIKE-SHE models could be used to investigate GIW connectivity and downstream affects for watersheds of diverse scales across which sensitivity of parameters may vary greatly.

3. Approaches for improved model parameterization and prediction testing for GIW hydrologic connectivity

Several empirical methodologies hold potential to improve the accuracy of mechanistic modeling approaches by providing parameter value estimates (e.g., GIW volumes, timing of storage and release of wetland flows), locations and the spatial distribution of GIWs, additional insights related to GIW hydrologic connectivity at watershed scales (e.g., by remotely sensed data or statistical models), improved conceptualizations for GIW hydrologic processes, and additional data for testing model predictions.

3.1. Statistical models

If field (e.g., discharge, precipitation) and spatial (e.g., location and area of GIWs, land cover) data are available at specific sites, statistical models similar to Creed et al. (2003) allow a steady state analysis that links landscape characteristics to watershed hydrology and water quality data. Using a regression-based approach, the authors found that "cryptic wetlands" (i.e., closed canopy wetlands with no indicator canopy species specific to wetlands) exerted considerable influence on dissolved organic carbon watershed export. Similar statistical approaches could therefore highlight important factors associated with GIWs (e.g., maximum and minimum volumes and surface depressional storages, distance to stream network, percent GIWs in watershed) that influence flows and also point to important variables to accurately parameterize in the distributed watershed-scale mechanistic models.

3.2. Mass balance and solute tracers methods

Empirically-derived mass balance analyses provide important process-level data that assist in building conceptual models of GIW hydrologic connectivity at specific locations and a database of parameter values for mechanistic models that simulate the interaction of different water sources at watershed scales. These analyses are based on the conservation of mass and typically use field measurements to elucidate the source of a dissolved element in surface waters by accounting for all known sources, losses, or sinks. As such, a current use for these mass balance approaches is to identify and calculate the source of different hydrologic fluxes (primarily groundwater) entering surface water systems, including lakes, rivers, and estuaries (Bencala, 1983; Charette et al., 2003; Cook et al., 2008; Farber et al., 2004; Raanan et al., 2009; Raanan Kiperwas, 2011). These approaches also have the potential to provide insight into the interaction between water bodies (e.g. GIWs and other surface waters), so long as all the sources and sinks of the modeled component are known, accounted for, and have a unique signature of that dissolved element (e.g., isotopic composition, ionic ratio, concentration). The fact that these analyses are based on collected samples provides a mean for validating their accuracy; however, they are also highly site specific and are unable to incorporate changes to the boundary conditions (e.g., variations in climate and land use).

Although methods for tracking flow pathways such as the use of empirically-derived mass balance models can improve mechanistic model performance and parameterization, they are complicated by spatial and temporal variations in hydrologic pathways and uncertainties in the location of GIWs. Tracer experiments using ^{15}N, bromide, salt solutions, or other conservative compounds are compromised by the wide spatial and temporal connectivity of aquatic systems (Bencala et al., 2011), the need for close proximity between release and measurement points for pathway delineation (e.g., Mulholland et al., 2004; O'Brien et al., 2012), and the requirement of low to moderate flow conditions (Alexander et al., 2009). Others have explored the use of alternative tracking materials. For instance, Old et al. (2012) developed a novel approach for delimiting transport pathways in headwater systems using fluorescing particles. This method has obvious applicability to determining hydrologic connectivity of GIWs; however, the approach is limited to overland flow.

3.3. Remote sensing and emerging geophysical techniques

Accurately determining the location and variations in the areal extent of GIWs through the use of remotely sensed and other geographic data can likewise inform mechanistic modeling approaches because the spatial location and extent of the GIWs influences the potential flow paths from GIWs to surface water systems (e.g., via soil hydraulic properties assigned to that location in the watershed and the flow transit distance to a stream). However, delimiting GIWs can be challenging due to their typical small size and structural/vegetative characteristics (Tiner et al., 2002). Various techniques have been employed to identify GIWs including a combination of digital raster graphics (digital versions of US Geological Survey 7.5° topographic maps), digital elevation models, and digital orthophoto quads (McCauley and Jenkins, 2005); National Wetlands Inventory data augmentation and manipulation (Martin et al., 2012); remotely sensed Landsat data (Frohn et al., 2012); or a combination of remotely sensed and GIS data (e.g., Reif et al., 2009). Based on a variety of these techniques, several recent studies characterize GIWs as abundant and ranging widely in size across landscapes in the Southeastern US (Lane et al., 2012) and southwestern Georgia (Martin et al., 2012), vernal pools in Massachusetts and New Jersey (Burne, 2001; Lathrop et al., 2005), and geographically isolated playa lakes in Kansas (Bowen et al., 2010).

New techniques for delimiting GIWs are emerging that can better quantify spatial location, size, and hydrologic functions (e.g., McLaughlin and Cohen, 2013), further informing modeling research to identify the extent of GIW hydrologic connectivity with other surface waters (Hwang et al., 2012; Lang et al., 2012; Pitt et al., 2012). The capabilities for remotely sensing wetlands through measuring reflected or absorbed wavelengths from the visible (0.3–0.7 μm) to thermal infrared (3–15 μm) is steadily increasing (see Sass and Creed, 2011). Adam et al. (2010) reviewed both airborne and satellite multispectral and hyperspectral sensor wetland discrimination and classification methods with applicability for delimiting GIWs. Lang et al. (2008) found that synthetic aperture radar data could be used to map forested wetlands and hydrologic pathways in Maryland and Lang et al. (2012) used aircraft-borne light detection and ranging (LiDAR) remotely sensed data to characterize wetland and hydrologic flow pathway delineations, consistent with the hypothesis made by Trettin et al. (2008). Further, recent advancements in high resolution LiDAR data and satellite imagery have increased the feasibility of identifying small GIWs with LiDAR-derived DEMs with grid cells as fine as 1 m × 1 m (Amoah et al., 2012; Lang et al., 2012). These fine-scaled data improve estimates of surface depressional water storage, an important parameter for most watershed-scale GIW connectivity modeling efforts. Hwang et al. (2012) recently applied remotely sensed hydrologic vegetation gradients (using the IKONOS satellite system) to detect lateral hydrologic connectivity in headwater systems. Finally, where the availability of remote sensing data are limited, Pitt et al. (2012) demonstrated that engagement with local experts and citizens can be useful to determine the location of GIWs and Shore et al. (2013) highlighted the development of catchment-scale hydrologic connectivity indices using GIS and other spatial analysis approaches.

Improved spatial and temporal resolution in satellite imagery and the increased availability and affordability of airborne remotely sensing data (e.g., US Geological Survey Center for LIDAR Information Coordination and Knowledge (http://lidar.cr.usgs.gov)) will therefore continue to increase our knowledge of the location and size of isolated wetland systems. However, empirical data that elucidate flow paths, and consequently assist with parameterizing models that link GIW systems to other waters, remains a significant research need.

4. Model selection: summary

Questions concerning the hydrologic connectivity of GIWs require timely answers, particularly to keep pace with decision making. Therefore, existing mechanistic modeling tools, with some modifications, are at the forefront of these inquiries. Determining the modeling approach necessary for research focusing on the extent to which GIW hydrologic connectivity exists within a watershed depends on many factors including, at minimum, the spatial scale and priorities of the specific research or policy question, the conceptual model of GIW dynamics in the system, the physiographic setting of the research, the expertise of the model user, and the costs of high data demands, computational intensity, and reduced uncertainty associated with the use of sophisticated coupled surface–subsurface models versus the benefit of simpler modeling approaches (e.g., groundwater or watershed modeling methods). The temporal scale selected for these approaches is directed by the model user and is also dependent upon each model's governing equations.

Given that hydrologic connections in many GIW systems are often highly variable (Leibowitz and Vining, 2003) and are influenced by a combination of surface, near surface, and groundwater processes, we suggest that coupled surface–subsurface flow models such as GSFLOW and coupled MIKE-SHE (and others not described herein, e.g., HydroGeoSphere, ParFlow) that focus on surface water–groundwater interactions may hold the most promise in the greatest number of situations. For example, if the modeler is relatively certain (based on field sampling or other data) that the GIWs in the study watershed fluctuate as discharge, recharge, and surface runoff systems throughout the year, a coupled surface–subsurface flow model may be appropriate. However, it should be noted that these models require a high level of modeling expertise and a wider array of data than the other model types discussed herein to produce meaningful results. Thus, the costs of setting up and implementing these models should be considered compared to the other model types. The other model types are often reasonable alternatives in study watersheds where specific flow regimes (e.g., GIW surface runoff versus groundwater dynamics) are dominant. For example, watershed models are widely-available for hydrological GIW research and would be particularly robust in regions where a confining clay layer and/or perched or shallow water table is present (e.g., Brooks, 2004; O'Driscoll and Parizek, 2003) and surface flow is the dominant runoff mechanism. However, the applicability of many watershed models (e.g., SWAT, HSPF) in groundwater-dominated GIW systems is somewhat limited, unless they are linked to a groundwater model. Groundwater models can address local and regional saturated subsurface flow paths issuing from GIWs in areas of the US, such as portions of the Prairie Pothole Region, where wetland complexes are often governed primarily by groundwater connectivity (see Euliss et al., 2004). However, the use of groundwater models alone, without the addition of models simulating rainfall-runoff processes, presents a challenge when asking watershed scale questions. Moreover, although the construction of a new mechanistic modeling tool would provide an approach for site-specific questions where GIWs are in close proximity to a stream or river and data on GIW hydrology are being collected, this would likely require more data and time than executing the modifications required for existing models.

5. Conclusions

Quantifying the extent to which GIWs are measurably linked to surface waters (streams, rivers, lakes, and other navigable water systems) via surface and/or groundwater connections remains a fundamental research gap for informing unresolved science and policy questions. We review select mechanistic modeling tools with their strengths and limitations that can assist in identifying the mechanisms of hydrological connections between GIWs and other surface water systems. These models may also provide information on the aggregated effects of GIWs on downstream flows at temporal scales selected by the model user and simulated by individual model's time step. Because this remains a developing area of research, each modeling approach involves alternative conceptual (e.g., repurposing parameters to consider GIWs explicitly) or structural (e.g., numerical and/or code) changes for GIW-related questions; however, we selected models that would require only limited modifications (e.g., changes to how the model is parameterized, creating links to a separate model, minor code alterations).

For the purposes of this discussion, we divided modeling approaches into three classifications: watershed models, groundwater models, and coupled surface–subsurface flow models. Given this characterization of available modeling techniques, each approach provides focused insights into specific hydrologic processes in the landscape (e.g., surface runoff, subsurface/groundwater transport, surface water–groundwater interactions). We suggest that coupled surface–subsurface flow models such as GSFLOW and coupled MIKE-SHE (and others not described herein, e.g., HydroGeoSphere, ParFlow) that focus on surface water–groundwater interactions exhibit the most promise for characterizing GIW connectivity across the majority of situations where hydrologic connections of GIWs are highly variable and are influenced by a combination of surface, near surface, and groundwater processes. However, it should be noted that these models are highly complex, involve a high level of modeling expertise, and have heavy data requirements. Therefore, a cost-benefit analysis may be appropriate prior to model selection. We also suggest that watershed and groundwater models are appropriate and would be robust in situations where one type of flow (i.e., surface water or groundwater) is dominant. Recent developments in remote sensing, tracer technology, field-based, and empirically-derived mass balance approaches can contribute to further advancements in mechanistic modeling and-as stand-alone methods-can also shed light on questions concerning hydrologic connectivity.

Given the related decision making issues that are at the vanguard of GIW protection, we anticipate rapid future growth in the science of GIW hydrologic connectivity modeling at the watershed scale. Close collaborations of the modeling community with hillslope, wetland, and watershed hydrology research scientists in addition to the remote sensing community are also imperative for most accurately and efficiently understanding connectivity of GIWs and other surface waters and their effects on downstream systems at watershed scales.

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