AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2017GL075238

Key Points:
- Groundwater discharge from the U.S. East Coast modeled to be 27.1 km^3/yr (22.8–30.5 km^3/yr), amounting to 13% of river discharge
- Half of coastal catchments discharged some groundwater that recharged in inland catchments and crossed watershed boundaries as groundwater
- We calculated that ~175,000 km^2 of the U.S. East Coast contributes to coastal groundwater discharge

Supporting Information:
- Supporting Information S1

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Citation:
Befus, K. M., Kroeger, K. D., Smith, C. G., & Swarzenski, P. W. (2017). The magnitude and origin of groundwater discharge to eastern U.S. and Gulf of Mexico coastal waters. *Geophysical Research Letters*, *44*, 10,396–10,406. https://doi.org/10.1002/2017GL075238

Received 9 AUG 2017
Accepted 12 OCT 2017
Accepted article online 18 OCT 2017
Published online 28 OCT 2017

The Magnitude and Origin of Groundwater Discharge to Eastern U.S. and Gulf of Mexico Coastal Waters

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Abstract Fresh groundwater discharge to coastal environments contributes to the physical and chemical conditions of coastal waters, but the role of coastal groundwater at regional to continental scales remains poorly defined due to diverse hydrologic conditions and the difficulty of tracking coastal groundwater flow paths through heterogeneous subsurface materials. We use three-dimensional groundwater flow models for the first time to calculate the magnitude and source areas of groundwater discharge from unconfined aquifers to coastal waterbodies along the entire eastern U.S. We find that 27.1 km^3/yr (22.8–30.5 km^3/yr) of groundwater directly enters eastern U.S. and Gulf of Mexico coastal waters. The contributing recharge areas comprised ~175,000 km^2 of U.S. land area, extending several kilometers inland. This result provides new information on the land area that can supply natural and anthropogenic constituents to coastal waters via groundwater discharge, thereby defining the subterranean domain potentially affecting coastal chemical budgets and ecosystem processes.

1. Introduction

The magnitude of terrestrially sourced groundwater discharging into marine waters, often referred to as submarine groundwater discharge (SGD), sets a first-order control on the potential influence these terrestrial waters can have on coastal and marine physical and biogeochemical processes (Moore, 2010; Rodellas et al., 2015; Santos et al., 2012). Discharging groundwater transports heat and solutes through the reactive subterranean interface between terrestrial and marine waters, transforming and delivering subsequent chemical species to coastal water bodies (Beusen et al., 2013; Erler et al., 2014; Kroeger & Charette, 2008). Depending upon the availability and character of these chemicals, groundwater discharge can supply critical nutrition or devastating contaminants to coastal ecosystems. Since solute concentrations in groundwater can exceed those in rivers, groundwater discharge may carry significant chemical loads despite having lower volumetric fluxes relative to rivers (Burnett et al., 2003; Rodellas et al., 2015). But, to quantify solute fluxes to coastal waters, the rates of groundwater flow and discharge that transport these dissolved chemicals from terrestrial to marine environments must also be known.

While the role of SGD in continental water and chemical budgets is well recognized (Beusen et al., 2013; Laruelle et al., 2009; Rabouille et al., 2001; Rad et al., 2007; Schopka & Derry, 2012; Zektser & Loaiciga, 1993), its quantification at the regional scale remains difficult. Many SGD studies have focused on quantifying the physical and chemical processes over a narrow (<100 m) transition from the terrestrial to the marine environments: important biogeochemical transformations in groundwater systems occur at or near the coastal interface and alter the chemical products reaching coastal waters (Beck et al., 2007). Field studies of SGD often rely on localized measurements or chemical analyses with assumptions of end-member concentrations that limit their applicability to describe adjacent or larger-scale systems. However, the hydraulic settings that control the advection of dissolved chemicals and the geometry of the freshwater-saltwater mixing zone may arise from distant inland hydrologic conditions (Michael et al., 2005). Together, geologic, hydrologic, and other landscape heterogeneities across spatial and temporal scales control the magnitude and location of SGD (Bratton, 2007; Michael et al., 2005; Russoniello et al., 2013; Sawyer et al., 2013) that shore-perpendicular transects may not fully quantify (Figure S1 in the supporting information). Studies focused on the coastal interface have constrained the mechanisms for how the final SGD products transform and reach coastal waters and are useful for assessing the net fluxes of carbon, nutrients, and other chemicals from terrestrial to marine systems. But, by focusing on the discharge locations, the origin and transport of the

solutes reaching coastal areas are often not considered. Thus, the terrestrial domain for quantifying the relevant contributing areas for SGD and its chemical constituents remains widely uncharacterized, resulting in a poor understanding of where land use changes or groundwater pollution could affect coastal ecosystems via multiscale groundwater pathways.

Whereas SGD refers to both saline and fresh groundwater discharge across an interface submerged beneath marine waters that can be traced to recharge areas either on or off shore, we interpret coastal groundwater discharge (CGWD) as groundwater discharge occurring near the interface of terrestrial and marine regimes supplied from recharge on land. This definition of CGWD is distinct from a previous use of coastal groundwater discharge defined as discharge associated with infiltrated seawater (Price et al., 2006). With our definition, CGWD has no requirement of discharging across an interface that is submerged by seawater (i.e., submarine). Thus, CGWD includes groundwater seeps and springs at the coast, groundwater discharge in coastal or tidal wetlands, and the fresh component of submarine groundwater discharge. It is this fresh component of coastal groundwater that transports the anthropogenic chemical loads originating on the continents to coastal waters (Kroeger & Charette, 2008).

Here we develop and apply a novel approach to calculate how terrestrially recharged groundwater discharges into coastal waterbodies along the U.S. East and Gulf of Mexico Coasts using regional, three-dimensional groundwater flow models as an important step toward quantifying chemical fluxes to coastal waters at the regional to continental scale. These models were developed using the best available continuous stratigraphic and hydraulic data, incorporating the most recent, highest spatial resolutions and with calibrated hydraulic properties, with domains extending tens to hundreds of kilometers inland to resolve groundwater flow paths and hydrologic connections at the regional scale. From the model results, we calculated the rates of groundwater discharge to coastal water bodies through individual coastal watersheds and simulated groundwater flow paths reaching coastal water bodies to predict the total land area capable of contributing to CGWD.

2. Hydrogeologic Settings

The natural hydrogeologic setting along the East and Gulf Coasts of the United States changes with the regional climate, geologic materials, and geologic histories. Thick coastal plain sedimentary sequences constitute the majority of the region with glacial sediment overlying crystalline rocks in New England. This hydrogeologic setting combined with the humid to subhumid climates of these coastal regions creates significant potential for CGWD that has been measured extensively at many spatial scales (Bokuniewicz, 1980; Charette et al., 2008; McCoy & Corbett, 2009; Moore, 1996). Dense population centers, urban and suburban development, and other land cover changes have also transformed the hydrologic conditions of the coastal aquifers. This modeling study focuses on the natural, long-term average groundwater discharge to coastal water bodies, using a steady state formulation of the groundwater models and exclusion of anthropogenic hydrologic conditions. To use groundwater models to predict future hydraulic conditions and water availability, incorporating the transient effects of human activities on hydrologic conditions would be imperative for guiding management decisions in specific locations. Many smaller-scale modeling efforts across the study domain have focused on calibrating transient flow models for quantifying groundwater availability that include human influences, and some of the resulting models provided the regional hydrogeologic frameworks used in this study (Campbell & Coes, 2010; Masterson et al., 2016).

The U.S. East and Gulf Coasts can be divided into five hydrogeologic regions ranging from Maine to Texas (Figure 1). The five regions include the sands and gravels of the glacial origin aquifer system of New England (United States Geological Survey Aquifer Code: N100GLCIAL), the North Atlantic Coastal Plain aquifer system ranging from New York to North Carolina (S100NATLCP); the Southeastern Atlantic Coastal Plain aquifer system in North and South Carolina (S100SECSLP); the Floridan aquifer system in Georgia, Florida, and Alabama (S400FLORDN); and the coastal lowlands aquifer system in the central and western Gulf of Mexico covering portions of Alabama, Mississippi, Louisiana, and Texas (S100CSLLWD), which in this study are split into eastern and western Gulf of Mexico model regions. The published hydrogeologic framework data are highly constrained and were derived from integrated borehole data, geologic mapping, and calibrated hydrologic models (Table S1 in the supporting information) (Schlische, 1992; Martin & Whiteman, 1999; Ator et al., 2005; Resor & DeBoer, 2005; Thompson et al., 2007; Campbell & Coes, 2010;

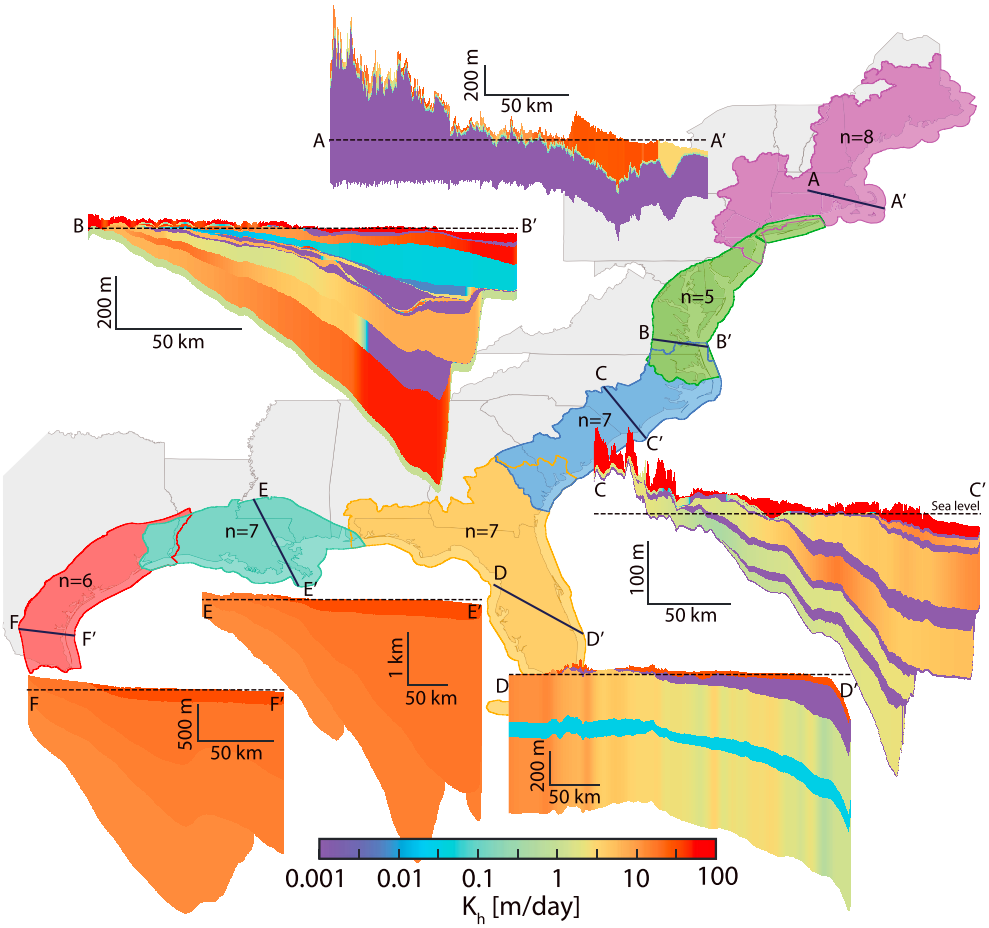

Figure 1. Overview of the groundwater models for regional hydrostratigraphic inputs and broken up into smaller overlapping models (n = number of models per region). For each region, a representative cross section shows the horizontal hydraulic conductivity (K_h) structure. AA′: New England glacial aquifer region, BB′: North Atlantic coastal plain aquifer system, CC′: North and South Carolina coastal aquifer system, DD′: Floridan aquifer system, and EE′ and FF′: Coastal lowlands aquifer system. The horizontal dashed lines in the cross sections represent sea level.

Maine Geological Survey, 2011; Soller et al., 2012; Dalton et al., 2014; Gleeson et al., 2014; Nielsen & Locke, 2015; Williams & Dixon, 2015; Masterson et al., 2016; Williams & Kuniansky, 2016; Bayless et al., 2017). These data sets spanned each subregion and supplied the model geologic structure and hydraulic properties: the horizontal hydraulic conductivity (K_h), vertical hydraulic conductivity (K_v), the number of model layers, the extent of various units, and the thickness of the layers (Table S1). More information on the hydrogeologic framework of each of these regions can be found in the supporting information and the data set sources.

3. Methods

3.1. Model Domain Development

The groundwater flow models were developed from subregional portions of the five hydrogeologic regions. The hydrogeologic regions defined spatially consistent hydrostratigraphic data sets that often differed from the sequences defined in neighboring regions. We split each hydrogeologic region into many overlapping smaller groundwater flow models to allow them to have higher spatial resolution, and thus to more accurately model groundwater flow to either the surface drainage (stream) network or coastal waters. To reduce the size of model domains and minimize potential boundary condition effects, the study regions were divided according to estuarine-based watershed delineations at the eight-digit Hydrologic Unit Code (HUC8) scale using a modified National Oceanographic and Atmospheric Administration Coastal Assessment Framework data set that contains both watersheds (count = 3,100, area median = 0.42 km^2, area interquartile range = 0.12–3.8 km^2, shoreline median = 3.3 km, and shoreline interquartile range = 1.6–10.7 km) and

nearshore waterbodies (count = 433, area median = 175 km^2, and area interquartile range = 27–672 km^2) (Herrmann et al., 2015). Adjacent HUC8 watersheds alongshore and inland from coastal areas targeted for calculating CGWD served as buffers in each model to minimize the effect of no-flow boundaries on the targeted groundwater systems. Each domain was manually inspected and merged with other domains with significant spatial overlap, resulting in 40 overlapping model domains extending tens to hundreds of kilometers inland and along the coast (Figure S2).

3.2. Model Implementation

The steady state groundwater flow problem was solved in three dimensions using the U.S. Geological Survey MODFLOW program (Harbaugh, 2005; Niswonger et al., 2011) driven by a Python programming environment (FloPy, version 3.2.6) (Bakker et al., 2016). A suite of boundary conditions was used to maximize the ability of the models to accurately predict the groundwater fluxes to either stream base flow or CGWD. To simulate this hydrologic partitioning, a paired recharge-seepage boundary condition with recharge derived from Reitz et al. (2017) was applied for the land surface that can accurately describe a wide range of otherwise unknown or variable hydraulic conditions, including base flow (Sanford, 2002). The models were constructed with 250 m by 250 m cells with geologically prescribed thicknesses to provide high-resolution topography at the regional scale (Befus & Kroeger, 2017), setting the vertical threshold for groundwater discharge from the recharge-seepage boundary. The seafloor was set as a general head boundary, accounting for additional resistance to groundwater discharge caused by the increased density of seawater. Water table elevations in the unconfined layers of the models were calculated as part of the solution process and compared to measured water table elevations (Krause & Boyle, 2005).

To postprocess the model results, the U.S. Geological Survey program ZONEBUDGET (Harbaugh, 1990) was used to calculate the groundwater budget and solve for the CGWD for each HUC8 watershed by integrating cell-by-cell water budgets. Recharge areas contributing to CGWD were calculated from the model results with the particle tracking software MODPATH (Pollock, 2012). Further details on the models and postprocessing are available in the supporting information.

4. Results

4.1. Origin of Coastal Groundwater Discharges

The particle tracking results predicted that groundwater recharge areas and flow path length contributing to CGWD are widely variable but could be located tens to hundreds of kilometers inland (Figure 2). Across the entire Atlantic and Gulf of Mexico coast, some portion of the recharge occurring within 175,723 km^2 of land ultimately supported CGWD. Recharge areas contributing to coastal groundwater discharge mainly resulted from short flow paths ($<$5 km), but some areas with thick coastal sediments or confining units contained very long CGWD flow paths ($>$50 km). From North Carolina south to northern Florida and for much of the western Gulf of Mexico, aquifers with recharge areas extremely far inland contributed to shallow CGWD. In many parts of Texas, the contributing areas extended to the inland boundary of the flow models (Figure 2b). However, much of New England and parts of Florida did not show CGWD supplied by flow paths starting more than ~10 km inland. Along the central Gulf of Mexico coastline, CGWD contributing areas were concentrated along the coast with tendrils of flow paths occasionally reaching tens and rarely to hundreds of kilometers inland. For over a third of coastal catchments, all recharge discharged as CGWD (1,183 out of 3,148; 37.6%), but these catchments were primarily small and represented only 1.6% of the total area of coastal catchments. Many more catchments contributed to CGWD from at least 50% of their area (2,556 catchments; 81.2%). It is important to note that these contributing areas to CGWD are not associated with a particular flux, only that a water molecule recharged in these areas could become CGWD. The majority of the CGWD flux is expected to be supplied by recharge that occurs close to the coast, but the degree to which this assumption holds is currently unquantified.

4.2. Magnitude of Coastal Groundwater Discharges

From our groundwater modeling results, a total of 27.1 km^3/yr of terrestrially recharged groundwater discharged from the Atlantic and Gulf coastal unconfined groundwater systems. To constrain the uncertainty in CGWD arising from the recharge rate, we ubiquitously altered the recharge rates by ±50% for all of the models. These recharge scenarios increased the total modeled CGWD by 3.5 km^3/yr for +50% recharge and decreased by 4.2 km^3/yr for −50% recharge, with CGWD ranging from 22.8 to 30.5 km^3/yr. A previous

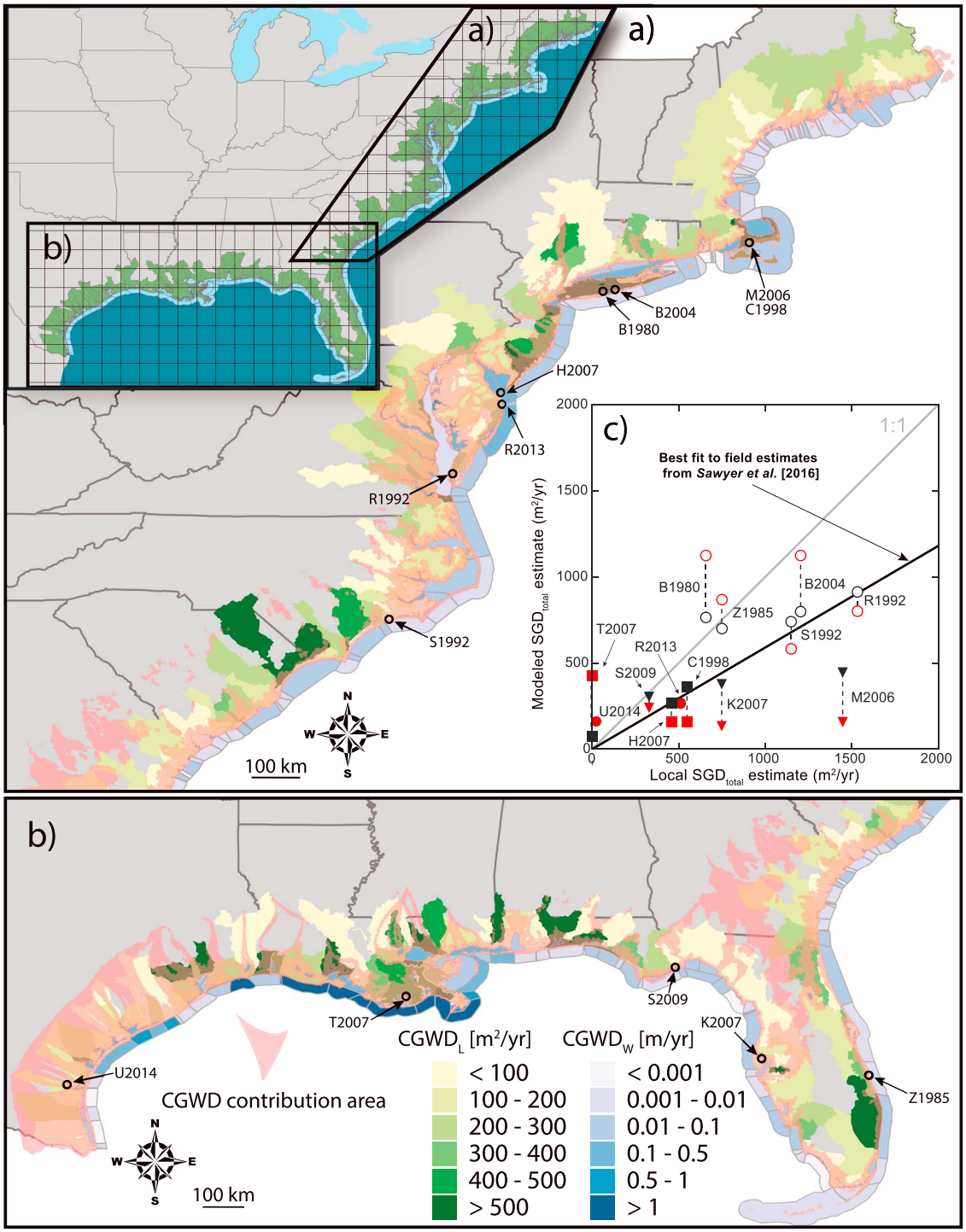

Figure 2. The magnitude of the coastal groundwater discharged from coastal watersheds, $CGWD_L$, normalized by coastline length and the amount of coastal groundwater received by coastal water bodies, $CGWD_W$, normalized by the area of the receiving waterbody varied widely along the (a) U.S. East and (b) Gulf of Mexico Coasts. (c) Comparison of field-based local estimates of SGD to model outputs from Sawyer et al. (2016) in black and to the current analysis in red. The circles indicate field SGD estimates from seepage meters, squares from solving a water budget for SGD, and triangles represent an SGD estimate derived from multiple methods. Model estimates were converted to total SGD with an empirical fit to global field estimates: $SGD_{total} = 1.1\ CGWD_L + 470\ m^2/yr$ (Prieto & Destouni, 2011). See Table S2 for the full reference information in Figure 2c.

model estimate of the fresh SGD to both eastern and western contiguous U.S. coastal waters was 15 ± 4 km^3/yr, though a comparison to compiled literature on field estimates of discharge suggested a total flux of up to 25 ± 7 km^3/yr (Sawyer et al., 2016). Thus, our groundwater models estimated that CGWD for the eastern U.S. was up to twice as large as the previous model calculated for both coastlines. Despite having much larger integrated fluxes, our models often predicted smaller magnitude CGWD fluxes for specific coastal areas when compared to both the contiguous U.S. water budget analysis and field studies (Figure 2c) (Bokuniewicz, 1980; Bokuniewicz et al., 2004; Cambareri & Eichner, 1998; Hays & Ullman, 2007; Kroeger et al., 2007; Mulligan & Charette, 2006; Reay et al., 1992; Russoniello et al., 2013; Santos et al., 2009; Simmons, 1992; Thompson et al., 2007; Uddameri et al., 2014; Zimmermann et al., 1985).

We calculated CGWD from individual catchments and to distinct receiving waterbodies directly from the groundwater flow model results, taking a novel bilateral coastal continuum perspective for CGWD that can be used to understand how terrestrial processes affect CGWD and how offshore ecosystems and environments respond to CGWD fluxes. The CGWD from each coastal watershed was calculated by integrating the groundwater flux across the land-sea interface in the top model layer. Similarly, the CGWD received by a waterbody was calculated by integrating the CGWD flux to the waterbody from land in the top model layer. The spatially averaged CGWD per unit area of waterbodies, $CGWD_W$ (m/yr), was the total CGWD (m^3/yr) received by the waterbody from all contributing catchments divided by the waterbody area (Figure 2). The CGWD perspective from land, $CGWD_L$ (m^2/yr), represented discharge from specific terrestrial catchments to all receiving waterbodies and was normalized per unit length of coastline (Figure 2). $CGWD_W$ and $CGWD_L$ are the benthic and lateral fluxes of terrestrially supplied SGD, respectively. Both normalized CGWD results contained no clear patterns related to regional geology or climate, and neighboring catchments and waterbodies were extremely variable. Across the study domain, estuaries and bays received at least an order of magnitude more CGWD than waters farther offshore. For coastal waters off the Mississippi River delta and most of the Louisiana coast, the models calculated markedly higher $CGWD_W$ (>1 m/yr) compared to all other offshore areas. The high modeled CGWD in that portion of the Gulf Coast likely resulted from a thick surficial model layer, which could overpredict the potential for such large benthic fluxes. We note, however, that the model results were similar to nearby field estimates (Kraemer & Reid, 1984; Krest et al., 1999; McCoy et al., 2007; Moore & Krest, 2004).

The percent of groundwater recharge, R, supplying CGWD was calculated for coastal catchments to determine the partitioning of coastal groundwater systems to discharge locations on land (i.e., rivers, springs, and lakes) and at the coastal interface (Figure 3a). R was calculated by integrating the recharge in each coastal catchment, but CGWD could incorporate flow paths that recharged farther inland than the coastal catchment. Thus, $CGWD_L/R$ exceeded 100% for 1,521 of the 3,239 (47.0%) coastal catchments in the analysis. This indicates that groundwater flow across surface water divides was a significant source for CGWD reaching the coastal waters of the eastern U.S., especially for specific catchments within each of the geographic regions, including the central Texas Gulf Coast, the Mississippi Delta, and sporadically along the eastern seaboard. High $CGWD_L/R$ values for islands created a near continuous strand along the East Coast, even where mainland watersheds contained lower ratios (Figure 3a). Catchments with $CGWD_L/R > 100\%$ were primarily either relatively narrow or had long coastlines relative to their area.

Similarly, the relative magnitude of CGWD to river discharge, Q_R, was calculated for every coastal catchment to quantify the significance of CGWD in transporting both freshwater and chemical constituents to marine environments (Figure 3b). We calculated Q_R by spatially joining and integrating the NHDPlusV2 modeled streamflow results to the HUC8 catchments used in our analysis. More information on the NHDPlusV2 data set is available in the NHDPlusV2 documentation (McKay et al., 2012). Thus, each HUC8 coastal catchment was assigned a mean annual river discharge from NHDPlusV2 that could be compared to the $CGWD_L$ from that catchment, resulting in 176 aggregated catchments (Figure 3b). In total, CGWD represented about 13% of the integrated annual river flows reaching the coast for the eastern U.S. (13.1% of Q_R = 224.5 km^3/yr for the "natural," C-version, without human-induced hydrologic impacts and 12.5% of Q_R = 236.1 km^3/yr for the calibrated to measured data, E-version, NHDPlusV2 runoff estimates). Our analysis predicted that 87 catchments (49.2%) supplied CGWD that was ≤5% of the modeled streamflow discharging from those catchments to marine waters, whereas 146 catchments (82.4%) supplied CGWD at a rate ≤20% of river discharge. Thus, approximately 18% of catchments along the U.S. East and Gulf Coasts support CGWD in excess of 20%

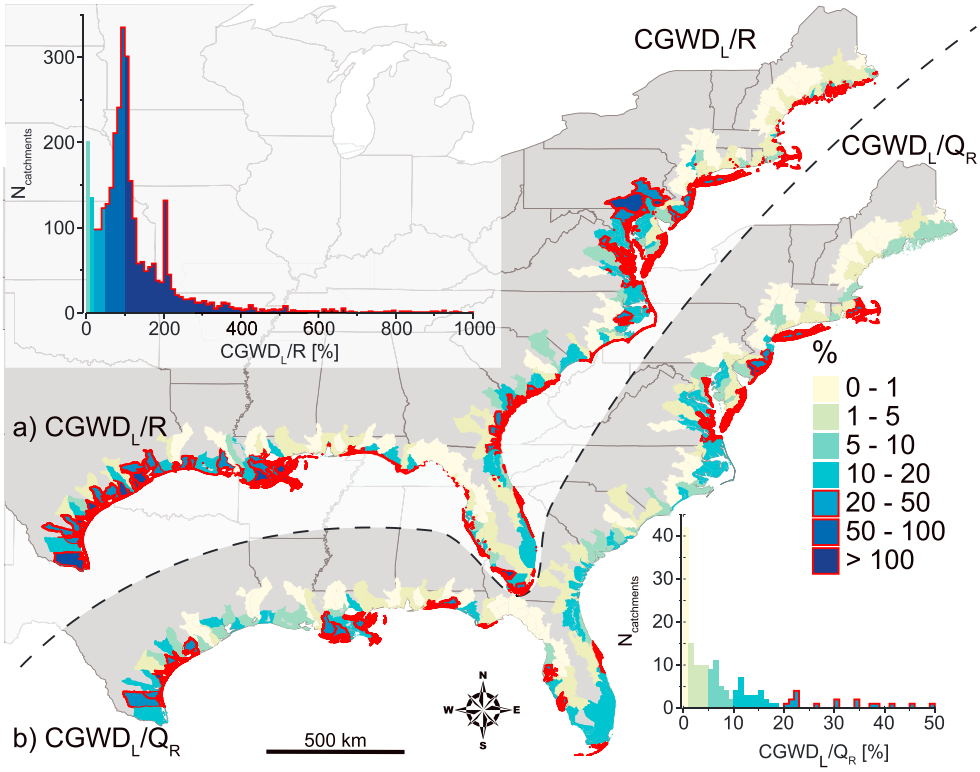

Figure 3. Maps showing the comparison of the percent of the coastal groundwater flux from coastal catchments, $CGWD_L$, relative to (a) the groundwater recharge, R, received and (b) the amount of surface water discharge, Q_R, exported by those catchments. The histograms show how many catchments, $N_{catchments}$, are within each percentage range, where every catchment contributing to CGWD was considered in $CGWD_L/R$ (n = 3239), while $CGWD_L/Q_R$ was calculated for aggregated catchments to match co-located NHDplusV2 terminal and coastal catchments (n = 176) shown for the "natural" C-scenario for Q_R. Values greater than 20% are highlighted in red.

of river discharges, especially in concentrated areas around Corpus Christi and San Antonio Bays in southern Texas, the eastern side of Pensacola Bay on the panhandle of Florida, the Indian River in eastern Florida, the lower Delmarva Peninsula and near the Lynnhaven river at the outlet of the Chesapeake Bay, bays in southern New Jersey, and the northern side of Long Island (Figure 3b).

5. Discussion

5.1. Limitations and Simplifications

Several sources could contribute to overpredicting the inland extent of the recharge areas supporting CGWD. First, by allowing tracked water particles to remain in the groundwater systems after a partial sink was encountered along the flow path, our results could artificially allow particles recharged far inland to be discharged at the coast. Breaking up the model into more layers would create less potential for weak sinks to influence groundwater flow paths supplying CGWD, but these additional layers would significantly increase the model size and computational resources required to solve the flow problem and conduct the particle tracking. Second, formulating the model domains with the fewest possible layers could have allowed distant inland areas to over contribute to CGWD. For example, in the central and western Gulf of Mexico regions, the hydrostratigraphy was defined by several homogeneous but anisotropic units with high permeability ($K_h > 10$ m/d, $K_h/K_v = 10$), which may have allowed more groundwater connectivity between the units than the real distribution of interbedded clay lenses permit (Thompson et al., 2007) and more extensive CGWD contribution areas. Higher-resolution hydrostratigraphic data would be required to more accurately model the groundwater flow in these systems. Finally, the seaward-edge boundary conditions for the geologic units in the models were set as general head boundaries assuming that all overlying materials were filled with saltwater. Thus, by not modeling the freshwater-saltwater interface directly, our models would predict slightly lower water tables in coastal areas and allow more groundwater to discharge as CGWD instead of to inland seeps and springs.

Beyond simplifications in the model, differences existed between how the field studies calculated SGD relative to the model-based CGWD results. The SGD field studies estimated fluxes for particular sites within a waterbody, where our model-based flux was normalized by the total area of the waterbody defined by the watershed-waterbody input data (Herrmann et al., 2015). Thus, by evenly distributing the modeled CGWD flux across a large area, our normalized CGWD fluxes should be lower than field studies that primarily calculate SGD rates relatively near the shore, and extrapolation of those rates to the entire waterbody does not account for the decaying exponential behavior of SGD farther offshore (McBride & Pfannkuch, 1975) (Figure 2c). It is also important to note that the comparison with field estimates required converting all CGWD fluxes to a total (fresh and saline) SGD flux using an empirical equation derived from uncertain and site-/scale-specific field measurements (Prieto & Destouni, 2011).

5.2. Comparison With a Continental-Scale Estimate

Comparing our CGWD results to the only other continental-scale estimate, our magnitude of CGWD for the East and Gulf of Mexico coastal areas was significantly larger than the NHDPlusV2-based total CGWD for the entire U.S. (Sawyer et al., 2016). The size of the contributing areas to CGWD in Sawyer et al. (2016) was prescribed as the NHDPlusV2 coastal catchment areas, defined as only the watersheds containing first-order streams flowing directly to marine waters with a median area of 0.17 km^2 and did not consider cross-watershed groundwater flow (Schaller & Fan, 2009; Winter et al., 2003). Conversely, the HUC8 coastal catchments in this analysis had a median area of 2,550 km^2 and were not used to estimate contributing areas to CGWD (Figure S4). Instead, our particle tracking analysis calculated the contributing areas to be much more extensive (~5.4 times larger on average) than the NHDPlusV2 coastal catchments with a median area of 0.92 km^2.

Importantly, our groundwater flow models allowed recharge to discharge either to the drainage network or as CGWD, a hydrologic partitioning that was not incorporated in the Sawyer et al. (2016) analysis. Instead, Sawyer et al. (2016) defined fresh SGD as the groundwater recharge to a coastal watershed, which was prescribed by the river base flow parameter calculated by land surface climate models on an ~12 km grid that do not consider groundwater flow between model cells. Conversely, not all groundwater recharge in coastal areas in our models would become CGWD, but the groundwater flow models allowed recharge from further inland to support CGWD. The combined influences of groundwater flow in our models create the potential for both more and less CGWD relative to Sawyer et al. (2016): the modeled partitioning between groundwater discharge to rivers or coastal areas would result in less CGWD if the same land areas were considered, but regional-scale groundwater flow, sometimes across watershed boundaries, in our models allowed substantially larger source areas than Sawyer et al. (2016). This latter difference in contributing areas was responsible for the larger magnitude of CGWD in our analysis compared to the estimates by Sawyer et al. (2016).

While our models predicted more CGWD at the continental scale than Sawyer et al. (2016), the magnitude of $CGWD_L$ once converted to total SGD was often lower than Sawyer et al. (2016) and the SGD measured in many field studies (Figure 2c). This difference is mainly explained by the much longer coastline considered in our analysis than the NHDPlusV2 coastline used by Sawyer et al. (2016), largely due to NHDPlusV2 coastal catchments often not following the coastal topology (Figure S5). The total East Coast coastline length in that analysis was 43% of the coastline length from the larger-scale watersheds used in this analysis. This difference in coastline length overcame the larger magnitude of CGWD predicted by our models, resulting in less $CGWD_L$ per unit length of coastline relative to the NHDPlusV2 analysis.

5.3. Implications for Coastal Systems

We found that groundwater discharge to coastal waters is not solely supplied by recharge within a kilometer of the coast or even to entire HUC8 coastal catchments. We also found that almost one third of the catchments in this analysis received groundwater from catchments inland, across a watershed boundary. Thus, the extent of coastal landscapes that can impact the quantity and quality of CGWD has been quantified for the first time for a continuous, continental-scale coastline consisting of unique geologic and hydrologic settings. These CGWD contributing areas can be used to assess the potential impacts of land use and land cover change on coastal ecosystems. For example, nitrogen transported to coastal waters via SGD present an increasing threat in developing areas (Beusen et al., 2013). However, the health of coastal ecosystems relies not only on SGD offshore but also on coastal features that interact with and affect discharging groundwater,

including fresh tidal wetlands, estuaries, bays, and marine waters that receive CGWD. Thus, delineating CGWD contributing areas can guide the choice of future management study domains that require insights into the role of coastal groundwater on physical, chemical, or ecological processes.

Our models indicated that the magnitude of CGWD reaching coastal U.S. waters along the Atlantic Ocean and Gulf of Mexico is significantly larger than previously estimated by Sawyer et al. (2016). Roughly half of the coastal catchments along the eastern and southeastern U.S. released CGWD that was $\leq$5% of the coastal river discharge from the catchment. Previous studies had suggested that $<$5–10% was an upper limit for the ratio (Burnett et al., 2003; Sawyer et al., 2016; Taniguchi et al., 2002). However, we found that about one third of catchments have CGWD/Q_R relationships between 5 and 20%. Therefore, in a substantial portion of the estuaries, embayments, and coastal ocean areas that comprise the U.S. coastline, coastal groundwater systems may play a larger role in coastal water budgets than previously thought. Further, given that concentrations of chemical constituents are commonly greater in groundwater than in rivers (Burnett et al., 2003; Kroeger et al., 2007; Rodellas et al., 2015; Slomp & Van Cappellen, 2004), the chemical loads carried by CGWD may be even more significant at both local and regional scales.

In our analysis, we integrated the model-derived CGWD fluxes for entire catchments and coastal waterbodies, resulting in a single estimate per landscape feature. Thus, we did not account for the offshore location where the CGWD occurred, but spatial variability in the magnitude of the CGWD is expected and the discharge is likely concentrated near the coastline (Bokuniewicz, 1992; Taniguchi et al., 2006), except where confining units and structural features extend fresh discharge farther offshore (e.g., Hughes et al., 2009). The extreme variability in the annual CGWD fluxes among receiving waters, and in the relationships between CGWD, groundwater recharge, and river discharge at the catchment-scale, suggests that field-derived estimates of CGWD are unlikely to be representative at larger scales or even for nearby coastal settings, creating a significant challenge for closing coastal water and chemical budgets. The heterogeneity of the terrestrial landscape due to geology, topography, and hydrology combine with the complexity of the coastline to create an inherently complex, three-dimensional groundwater flow system that varies across scales with the sources of the heterogeneities. Future studies that combine modeling and field measurements of CGWD should aim to overcome these disconnects that arise when comparing results across the spatial scales of each approach.

6. Conclusions

We modeled regional, three-dimensional coastal groundwater systems along the East and Gulf of Mexico Coasts of the U.S. to quantify the magnitude of CGWD and the degree to which coastal landscapes contribute to fresh groundwater discharge at the coast. By comprehensively modeling the hydrogeology of the land-sea margin, allowing sea level to define the terrestrial-marine interface and extending the numerical models to consider hydrogeologic processes as far as tens to hundreds of kilometers inland, our estimate of CGWD, 27.1 km^3/yr, was approximately twice as large as a recent estimate using an assumption that recharge supporting CGWD occurs only in small watersheds that comprise the coastal fringe. We also found that groundwater flow paths contributing to CGWD extend well inland of NHDPlusV2 coastal catchments, and in some cases extended farther inland than the larger, HUC8 coastal catchments. Our analysis calculated CGWD fluxes from specific coastal catchments and identified coastal waterbodies, providing spatially extensive results for future users interested in assessing the role of groundwater discharge in various coastal hydrologic and biogeochemical processes from terrestrial export and benthic flux perspectives.

Acknowledgments
K.M.B. was supported by the National Science Foundation (EPS-1208909). K.D.K, C.G.S, and P.W.S. appreciate the sustained support from the USGS Coastal and Marine Geology Program. K.D.K. acknowledges support from NASA Carbon Cycle Science grant NNX14AM37G. The IAEA is grateful for the support provided to IAEA-Environment Laboratories by the Government of the Principality of Monaco. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. All of the spatial data outputs of these analyses are available to download from the University of Wyoming Research Data Repository (https://data.uwyo.edu, https://dx.doi.org/10.15786/M2KG6V).

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