ANNUAL REVIEWS

Annual Review of Environment and Resources

Methods for Quantifying Interactions Between Groundwater and Surface Water

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Annu. Rev. Environ. Resour. 2024. 49:623–53

First published as a Review in Advance on July 18, 2024

The *Annual Review of Environment and Resources* is online at environ.annualreviews.org

https://doi.org/10.1146/annurev-environ-111522-104534

Keywords

groundwater–surface water interactions, measurement techniques, tracer methods, numerical models, scale effects, catchment, watershed

Abstract

Driven by the need for integrated management of groundwater (GW) and surface water (SW), quantification of GW–SW interactions and associated contaminant transport has become increasingly important. This is due to their substantial impact on water quantity and quality. In this review, we provide an overview of the methods developed over the past several decades to investigate GW–SW interactions. These methods include geophysical, hydrometric, and tracer techniques, as well as various modeling approaches. Different methods reveal valuable information on GW–SW interactions at different scales with their respective advantages and limitations. Interpreting data from these techniques can be challenging due to factors like scale effects, heterogeneous hydrogeological conditions, sediment variability, and complex spatiotemporal connections between GW and SW. To facilitate the selection of appropriate methods for specific sites, we discuss the strengths, weaknesses, and challenges of each technique, and we offer perspectives on knowledge gaps in the current science.

Contents

1. INTRODUCTION

Groundwater (GW) and surface water (SW) interact across multiple spatial scales ranging from pores to large basins and over temporal scales ranging from seconds to decades (1–3). Hydrologic exchange flows affect water-resource budgets (4, 5), regulate nutrient and pollutant fluxes across the interface between GW and SW, and modulate chemical concentrations along flow paths. These exchange flows, in turn, enhance biogeochemical processes (6, 7), with profound effects on water quality and ecosystem health (8, 9). Thus, understanding the underlying processes controlling spatiotemporal patterns and dynamics of GW–SW interactions and quantifying GW–SW exchange is crucial to evaluation and management of water resources and to sustaining healthy ecosystems.

GW: groundwater

SW: surface water

Interactions between GW and SW encompass hyporheic exchange (shallow mixing of GW and SW), SW infiltration, GW discharge, bank storage, and overbank return flows to floodplains under a broad range of conditions. GW–SW exchanges are affected by many factors, including physical and chemical properties of interface and aquifer sediments (6, 10), spatiotemporally dynamic SW networks (3, 11–13), and GW flow (14), as well as hydrological drivers of precipitation, evaporation, and water table depth. For the past several decades, human activities (e.g., land-use change, GW pumping, dam construction, and water diversion projects) and climate warming have combined to significantly alter the magnitude, location, and timing of exchanges (7, 15–18). GW and SW function as an integrated closely coupled system. As a result, understanding and predicting dynamic GW–SW exchanges require consideration of the hydrological, topographical, hydrogeological, and ecological processes operating across a spectrum of spatial and temporal scales (3, 19).

To delineate spatiotemporal patterns of GW–SW interactions and associated biogeochemical effects, many monitoring and observation techniques have been developed in addition to theoretical advances. These techniques include hydrometric tools, heat tracers, solute and isotope tracers, and hydrogeophysical methods (2, 20–26). For the characterization of biogeochemical effects induced by GW–SW interactions, new technologies have emerged, including microbial ecological analysis and high-resolution quantification of organic matter in SW and GW (27). Monitoring and observation data are then processed using mass balance techniques (28), hydrograph separation (29, 30), and a mix of analytical and numerical models (31–34). Numerical modeling, in particular, has evolved rapidly to provide deeper insights into the zones of GW–SW mixing, such as hyporheic and benthic zones and related exchange fluxes, GW discharge and surface infiltration, and GW–SW exchange at much larger scales (34–36).

However, when applying these methods to specific field sites, it is vital to understand the range of scales at which they are valid as well as their respective advantages and limitations. Numerous, interrelated factors must be considered. For example, measurements at fine scales, such as of the hyporheic zone, must often be upscaled because the consequences of hydrological exchange for downstream water geochemistry and ecology manifest themselves at a much larger scale, up to entire drainage basins (14), than a typical experimental reach length (e.g., less than a few kilometers). Furthermore, spatial heterogeneity and dynamic hydrological conditions complicate interpretation and upscaling of monitoring data (23). Each method or combination of methods has uncertainties associated with physico-chemical parameters describing the SW system and heterogeneous aquifer materials (14, 37). These measurement uncertainties, together with spatial and/or temporal sparsity of data, introduce errors and nonuniqueness into the interpretive model and may lead to a misinterpretation of GW–SW interactions and their control on biogeochemical processes. Thus, it is crucial to understand how to select the most suitable method(s) and how to appropriately interpret the monitoring data.

There have been a number of reviews of GW–SW interaction. Sophocleous (38) reviewed some of the fundamental exchange processes for rivers and lakes, whereas Boano et al. (35) and Hester et al. (36) discussed hyporheic exchange and Xin et al. (39) reviewed GW interactions in salt marshes. Kalbus et al. (1) reviewed the methods available for quantifying exchange fluxes, whereas Shanafield & Cook (2) focused on intermittent and ephemeral streams. Cranswick & Cook (40) and Rosenberry et al. (41) reviewed the magnitudes of reported exchange fluxes in river and lacustrine environments, respectively, and discussed some of the limitations of the different methods. McLachlan et al. (20) reviewed the application of geophysical methods, and Barthel & Banzhaf (42) and Brunner et al. (43) discussed GW modeling approaches. Importantly, some methods of investigation are better suited to specific scales, processes, and settings than others. Furthermore, some recent developments of methods have not been covered by previous studies.

With our review we endeavor to provide a state-of-the-art overview of methods for investigating and understanding interactions between GW and SW systems under a wide range of physico-chemical conditions, with the overarching aim of supporting the selection of the most suitable methods and interpretative models for specific applications. The article (*a*) evaluates the patterns and driving factors of GW–SW interactions across scales and environmental settings; (*b*) reviews the latest advancements in monitoring techniques and the interpretation of data; (*c*) provides direction on method selection to suit the spatial and temporal scale of the problem, while discussing strengths, limitations, and challenges; and (*d*) concludes with a discussion of existing knowledge gaps that should be addressed to deepen our understanding of GW–SW interactions.

2. PATTERNS AND CONTROLLING FACTORS OF GROUNDWATER–SURFACE WATER INTERACTIONS

2.1. Interactions Across Scales

GW–SW interactions refer not just to fluxes and water exchange at the GW–SW interface but also to flow patterns and associated biogeochemical and ecological processes in the transition zone near the interface. Clearly, GW–SW exchange generates multiscale patterns. Near rivers, hyporheic exchange includes water that originates from the river or stream, which migrates through porous subsurface sediments and bedrock fractures and eventually returns to the river. Near marine waters, the term "benthic exchange" is often used to describe this flow process, which can include tidal and wave pumping (44). SW infiltration, regional GW discharge, and return flow from overbank or coastal flooding also operate in both fresh and marine aquatic settings to form a broad continuum of interactions (41, 44, 45). GW discharge occurs across diverse SW systems, may be embedded in hyporheic and benthic exchange, and occurs via processes that range from spatially diffuse to spatially focused (**Figure 1**) (46).

GW–SW interactions span multiple spatial scales (47). Most studies have focused on the point scale (centimeters to meters) or the transect or reach scale (meters to hundreds of meters). Due to its ecologic significance, the hyporheic zone has attracted the attention of river research communities for decades, mainly investigating hyporheic exchange and associated biogeochemical processes that occur on timescales ranging from days to years. Boano et al. (35) reviewed key mechanisms, models, and biogeochemical implications of hyporheic flow and transport processes. More recently, larger-scale GW–SW interactions have been investigated to help manage water resources from a watershed standpoint (5). At large scales, GW flow paths are principally influenced by topography and geology and occur on scales ranging up to hundreds of kilometers (14). Harvey & Gooseff (14) argue that the connections between rivers and floodplains prolong physical storage and enhance reactive processes that alter water chemistry and downstream transport of material

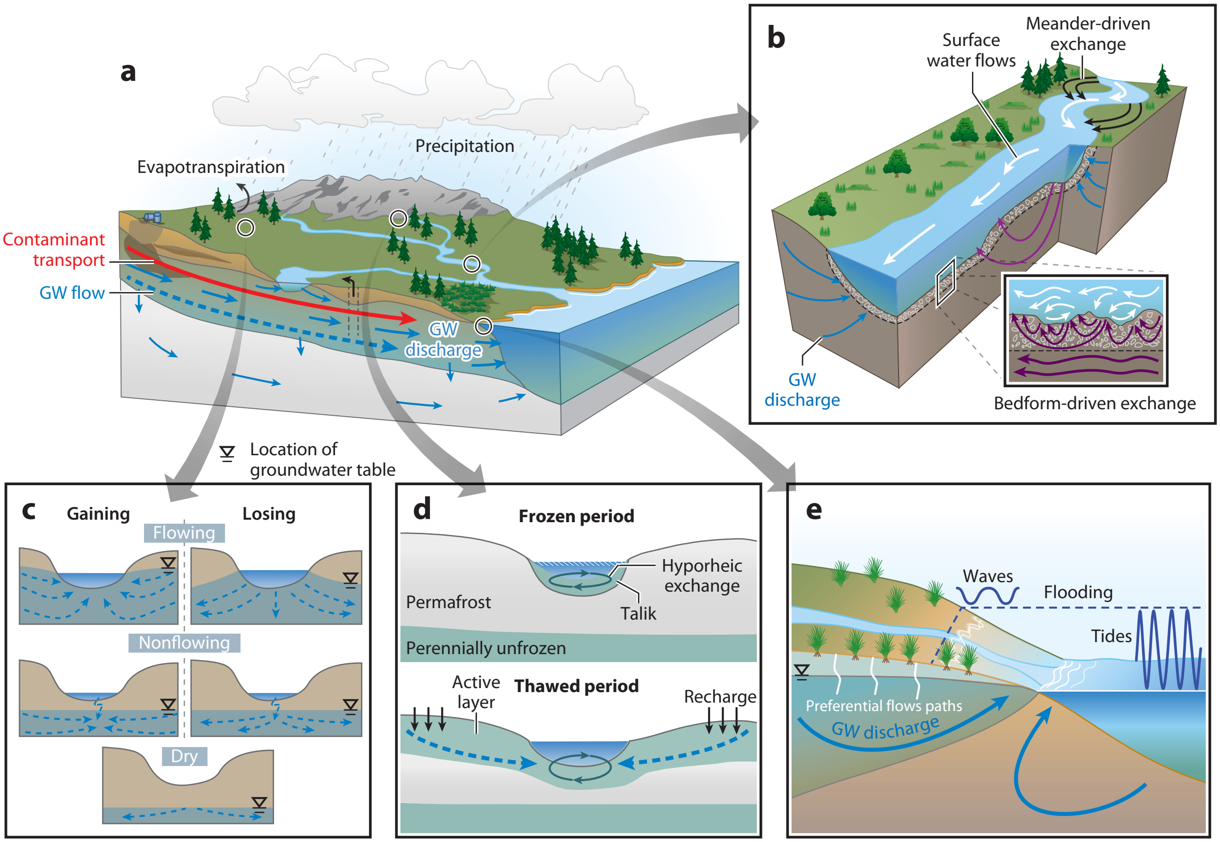

Figure 1

A conceptual model illustrating GW–surface water interactions across spatial scales, controlled by distinct factors, encompassing (*a*) the watershed scale, (*b*) perennial surface water [adapted with permission from Stonedahl et al. (58)], (*c*) intermittent surface water flow systems [adapted with permission from Gómez-Gener et al. (7) (CC BY-NC-ND 4.0)], (*d*) surface water in permafrost areas, and (*e*) salt water in marine coastal settings. Abbreviation: GW, groundwater.

and energy. River corridor science was proposed as a concept that integrates downstream transport with lateral and vertical exchange across interfaces (48, 49).

The focus of numerous existing studies of GW–SW interactions has been on the spatial and temporal variation of flow velocities, flow paths, and exchange rates between GW and SW at different spatiotemporal scales. Notable examples include studies addressing the exchange between the Amazon's main stem and its floodplains (50) and interactions between the Mississippi River and subsurface flow paths through both lateral exchanges beneath the river's meandering banks (51) and vertical exchanges beneath bedforms (52). More recently, studies have shifted from a pure hydrological focus to coupled hydrogeochemical and ecological processes. Reactive contaminant transport was found to be significantly affected by dynamic GW–SW hydrological exchange, and hydrogeochemical variations caused by flow and the distribution of geochemical properties of riparian sediments (6, 53–55). Wallis et al. (9) identified the river–GW interface as a hot spot for arsenic release. Guo et al. (56) conducted multicomponent reactive transport modeling analysis to quantify the response of GW quality to river–aquifer interactions during managed aquifer recharge. GW–SW mixing has also been shown to stimulate heterotrophic respiration, alter organic carbon composition, and exert a deterministic influence on microbial community assemblages (8, 57).

Talik: perennially thawed lateral or vertical conduits in permafrost

The characteristics of exchanges vary as a function of specific SW conditions, such as perennial SW, intermittent SW flow systems, SW in permafrost areas, and salt water of variable density (**Figure 1**). Prominent examples include the following: (*a*) The hydraulic connections between a perennial SW body and GW can change between a connected state, transitional state, and disconnected state depending on characteristics of surface flows and GW table depth (59). (*b*) Intermittent SW flow systems are subject to occasional, periodic, or protracted flow cessation and/or drying; hydraulic properties and hydrological drivers change through time, and correspondingly, the zone underneath the riverbed shifts from saturated to unsaturated (2, 60, 61). (*c*) In marine coastal settings, such as sandy beaches, estuaries, salt marshes, and mangrove ecosystems, variable density conditions occur due to differences in salinity where fresh GW from land mixes with saline water from the sea (39). (*d*) In frozen soils, the effective permeability and infiltration capacity of soils are diminished. Consequently, spatiotemporal changes in hydraulic properties and talik formation, expansion, and shrinkage associated with freeze-thaw cycles can affect flow paths and thus GW–SW interactions in permafrost regions (62). The quantity and duration of GW discharge to SW may be altered by changes in the timing and length of seasonal thawing in the subsurface and subsequent aquifer recharge of snow and/or ice melt (63).

2.2. Factors Controlling Groundwater–Surface Water Interactions

Complex spatiotemporal patterns in the exchange between GW and SW at multiple scales depend mainly on (*a*) hydraulic connections between GW flows and spatiotemporally dynamic SW systems (14, 64); (*b*) distribution of aquifer and interface sediments with heterogeneous hydraulic properties and patterns of GW flow (10, 65, 66); (*c*) complex geomorphological structures of SW networks, such as bedforms, bars, islands, and branching or meandering channels (including those in deltas and other coastal systems) (3, 12, 13, 35, 36, 67), and dynamic surface flow factors, including frequency, size, and duration of floods or storm surges (14, 68, 69); and (*d*) the results of anthropogenic activities, such as GW extraction, irrigation for agriculture, urbanization, and construction of dams, levees, and seawalls (16). The spatial scales affected by GW–SW interactions span orders of magnitude, extending from millimeter-scale circulation beneath the sediment–water interface to kilometer-scale paths through the landscape (70).

2.2.1. Effects of physical and biogeochemical properties of subsurface sediments and geologic factors. The topography, hydrogeologic properties, and processes at GW–SW interfaces are spatially and temporally heterogeneous, resulting in spatial variability of GW–SW flow patterns and exchange rates (11). Heterogeneity in permeability and porosity influences subsurface flow residence times and can create zones of spatially preferential GW–SW exchange. The aquifer media type (e.g., fractured/karstic versus porous aquifers) can determine localized or distributed exchange patterns, which further impact hydrological and biogeochemical conditions at the GW–SW interface (71). For rivers, at the reach or point scale, the texture of bed sediments determines the channel geometry, including bank-full width; sinuosity; and types, sizes, and spacing of bedforms controlling hydrologic exchange flows (64, 72), whereas at the basin scale, geologic factors, such as valley slope, width, and the distribution and structure of alluvial sediments are also important controls (47). At the interface between GW and intermittent SW flow systems or SW in cold regions, hydrogeologic properties in sediments near the SW channel are subject to change due to wet-dry and freeze-thaw cycles, further affecting GW–SW interactions (2, 62). Biogeochemical properties, such as cation exchange capacity and sediment's oxidative/reductive capacity, have long been known to be important to water quality (73) but are highly variable, making it difficult to predict pollutant attenuation and nutrient cycling that may occur over condensed length scales. Temporal variations in sediment permeability caused by variations in streambed temperatures and clogging of low-permeability layers in the streambed result in transient infiltration rates over time (59). These processes also have analogues in marine settings and coastal transition zones (e.g., deltas).

ET: evapotranspiration

GPR: ground penetrating radar

2.2.2. Effects of hydrological factors. The hydrological conditions of SW, such as water depth and currents, evaporation, and flood pulses (64, 72), and GW, such as water table depth, exhibit large variations in both space and time and play key roles in controlling GW–SW interactions (7, 17, 18). Temporal variability in hydrostatic forces can influence location and timing of GW–SW interactions and, consequently, biogeochemical reactions (35). Larsen et al. (17) found that over multiyear timescales, flood pulses that drive relatively deep flow paths were the dominant control on hyporheic fluxes and residence times but that evapotranspiration (ET) effects were discernible at shorter timescales (weeks to months) (74). Losing and gaining flow conditions can also act as the dominant control on water exchange, depending on the competitive interactions between the overlying velocity in the stream and the losing/gaining fluxes (75). Turbulent flow in rivers can drive GW–SW mixing within several millimeters of the sediment–water interface at timescales of milliseconds to seconds (20). At larger timescales, periodic variations in precipitation, snowmelt, ET, and flood pulses can modify, or reverse, GW–SW interactions (17, 18). GW table depth determines the connection state and flow path of GW and SW to some extent (60). In intermittent SW flow systems, the hydrological transitions among dry, nonflowing, and flowing conditions, combined with pulsed rewetting events and fragmented surface flow cessation, lead to spatiotemporally dynamic hydrological patterns and exchange rates (76). In some rivers, lakes, and coastal settings, GW–SW interactions can also be influenced by waves or tides, or driven by density contrasts. Other contributing factors in marine coastal settings include (*a*) (free) convection driven by density contrasts; (*b*) hydrodynamic processes such as tides, waves, and relative sea level changes (39, 77); and (*c*) bioirrigation and bioturbation by invertebrates, which can be particularly important in salt marsh or mangrove ecosystems and mud flats (78).

2.2.3. Effects of human activities and climate change. GW–SW interactions can strongly vary in response to human activities, such as GW extraction and dam construction. In evaluating the impact of 100 years of GW declines across the continental United States caused by pumping, Condon & Maxwell (4) show that loss of GW storage has resulted in widespread streamflow losses. Water transfer projects have been shown to raise the water table in water-receiving areas, which increases the risk of water salinization and water quality deterioration in arid-semiarid areas (79), and lower the water table in water-donor regions, which equally leads to negative impacts on water quality and ecology (15, 80). Climate change has already been shown to induce declines in GW discharge and levels, causing GW-fed lakes, springs, streams and wetlands to shrink or disappear in arid and semiarid areas (79, 81). Climate warming is causing permafrost thaw and spatiotemporal changes in snowpack cover and glacier melting, all of which significantly change GW discharge to SW in cold regions, such as the Qinghai–Tibet Plateau and Alaska (63, 82). A recent review provided a comprehensive look at the impacts of climate change and other anthropogenic activities on regional and global transformations in GW dynamics, including GW–SW interactions (83).

3. METHODS FOR MONITORING AND OBSERVATION

3.1. Geophysical Approaches

Noninvasive geophysical methods, including electrical resistivity, self-potential, induced polarization, electromagnetic induction, ground penetrating radar (GPR), and seismic approaches, are used to infer the distribution of subsurface geological, hydrological, and biogeochemical characteristics, and thus can be applied to characterize properties and processes at the GW–SW interface across space and time (20). Geophysical methods have been widely used to characterize the near-surface structure of GW–SW interfaces to (*a*) assess pollution pathways between GW and SW, such as those in the Columbia River (84) and in a riparian wetland in Boxford, UK, at small scales, and map subsurface heterogeneity with airborne time domain electromagnetic induction in association with other data sets at large scales (85), and (*b*) map zones of GW–SW connectivity by exploiting contrasts in electrical properties of GW and SW end members at site (86) to catchment scales (87). The majority of structural studies provide static snapshot images of the system. GPR and seismic methods have been particularly useful as they provide information about channel geometry and sediment structure at the sediment–water interface without the need for intrusive measurements (88).

Another important geophysical application is dynamic monitoring of hydrological processes at the site scale (20). SW systems, particularly rivers and beaches, exhibit dynamic erosional and depositional patterns, which are known to control flow and associated biogeochemical patterns near the GW–SW interface (89). For example, Christiansen et al. (90) show how to use time-lapse gravity measurements to assess river–riparian zone exchanges. Johnson et al. (84) used temporally distributed electrical imaging surveys at the Hanford Site in the United States to monitor GW intrusion associated with changes of river stage and to identify a permeable paleochannel in the riparian zone. Electrical resistivity surveys are also increasingly combined with tracer injection studies (91). Several methods (e.g., echo sounding, intrusive measurements, bulk electrical conductivity probes) have been used to assess changes in channel bed geometry (88). In recent years, emerging applications of biogeophysics aim to relate subsurface biological processes to geophysical properties, providing methods to characterize reactive conditions (92) and detect biogeochemical byproducts (93).

3.2. Hydrometric Techniques

Hydrometric techniques are classified into two types: (*a*) direct measurement of SW infiltration and (*b*) estimation of GW recharge.

3.2.1. Direct measurements of surface water infiltration. These methods are used to estimate transmission loss or infiltration of SW as a proxy for measuring GW recharge.

3.2.1.1. Infiltration method. The infiltration method involves artificially ponding water in a dry channel or depression while measuring the rate of infiltration. This information can then be used to calculate sediment properties, such as field saturated hydraulic conductivity (2). Measurements can be performed using an infiltrometer or permeameter at selected locations within the streambed (94), or by supplying water to a short reach of stream that has been isolated from the remainder of the channel (95). Being placed on the streambed, infiltrometers and permeameters are used to maintain a constant water level in the subsurface sediments at a specific depth by adding water. Measurements made by isolating a section of the stream channel have advantages over infiltrometer and permeameter studies in that they sample much greater water volumes while also allowing water to infiltrate through the stream banks, which may have a different permeability than the streambed (95). This method is normally used in dry channels to determine the interactions between intermittently flowing SW and GW systems.

3.2.1.2. Reach length or catchment-scale water balances. Gain or loss of SW within a reach or catchment is related to the contribution of surface inflow and outflow and GW discharge, and therefore the GW component can be separated with a mass balance approach (1, 23). The water balance method estimates the GW–SW exchange by calculating the difference of flow between cross sections with measured streamflow, which is sometimes referred to as a seepage run (1). To reduce uncertainty induced by river or streamflow recession after rainfall or snowmelt, measurements can be taken during low flow periods when flow is not changing quickly and GW–SW exchanges are most pronounced (96). Synoptic gauging that measures the change in streamflow across different segments of a reach of river or stream provides a large-scale view of streamflow inputs and outputs but does not identify discrete discharge zones (97). Multiple sites on a river must be gauged concurrently. It is also important to note that net inflow or outflow to streams, as determined by a mass balance for a channel section, has been shown to be much less than the gross exchange of GW and SW (98). Additionally, the resolution of the mass balance approach is only as reliable as the streamflow measurement itself, combining the uncertainty of paired upstream and downstream streamflow measurements. Therefore, it is often difficult to detect net changes that do not exceed a few percent of the total SW flow.

3.2.1.3. Floodwave front tracking. Data obtained from tracking the progression of a floodwave down a stream channel and monitoring the changes in velocity can be used to estimate infiltration along the longitudinal direction of SW flow (2). A change in velocity suggests water loss due to infiltration and can be used to estimate the infiltration amount if other inflows and channel geometry are known. The models for estimating the infiltration loss with floodwave progression vary from the simpler Muskingum–Cunge method (99) to the full Saint-Venant equations, which combine the continuity and momentum equations (100). These methods can be used as the stream both wets and dries as well as over longer timescales (2). When using this method, the need for adequate representation of the channel geometry was demonstrated by Noorduijn et al. (100).

3.2.2. Measurements of groundwater recharge. The SW infiltration is not necessarily equal to GW recharge, especially when delays exist between infiltration and GW recharge at locations characterized by substantial depths to water tables (101). Even when this time delay is accounted for, recharge is less than infiltration due to other factors, such as ET and antecedent soil moisture. In view of these issues, some studies have tried to estimate the proportion of infiltration that becomes recharge (95). The duration of flow required to produce GW recharge is affected by the water table depth below the streambed, the soil texture, and the antecedent soil moisture content (95). Very large floods that inundate floodplain areas tend to produce large transmission losses but proportionally less aquifer recharge due to lower infiltration rates and greater ET losses (102).

3.2.2.1. Measurement of hydraulic gradients and hydraulic conductivity. Subsurface exchange fluxes can be estimated by measuring hydraulic head gradients with monitoring wells and portable piezometers and pairing these with estimates of sediment hydraulic conductivity to compute fluxes based on Darcy's law (97). Various types of miniaturized drivepoints have been developed for easy installation in difficult materials, such as rocky streambeds or muddy seabeds, without the need for a pilot hole (97). Drivepoints with short, well-defined screens also function for measuring hydraulic conductivity using slug test approaches and pore water chemistry profiles to support hydrogeologic modeling (103, 104).

3.2.2.2. Groundwater mounding. GW mounds can develop when water infiltrating through a streambed or shoreface reaches the water table and are mainly characterized by GW level variations. Changes in GW levels close to or beneath the stream or shoreline can be monitored relatively easily using monitoring wells. With different equations, such as the convolution approach and Boussinesq equation, variations in the GW mound in response to changes in SW levels can be used to calculate changes in GW storage and, thus, the amount of SW infiltration to GW (2). There are many applications that use the GW mounding method to estimate aquifer recharge depending on the hydrogeologic setting (2).

FO-DTS: fiber-optic based distributed temperature sensing

TIR: airborne thermal infrared remote sensing

3.2.2.3. Seepage meters. Seepage meters are the only available tool to directly measure GW discharge across submerged sediment boundaries of lakes, wetlands, and streams. The original design of a seepage meter consists of a bottomless cylinder inserted into the sediment and vented to a deflated plastic bag to measure water inflows or losses (105). In case of SW infiltration into the sediment, a known water volume is added to the plastic bag prior to installation, and the infiltration rate is calculated from the volume loss. The design has been modified to improve performance in freshwater (106) and marine settings (107) by covering the collection bag with a rigid container to isolate it from pressure changes, adding a piezometer, replacing the bag with heat-pulse/ultrasonic/electromagnetic/dye-dilution meters to continuously record the water flow rate (97), and minimizing bag exposure to currents (108).

3.3. Tracer Methods

Both natural and artificial tracers, such as heat, solutes, and environmental isotopes, are widely used to trace GW–SW exchanges.

3.3.1. Heat as a tracer. Diurnal and annual changes in water temperature make heat a natural tracer to infer GW flow rates and patterns (109, 110). Measured temperature signals, both vertically beneath streambeds (111) and longitudinally within streams (112), have been used to quantify GW–SW exchange rates (113). Because GW tends to be cooler than SW in the summer and warmer in the winter, streambed–SW temperature gradients can be used to map GW–SW exchange (109) and quantify time series of GW–SW fluxes at a point (111), with shallow subsurface temperature methods being sensitive to both gaining and losing conditions. Longitudinal characterization of GW contributions to streamflow, as either baseflow or bank-storage return flow at the reach scale, has employed fiber-optic based distributed temperature sensing (FO-DTS) just above the streambed (110, 114) and airborne thermal infrared remote sensing (TIR) (112), both of which can provide high-spatiotemporal-resolution information on GW discharge to the stream. FO-DTS data collected over time can identify areas of GW discharge based on temperature contrast and buffering of temperature change (115), whereas TIR utilizes daily to seasonal temperature contrasts between SW and GW. However, these methods cannot often be used to quantify GW–SW fluxes (22). The FO-DTS methods excel at providing continuous data sets that monitor water temperature at the streambed interface where discharge occurs (116), whereas TIR can be applied at broad scales in areas that are difficult to access (112, 117). Both techniques produce snapshot characterizations in time during the data collection campaign and can be impacted by thermal stratification in poorly mixed streams, particularly TIR imaging, which does not penetrate the water column. An increasing number of studies also use large-scale heat tracing over time to detect relative GW influence on streamflow by comparing metrics of paired local air and stream temperature time series (118), including inference of deep versus shallow GW discharge dominance and change following wildfire (119).

3.3.2. Environmental tracers. Environmental tracers have been widely used for estimating GW discharge to rivers (24, 25) and marine waters (120) over the past few decades. This method is appropriate for reach- or embayment-scale estimation of GW inflow to SW. Commonly used environmental tracers include solute tracers, such as chloride, chlorofluorocarbons, and other major ions (17, 28); water stable isotopes such as ^{2}H, ^{18}O, and $^{87}Sr/^{86}Sr$; and radioisotopes such as ^{222}Rn, $^{3}He/^{4}He$, ^{224}Ra and ^{223}Ra, SF_6, and ^{3}H (2, 121). While chemical tracers and stable isotopes are useful for distinguishing between sources of water in an aquifer and quantifying hydrologic exchange flux (122), radioisotopes can be used to estimate GW age and/or residence (transit) times from days to thousands of years (2). Environmental tracers should be naturally present at different levels between GW and SW to calculate mixing between waters from various source areas and exchange fluxes between those areas. Uncertainties in the environmental tracer method may arise from spatiotemporal variations of tracer concentrations in GW and SW, leading to difficulties in defining end-member concentrations; uncertainties can also arise from incomplete mixing in SW and inappropriate sampling resolution (24, 45, 123). Evaluation of the uncertainty for a single tracer is challenging in practice; thus, simultaneous use of multiple tracers in combination with other methods, such as the flow-gauging-based method in rivers or geophysical data acquisition, could provide a more complete understanding of GW–SW interactions.

3.3.3. Injected solute and dye tracers. Manual injection of tracers in rivers and streams provides an alternative to natural tracers for identifying GW–SW interactions across scales (124). For the reach scale, dilution expressed through breakthrough curves downstream of the tracer injection location can be used to estimate GW inflow. By pairing tracer injections over short and longer nested reaches, cross streamflow gains and losses can be estimated (98). For the hyporheic zone scale, the vertical profile of tracer concentration below the sediment–water interface can be used to depict the extent, fluid flux, and reactivity (125). Tracer injection can also be combined with electrical resistivity imaging to directly visualize the extent of the hyporheic zone as the injected tracer may reduce the electrical resistivity of porewater (26, 126). The original method to analyze the transport of an injected tracer relies on the concept of lumped transient storage to represent the exchange between the flowing water and the hyporheic zone or static water. This method has evolved to address different transport scenarios and environments by including multiple transient storage terms (127, 128). Although conservative tracers (e.g., Br^-, Cl^-) are sufficient to estimate fluxes, there is growing interest in using tracers to identify the extent of biogeochemical reactions in rivers and hyporheic zones. The smart tracer method was thus developed to identify metabolically active zones (129). A commonly used smart tracer is resazurin, which can be irreversibly reduced to resorufin under mildly reducing conditions in the presence of respiration. The differing reaction and decay characteristics of resazurin and resorufin can be exploited as an indicator of the sediment's capacity to drive redox-induced transformations along the studied reaches. In a combined amendment with a conservative tracer (bromide), measured depth profiles of reactive tracers could be used to identify highly reactive aerobic zones within a hyporheic zone (130). The smart tracer method can be extended to include multiple storage zones for better partitioning of metabolically active and inactive zones (131). Smart tracers can be combined with nonreactive tracers and environmental DNA to provide new insights into linkages between GW and SW and associated aquatic processes (132).

4. METHODS FOR MODELING AND INTERPRETATION

4.1. Mass Balance Approaches

The mass balance of solutes is the theoretical basis of tracer-based methods (e.g., environmental and injection tracers) for estimating GW–SW interactions (28). Mass balance equations for tracers may vary depending on physico-chemical properties. For conservative tracers, such as Cl^- and Br^-, mass balance is mainly controlled by GW inflow to SW and SW outflows to GW. In contrast, for dissolved gases (e.g., radon, chlorofluorocarbons, helium), gas exchange at the air-water interface needs to be included in the mass balance equation. Gas transfer velocity for large open waters (e.g., oceans, lakes) is affected by many environmental factors, such as temperature and wind velocity (133). Particular attention should be paid to radon, which not only decays rapidly (with a half-life of 3.8 days) but also may be produced, albeit at variable rates, within sediments and bedrock. Different conceptual models for GW–SW interactions lead to differing mass balance equations—thus, a combination of multiple tracers with spatial and temporal replication could help to reduce model uncertainty and nonuniqueness (45).

Various approaches to model and characterize mass transport in streams using injected tracers have been proposed (35). In many approaches, the stream–aquifer system is idealized as a 1D problem, and the zone of GW–SW mixing is represented as an immobile zone connected to the mobile stream by a mass transfer process. Breakthrough curves at downstream monitoring stations are the key field observation for inferring the properties of the storage zone, as the degree of tailing reflects the rate of transfer in or out of the storage zone and the residence time there. However, it is difficult, if not impossible, to separate storage in porous media (such as the hyporheic zone) from storage in pools or other slow-moving portions of the SW without monitoring breakthrough curves in the hyporheic zone using mini-point piezometers or similar samplers (89, 124). A variety of mass balance equations with different numbers of storage zones have been developed for characterizing complex behaviors of observed breakthrough curves (131).

4.2. Hydrograph Separation Techniques

In streams, tracer-based hydrograph separation using isotopic and geochemical tracers has been routinely applied for reach or catchment water balance analysis by separating streamflow into temporal and spatial origins of different components, such as baseflow and quickflow (29, 30). The baseflow is normally assumed to represent GW discharge into the stream (134), and this assumption may be inappropriate in cases where drainage from bank storage and soils contributes to streamflow (135). The limited number of streamgauging stations constrains the resolution of this method, and gauge locations are often not well distributed across varied types of land use and hydrologic terrain (136). Results are usually integrated over long stream reaches (tens of kilometers). The proportion of GW flow can be inferred from numerous hydrometric-based, chemical, or isotope-based methods developed over the past four decades. Detailed reviews of these types of methods are provided by Mei & Anagnostou (137) and Klaus & McDonnell (138). It is noteworthy that hydrograph separation is particularly useful for identifying event-induced (e.g., rainfall) baseflow. This contrasts with the environmental tracer method, which can only estimate GW inflow under steady flow conditions. One main difficulty of applying tracer-based hydrograph separation is that the isotope composition and tracer concentrations in different end members, such as event and pre-event waters and GW, are often similar and vary spatially and temporally (1). Tracer-based hydrograph separation yields GW discharge rates from reach to catchment scales.

4.3. Analytical Solutions

Analytical solutions to simplified model formulations have often been used to estimate pressure head and temperature in order to quantify the range and rates of GW–SW interactions for strict conditions, such as steady state, and for simple boundary conditions (139). As an example, the analytical solution for the effect of riverbank storage on flood peak timing and streamflow evolves from earlier efforts by Hunt (140), who used a convolution integral. This effort was furthered by Åkesson et al. (141), who examined the impact of river floodwaves on GW in a homogeneous aquifer. Solutions have also recently been proposed to consider the factors of stream bank storage effects during floods (142), lateral flow in higher permeable layers and interplay between vertical flows induced by recharge and flood events (143), and changes in water content from unsaturated to saturated zones (144).

Numerous analytical methods have been proposed to estimate fluid fluxes using natural thermal signals measured in saturated sediments, particularly amplitude and phase for specific frequencies, such as diurnal fluctuations (31, 111). The reliability of flux estimates by analytical methods depends on many factors, such as sensor deployment, signal processing techniques, and selection of thermal parameters (145). However, the implied assumption of steady state will often be too restrictive for practical use when applying analytical solutions. For example, methods that utilize phase information have poor performance under unsteady flow (31). Studies have also leveraged analytical solutions to estimate sediment thermal properties from natural temperature signals (146). Analogous to the aforementioned solutions that use temperature data, analytical solutions that leverage solute concentration data also exist and have been widely used in marine settings.

Also, in lake and seafloor sediments, a number of analytical solutions have been presented for estimating GW discharge as a function of offshore distance (147). Solutions also exist for modeling small-scale benthic exchange processes. For example, tidal pumping has been described for sinusoidal changes in the water level alongside a dipping shoreface (148). Analytical solutions also exist for wave-driven pumping above a planar bed (149). Though simplistic, these solutions can be linked with hydrodynamic circulation models to consider spatial and temporal dynamics in benthic exchange within enclosed estuaries and broader shelf environments (150).

4.4. Numerical Models

Numerical modeling has made important contributions to our understanding of GW–SW interactions by overcoming the often stark limitations of analytical solutions, particularly for heat tracers (32–34) and for assessing complex patterns of GW–SW interactions using heat, solute and environmental tracer data (34). With increasing scale, starting from the pore scale, the focus of model applications successively shifts from local fluid dynamics toward regional environmental flows sustained by GW, in the case of large regional-scale models. Model flexibility enables the inclusion of complex flow channel geometry, 2D or 3D systems, different types and combinations of boundary conditions, and spatially variable initial conditions, and consideration of coupled flow-heat-solute transport processes under transient conditions (33). Numerical models are typically coupled with parameter inversion methods to estimate fluxes (32). For numerical studies of rivers that focus on the pore, hyporheic zone, and reach scales, a growing effort has been made to quantify solute transport processes and to unravel the hydrologic controls on biogeochemical processes and the condition of aquatic ecosystems (53, 151). Under assumed steady-state conditions, exchange fluxes are typically quantified from field data using transient storage models or their variants (152). Recent extensions of the transient storage model overcome the limitation of specificity by simulating multiple storage zones with distinct residence time distributions, such as continuous time random walk models (153). Others overcome these limitations through more detailed characterization of the storage–exchange processes or physically based scaling relationships involving easily measured physical variables (12). The physics-based coupling scheme is computationally expensive given the disparate flow rates in SW versus GW. Specifically, the time steps of the numerical solver need to be reduced to adapt to the fast flow of SW. As the model scale increases to the watershed scale or beyond, a variety of distributed hydrological models that previously simplified GW as a single bathtub reservoir have been made more physically realistic by coupling SW models with GW models such as MODFLOW (the US Geological Survey modular finite-difference flow model). A detailed review of such types of models is provided by Ntona et al. (154). A clear trend seen in newly emerging large-scale models is a full coupling of the shallow water equation with the Richards equation for SW or GW flow (e.g., ParFlow and HydroGeoSphere, respectively). The full coupling scheme can provide an explicit representation of complex landscapes (e.g., hillslopes), which are typically overlooked in distributed hydrological models (155).

5. CHOOSING THE APPROPRIATE METHOD

5.1. Factors to Consider

There is a need for guidance to design field campaigns and select methods that both contribute to study goals and work well under site-specific conditions. Hammett et al. (21) provide a spreadsheet-based GW/SW-Method Selection Tool (GW/SW-MST) to help users identify appropriate methods from a toolbox of 32 methods. Users can input their GW/SW-related study goals and site parameters/characteristics to identify a suite of methods that are both feasible and likely to contribute to the characterization objectives. Shanafield & Cook (2) propose several factors for selecting methods to estimate GW recharge beneath intermittent SW flow systems. In general, when choosing a method to estimate or measure GW–SW interactions, several factors need to be considered:

1. Methods must be customized according to the study goal, which will dictate the desired spatiotemporal resolution of exchange rates, the extent of the field site, and the time span of the study. Regional assessment of water resources or the fate and transport of solutes requires methods that allow measurements on larger scales. In contrast, investigations of the spatiotemporal variations of exchange processes, their rates, and flow paths between SW and GW require measurements with high spatial and temporal resolution, such as temperature profiling or piezometer methods with automated, continuous monitoring. There is always a trade-off between cost and the need for tighter instrument spacing and/or the frequency of data collection, depending on the study purpose. The purpose of the study affects method selection because some methods do not distinguish between hyporheic, bank storage, and net GW inflows and outflows, whereas other methods only estimate some types of exchange (40). For example, seepage meters measure water exchange but do not identify the driving process, while water balance approaches usually do not capture hyporheic exchange, and environmental tracer methods provide a combined flux but may under- or overestimate some components depending on the different tracer concentrations in the inflows (40, 45).
2. Site parameters/characteristics, including the lithology, geological and hydrogeological conditions, and overall setting (e.g., stream or river, lake or wetland, and coast or estuary) will largely determine the most appropriate methods. For example, on a heavily armored or rocky riverbed, it is difficult to install equipment for some point-scale methods, such as seepage meters, permeameters, and piezometers, and noninvasive geophysical methods could be advantageous. The spatially variable and transient distribution of clogging layers at the streambed calls for time-integrated methods or continuous monitoring. It is hard to directly access large rivers with high flows and deep channels as there is a risk of equipment loss or damage due to floodwaters and bed scouring. Temperature-based methods may be hard to apply with a lack of substantial contrast between GW and SW temperatures.
3. Site accessibility, equipment costs or availability, and field time should also be considered for choosing the quantification method. The selection of methods that are suited to a similar scale may depend on which one is more easily operated considering factors such as accessibility of the study site, portability of the equipment, cost, and human resources. The balance between equipment and labor costs should be evaluated. For example, methods that use sensors with data loggers for water levels and temperature may require more expensive equipment (including the monitoring wells, especially for a location with a large depth to GW) but fewer visits to the field site, whereas methods that require samples may be cost prohibitive by requiring many visits to a site for collecting samples. Some SW sites are good

targets for drone to satellite remote sensing, while others, such as small headwater streams, may only be tractable by direct contact methods.

5.2. Application Scales

Depending on the study purpose, methods must be chosen that are appropriate for the respective spatial and temporal scale. The scales of different methods were reviewed by Larsen et al. (17), Shanafield & Cook (2), McLachlan et al. (20), and Kalbus et al. (1) (**Figure 2**). Point-scale measurement approaches, such as seepage meters, temperature sensors, and head measurements, have been used effectively at relatively small scales ranging from vertical deployment of sensors at a single point to horizontal layouts across larger features such as a gravel bar or meander and, at most, deployment along a short stream reach. For tracer tests, the portion of sampled aquifer volume is larger, on the scale of meters around the sample point. Solute tracer methods for the estimation

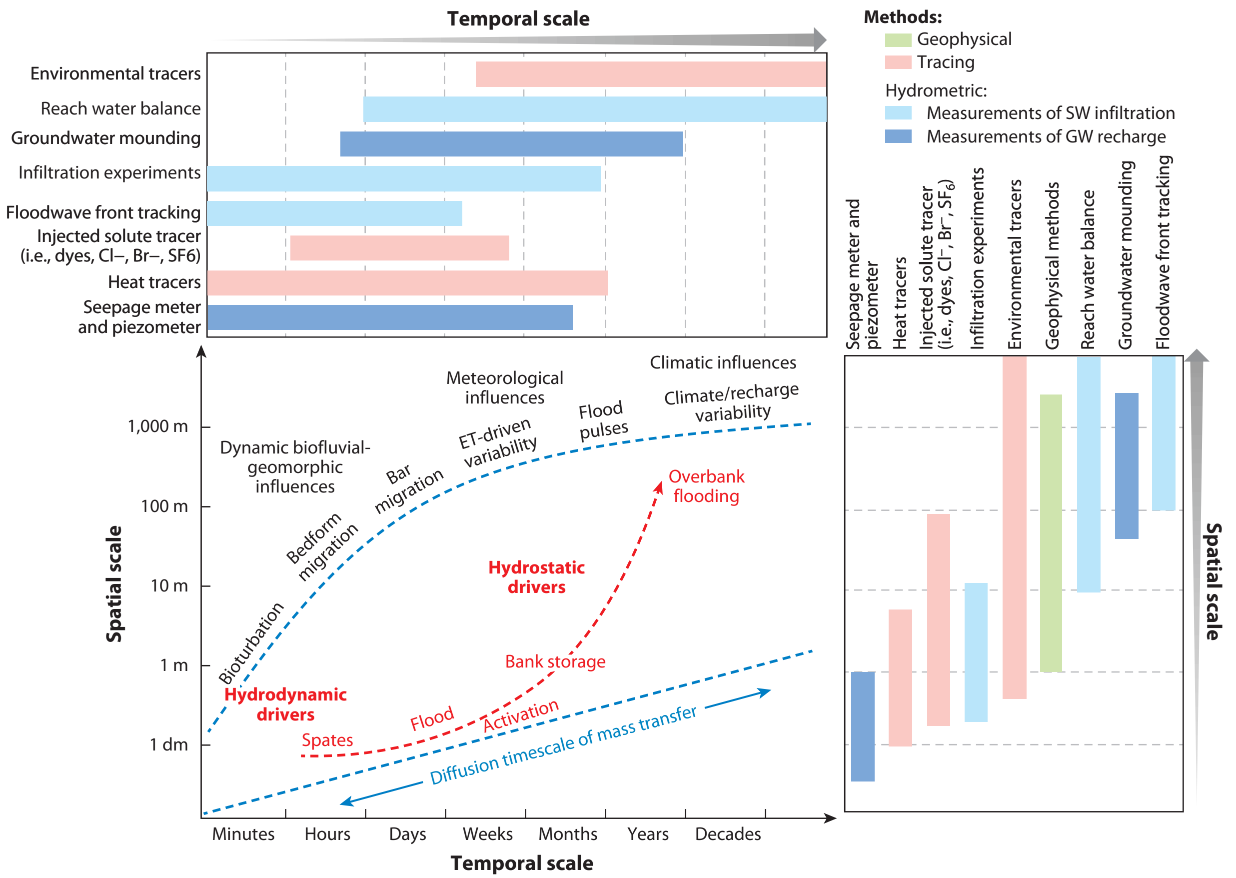

Figure 2

The main factors controlling GW–SW interactions across various scales, as well as the spatial and temporal scales at which different methods have been employed to estimate GW–SW interactions. The dashed lines delineate the approximate spatiotemporal limits of hyporheic flow. Important regimes of hyporheic flow are denoted in red. External biological, fluvial, and geomorphological influences are shown in black. Abbreviations: ET, evapotranspiration; GW, groundwater; SW, surface water. Graph in lower left adapted with permission from Harvey & Gooseff (14). Data are from Kalbus et al. (1), Shanafield & Cook (2), Larsen et al. (17), and McLachlan et al. (20).

of transient storage work well on the reach scale. Measurements of the temperature gradient at the GW–SW interface provide flux estimates from the point to reach scales. Environmental tracer methods have been used to estimate GW inflows to SW over reach lengths up to 120 km, with a resolution dependent on the sampling distance (156). Geophysical tools characterize subsurface parameters at vertical scales of centimeters to hundreds of meters and horizontal scales of meters to hundreds of meters. Methods based on SW flows (streamflow difference and floodwave front tracking) average GW–SW exchange rates over the reach length between measurement transects, ranging from several meters to several tens of kilometers. In comparison, GW-based methods (GW mounding and chemical tracers) provide estimates of recharge with spatial scales of tens of meters to a few tens of kilometers, depending on the distance of the observation locations from the river.

Method selection also depends on the investigation timescale. Seepage meters and passive samplers can collect water over hours to weeks or longer and, thus, yield time-averaged or temporally variable fluxes. Hydrograph separation gives estimates of the GW contribution to streamflow averaged over the duration of the recorded hydrograph, typically from several years to decades. Automated sampling methods or data loggers can operate at different time intervals for a long period, allowing for observations of a range of temporal variations. In particular, parameters that can be determined continuously at constant intervals using probes, such as for pressure or temperature, are suitable for long-term monitoring and can be analyzed in the frequency domain using Fourier transforms and wavelets as an added benefit.

The resolution of the various methods is also different and dependent on the purpose of the study (whether it is meant to capture exchange processes and flow paths; or to quantitatively estimate recharge resulting from individual events, annual average recharge, or longer period recharge; or to evaluate associated solute or heat transport). Geophysical methods can have temporal resolutions of minutes to hours. Methods that use sensors capable of measuring parameters such as water levels, salinity, and temperatures at short time intervals (seconds to minutes) normally have a relatively fine temporal resolution. Where a gauging station exists nearby with longer-term data, streamflow-based methods can be advantageous. The temporal resolution of the GW mounding method depends on the period of the GW mound formation and decay, which is related to the hydraulic diffusivity of the aquifer and the distance between the streambed and the water table, and which varies from a few hours to a few years (17). Environmental tracer methods provide average recharge flux over periods from days to tens of thousands of years, depending upon the method used for determining the GW age. The temporal resolution of solute tracer method depends on the sampling frequency during the experiment.

5.3. Advantages and Limitations of Various Techniques

The use of piezometers, seepage meters, and boreholes provides direct measurements but may be limited by site conditions, environmental protection, or installation costs (20). Dense deployments of point measurement devices can yield detailed information on parameter variability, but information in the reaches between the measurements remains unclear. Extreme values of the measured parameter may be missed, thus influencing summary statistics. Conversely, tracer experiments provide information that is averaged over larger volumes and therefore may be used to characterize spatial heterogeneity, e.g., identifying low-mobility and high-mobility zones in the subsurface (20). Geophysical techniques are sensitive to subsurface geophysical properties and hence act as proxies for geological, hydrological, and biogeochemical parameters. Furthermore, given that multidisciplinary research has been essential in GW–SW interface research (19), the wider application of geophysical tools, and better integration with direct contact methods, would be beneficial. Shanafield & Cook (2) review pertinent temporal and spatial scales, appropriate uses, and advantages and limitations of seven methods for quantifying infiltration in intermittent SW flow systems. It is common to use methods that estimate transmission loss or infiltration as a proxy for measuring GW recharge. These methods, which measure the total change in streamflow over a defined reach of a river or stream, give a much larger view of discharge at the streambed interface (one that would require many measurements from seepage meters or mini-piezometers to make comparison possible) but do not identify where discrete discharge zones are located. Methods that integrate over large sample volumes provide reliable estimates of average values but do not enable a detailed characterization of the spatial heterogeneity of a given parameter. Detailed advantages and limitations of various techniques are summarized in **Table 1**.

6. APPLICATION CHALLENGES FOR DIFFERENT METHODS

6.1. Scale Effect

The data obtained with point-scale measurement approaches are representative of only a very small portion of a much larger, complex system and generally do not enable the estimation of reach-averaged conditions at distances of hundreds of meters to tens of kilometers (14). However, the consequences of hydrologic exchange for downstream water quality and ecology manifest themselves at much larger scales of entire drainage basins and ecoregions (14). It is essential to understand the cumulative effect of small-scale processes. In comparison, the methods of environmental tracers, solute tracers, water balance, and GW mounding can provide reach-scale averaged exchange rates, but they cannot provide detailed information on spatiotemporal distributions of exchange and flow paths.

With most methods, the scale of measurements conducted in heterogeneous media may significantly influence results. As a classic example, estimates of hydraulic conductivity scale by orders of magnitude with the test radius (1, 2). The scale dependency of measurements in heterogeneous media implies that even a dense grid of point measurements may deliver results that differ considerably from those obtained from larger-scale measurements because the importance of small heterogeneities, such as narrow high-conductivity zones, may be underestimated (1). A better representation of the local conditions that accounts for the effects of scale on measurement results can be achieved by conducting measurements at multiple scales within a single study site.

6.2. Impact of Hydrogeological Complexity

The complexity of hydrological and geological factors makes the processes affecting GW–SW interactions difficult to measure and interpret. These factors include three aspects. One important factor is spatially and temporally variable hydrological conditions, such as variations of water levels, spatial variability in recharge and seepage, and potential difficulties in linking a specific flood event to a change in GW level (2). Relatively rapid changes in GW–SW exchanges (occurring over days to months) may be hard to capture without a long-term study due to temporally variable hydrological conditions, such as the sparse flood events in intermittent SW flow systems. The second complicating factor is the variable properties of sediments, including sediment heterogeneity and temporal changes in sediment characteristics, which are normally hard to obtain. Frequent scouring and deposition of the streambed during flood events make it difficult to estimate streambed geometry, and flood events themselves are unpredictable and transient in nature (2). These move the instruments used for measuring temperature and head pressure, complicating the interpretation of the monitored data. The third factor is the difficulty of accessing and collecting data in typically remote areas. Moreover, many field measurements are often taken at one location and for short periods of time, and therefore, the ability to extrapolate GW–SW exchange over larger spatial and temporal scales is empirically constrained (11). Coluccio & Morgan (23) provide an

Table 1 Advantages and limitations of various methods for studying GW–SW interactions

Type of method	Monitoring method(s)	Interpretation method(s)	Advantages	Limitations	Suitable SW settings
Geophysical methods	Electrical resistivity, self-potential, induced polarization, electromagnetic induction, ground penetrating radar, seismic methods	Geophysical models combined with numerical models	■ Are minimally invasive and spatially referenced ■ Provide information on GW–SW exchange beyond the SW channel ■ Monitor dynamic hydrological processes	■ Exchange rate is difficult to quantify. ■ Geophysics is inherently uncertain, is typically impacted by the properties of pore water and geology together, and is often sensitive to bulk physical properties. ■ Site-specific considerations are a factor. ■ Methods often need calibration with intrusive methodologies. Main source: McLachlan et al. (20).	All—good for marine coastal settings and areas of inland saline GW and contamination
Hydrometric methods 1: measurements of SW infiltration	Infiltration experiment	Water balance method	■ Estimate streambed hydraulic properties where it is not convenient to sample ■ Provide an estimate of the variability of infiltration rates	■ The hydraulic properties measured may not always be indicative of variable infiltration rates during flood events. ■ The hydraulic conductivity measured between flow events is only a snapshot estimate. ■ Need to consider the transient state of saturated to unsaturated condition beneath the streambed.	Intermittent SW flow systems
	Reach length or catchment-scale water balance	Water balance method	■ Identify hot spots of river gains and losses at a broad scale ■ Determine averaged losses or gains over the river reach ■ Better suited for relatively homogeneous aquifers ■ Simple and quick to calculate	■ Expensive, low resolution, and time consuming. ■ The method cannot quantify the water exchange spatially within reaches (11). ■ Measurement errors of surface flows are caused by macrophytes in the streambed, shifting river margins, high sediment load, or unstable streambeds. ■ Uncertainties increase when calculating catchment-scale water budgets as exchange rates are also limited by the accuracy of other measured components in the budget.	All
	Floodwave front tracking	Water balance method	■ Capture the infiltration throughout a wide spatial range of intermittent and ephemeral stream channels (100)	■ Potential sensitivity to the stream geometry, which can be difficult to adequately parameterize over long reaches and can be altered during flood events (100).	Intermittent SW flow systems

(*Continued*)

Table 1 *(Continued)*

Type of method	Monitoring method(s)	Interpretation method(s)	Advantages	Limitations	Suitable SW settings
Hydrometric methods 2: measure-ments of GW recharge	Measurement of hydraulic gradients and hydraulic conductivity	Darcy method, analytical solutions, numerical models	■ Appropriate in small-scale applications and in detailed surveys in heterogeneous environments ■ Easy and quick to install piezometers and measurements are straightforward to analyze ■ Can use existing well networks	■ Hydraulic conductivity varies significantly across an area, and it is difficult to extrapolate values to represent a large area (96). ■ When conducting permeameter tests in the laboratory, the natural structures and stratification of the sediment are disturbed (1), and the conductivity value does not represent the vertical or horizontal conductivity and does not provide any information on preferential pathways (23).	All except for frozen or highly armored ground setting
	Seepage meter	None	■ Directly measure the GW recharge amount ■ Measure temporal and spatial variability of fluxes at point scale ■ Focus on specific, small areas of the stream with each measurement	■ It can be difficult to distinguish hyporheic exchange from GW discharge. ■ Seepage meter housings can induce interstitial flow into the seepage meter pan (41, 71). ■ Current or waves may affect the hydraulic head in the bag or may distort or fold the bag.	All except for frozen or highly armored ground setting
	GW mounding	Water balance method, numerical models	■ Yields actual recharge estimates and not infiltration because changes in the GW levels themselves are used ■ Can be used for relatively long-duration flood events	■ Uncertainties in hydraulic properties are associated with medium heterogeneity (2). ■ The assumption of Dupuit flow can lead to errors in GW level calculations when the observation well is very close to the stream (59). ■ Recharge rates are possibly underestimated since temporal variations in SW infiltration are damped during flow through deep unsaturated zones.	Perennial SW and intermittent SW flow systems

(Continued)

Table 1 (*Continued*)

Type of method	Monitoring method(s)	Interpretation method(s)	Advantages	Limitations	Suitable SW settings
Tracer method	Injected solute tracer	Hydrograph separation, water balance method, analytical solutions, numerical models	■ Semi-quantitative and relatively low-frequency ■ Stream tracer experiments have the advantage of spatial averaging at the reach scale. ■ Can be applied to the locations of study interest	■ The method is expensive and time consuming. ■ Injections are usually restricted to times of steady flow. ■ Sampling periods are limited for timescales longer than that of the introduced tracer. ■ Hydrochemistry of the baseflow and storm event water composition may be similar, or they may not be constant in time or space (157). ■ Chemical tracers may be affected by biogeochemical processes. ■ Low tracer concentrations may cause analysis errors.	All
	Environmental tracer	Hydrograph separation, water balance method, analytical solutions, numerical models	■ Identify interactions on large scales and provide estimations of seepage flux on the point scale ■ Contain past flow information and provide information on long-term fluxes, particularly when tracers such as ^{14}C are used	■ The method has low frequency and resolution and is expensive. ■ The required assumption that GW flow is under a steady state condition does not apply for rivers under highly dynamic flow conditions. ■ The method requires choosing end-member concentrations that are uncertain spatiotemporally for GW and river water (45). ■ When an environmental tracer is used as a dating tool, uncertainties are also introduced in converting GW velocities to recharge rates.	All
	Heat tracer	Analytical solutions or numerical models	■ Duration from short to long periods ■ High-frequency and high-density data ■ Offer many techniques at varying spatial and temporal scales ■ Range in cost and complexity, and thus can be tailored to suit a study's needs	■ A temperature gradient between GW and SW might not always be present for methods based on temperature contrast. ■ Small temperature differences may increase method imprecision. ■ For certain types of analysis, temperature needs to be measured continuously (31).	All

Abbreviations: GW, groundwater; SW, surface water.

overview of characteristics specific to braided rivers and emphasize the currently limited understanding of how characteristics unique to braided rivers, such as channel shifting, expanding and narrowing margins, and a high degree of heterogeneity affect GW–SW flow paths.

6.3. Quantitative Uncertainty Analysis

Uncertainties in measurements made by seepage meters in streambeds are related to design limitations of the devices, disturbance of flow paths due to instrument installation, velocity heads imposed by wave and current interference, gas release in bed sediments, improper seals between the meter and the bed, small-scale spatial heterogeneities, and the combined effect of slow seepage rates with a moving streambed (97, 158). Other methods, such as multiple tracer injections and the measurement of isotopic and temperature signatures, to infer features of GW inflows to SW may be similarly influenced by sediment heterogeneity, installation difficulty, and the challenges of working in a continuously evolving system (due to the transport of sediment, temporal variability of flow, etc.) (37, 97). The range of measured flux for different methods depends on both the experimental design and the characteristics of the method itself. The accuracy of a hydrologic exchange flux measured using a radioisotopic tracer will be determined by the decay timescale of the tracer relative to the transport timescale in the system. Higher fluxes and greater accuracy are associated with greater resolution of head measurements. Heat tracing can only detect fluxes within a certain range, and extreme high or low fluxes are undetectable. The range of detection for solute tracer experiments is determined by the timescale of the tracer injection and observation time of tracer movement, both of which affect the observable timescales of exchange and storage processes (14).

Indirect methods for measuring the flux with a water balance, or Darcy flux calculations, are subject to biases related to conversion of the measured quantities to flow rates (97). Goodrich et al. (159) provide a concise table of the trade-offs between data requirements, analyses, and uncertainties for several of the methods. Uncertainty for an individual study may depend on several factors, including uncertainty in the underlying parameters and in model conceptualization and data analysis. Underlying parameter uncertainty may include the rates of decay of radioisotopes such as tritium, or sediment properties such as hydraulic conductivity (14). For example, Darcy calculations rely on accurate estimates of hydraulic conductivity and hydraulic gradient values, both of which are associated with high potential errors (160). Uncertainties that influence model conceptualization include inadequate spatial resolution or incorrect identification of end-member sources in chemical mixing analyses, and uncertainties may also be introduced by assumptions made about the system during data analysis. Hydrograph separation is based on the assumptions that stream discharge can be directly correlated to GW recharge, and several other factors are neglected in this approach, such as ET and bank storage, leading to considerable uncertainties (135). Tracer-based hydrograph separation further assumes that pre-event water and event water are clearly different in isotopic or chemical composition and that the composition is constant in space and time; both conditions are often not met (157). Similarly, environmental and heat tracer measurements in SW rely on pronounced differences between GW and SW, incorporating some degree of uncertainty. Flux estimates based on temperature gradients in the streambed are calculated on the assumption of vertical flow beneath the stream, which may not be true in the vicinity of the riverbanks or because of influences of hyporheic water movement.

7. KNOWLEDGE GAPS

Knowledge in several critical areas could enhance our understanding of GW–SW interactions. Firstly, there is a pressing need to understand how dynamic elements, such as changing aquifer permeability in cold regions, shifting coastlines, or riverbed mobility, influence GW–SW interactions, as these dynamics reshape subsurface structures, aquifer heterogeneity, and fluid control mechanisms. Secondly, a more integrated hydrogeological and geochemical monitoring paradigm could support multidimensional analyses and foster cross-disciplinary collaborations. This is especially important given the existing gaps in methods assessing biogeochemical conditions. Thirdly, new advances in 3D models for understanding coupled ecological, hydrological, and solute transport processes will be crucial, given the complexities of physical conditions exacerbated by climate warming and human activities. However, greater model complexity often necessitates new and diverse data types for model calibration and validation. Lastly, bridging local and regional perspectives remains a challenge. Efficient methodologies to cohesively scale from localized observations to broader regional to continental scales will be a cornerstone for holistic understanding of GW–SW interactions in the future.

SUMMARY POINTS

1. GW–SW interactions are influenced by many factors at various spatial and temporal scales, necessitating tailored methods to investigate the flow paths, exchange rates, and associated biogeochemical processes between GW and SW.
2. Geophysical methods offer a minimally invasive approach for examining sites and can map the spatial variations in interaction zones beyond just the SW channels. These methods also monitor dynamic hydrological processes but require complementary techniques for quantifying exchange rates. One category of hydrometric methods estimates SW infiltration, while another measures GW recharge directly. Natural tracers like hydrogeochemical, isotopic, and heat tracers can track interaction patterns and quantify exchange rates. Artificial conservative or reactive tracers can be introduced into the GW–SW system to further understand hydrological processes, solute transport, and contaminant decay.
3. Each monitoring method is suited for specific applications, goals, and sites. Point-scale methods, such as seepage meters and piezometers, provide detailed information on GW–SW interactions. In contrast, reach- or catchment-scale water balance methods offer a broader, averaged view. Consideration should be given to the advantages, limitations, and disadvantages of each method when choosing the best fit for a particular problem.
4. Mass balance and hydrograph separation techniques are relatively simple tools for interpreting monitored data but lack the ability to identify detailed spatiotemporal variations. Analytical models are easily implemented for interpreting heat and solute transport under simple conditions, whereas numerical models with complex initial and boundary conditions can account for intricate hydrological and biogeochemical processes, thus capturing information about GW–SW interactions under variable conditions.
5. Results obtained at finer scales usually need to be extrapolated to larger scales, as the outcomes of hydrological and associated biogeochemical processes at smaller scales accumulate and manifest at larger scales. This may be accomplished using remotely sensed data and refined hydrogeological mapping, although the lack of transferability across scales remains a fundamental challenge. Long-term monitoring is essential for some research objectives, given that dynamic hydrological conditions make short-term monitoring insufficient for predicting long-term trends.

6. The complexity of hydrological conditions, aquifer heterogeneity, and uncertainties tied to different methods can make data interpretation challenging. Therefore, a multidisciplinary approach is essential for studying GW–SW interactions.

FUTURE ISSUES

1. Currently, our understanding is limited on how certain unique characteristics, such as dynamic permeability, riverbed mobility, and shifting rivers or coastlines—like changing channels and eroding beach faces—impact GW–SW interactions. As these morphological elements shift and create new erosional and depositional features, they also change the subsurface structure and the associated permeability heterogeneity that controls fluid flow. Existing methodologies need to be extended to quantify these dynamic interactions effectively.
2. For a more comprehensive understanding of GW–SW interactions, it is necessary to incorporate multidimensional analyses, interface hydraulic characterization, and spatial variability into our modeling frameworks. Cross-disciplinary collaborations are also essential for providing a broader perspective. Methods for assessing hydrobiogeochemical conditions are still underdeveloped, necessitating interdisciplinary research to enhance our understanding of GW–SW interactions and their biogeochemical implications.
3. Understanding the ecological-hydrological links under various forcing factors and boundary disturbances requires advanced monitoring techniques and high-efficiency 3D models. These models are crucial for accurately simulating coupled GW–SW interactions and solute transport processes, especially in systems with oscillating flow directions, distinctly 3D flow systems, and periodic flooding.
4. Linking small-scale drivers to their broader fluvial and geomorphic context, as well as understanding their hydrological, biogeochemical, and ecological consequences, is a major challenge. Developing effective methods for scaling from local observations to regional and continental implications is crucial for a holistic understanding of GW–SW interactions.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the US government.

AUTHOR CONTRIBUTIONS

R.M. contributed conceptualization, formal analysis, methodology, writing of the original draft, writing the review, and editing. K.C. contributed formal analysis, writing of the original draft, writing the review, and editing. C.B.A., S.P.L. II, M.A.B., P.G.C., S.M.G., H.P., B.R.S., and Z.G. contributed writing the review and editing. A.H.S. and X.J. contributed formal analysis, writing the review, and editing. C.Z. contributed conceptualization, funding acquisition, writing the review, and editing.

ACKNOWLEDGMENTS

This work was funded by the Ministry of Education of China (grants B18049 and D20020). M.A.B. was supported by the US Geological Survey Next Generation Water Observing System. A.H.S. acknowledges funding from the US National Science Foundation (EAR-1752995).

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