Groundwater

Methods Note/

GW/SW-MST: A Groundwater/Surface-Water Method Selection Tool

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Abstract

Groundwater/surface-water (GW/SW) exchange and hyporheic processes are topics receiving increasing attention from the hydrologic community. Hydraulic, chemical, temperature, geophysical, and remote sensing methods are used to achieve various goals (e.g., inference of GW/SW exchange, mapping of bed materials, etc.), but the application of these methods is constrained by site conditions such as water depth, specific conductance, bed material, and other factors. Researchers and environmental professionals working on GW/SW problems come from diverse fields and rarely have expertise in all available field methods; hence there is a need for guidance to design field campaigns and select methods that both contribute to study goals and are likely to work under site-specific conditions. Here, we present the spreadsheet-based GW/SW-Method Selection Tool (GW/SW-MST) to help practitioners identify methods for use in GW/SW and hyporheic studies. The GW/SW-MST is a Microsoft Excel-based decision support tool in which the user selects answers to questions about GW/SW-related study goals and site parameters and characteristics. Based on user input, the tool indicates which methods from a toolbox of 32 methods could potentially contribute to achieving the specified goals at the site described.

Introduction

Groundwater/surface-water (GW/SW) exchange and hyporheic processes are topics of increasing attention in the hydrologic literature (Hayashi and Rosenberry 2002; Rosenberry and Labaugh 2008; González-Pinzón et al. 2015; Harvey 2016; Conant Jr. et al. 2019) as a consequence of their relevance to diverse issues spanning ecology, environmental health, climate change, sustainable development, contaminant transport, and nutrient cycling. Numerous field methods exist to assess GW/SW and hyporheic exchange over a range of spatial scales (i.e., point, reach, or watershed), ranging from quantitative measurements of seepage to qualitative interpretation

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of geophysical measurements (e.g., electrical resistivity) and temperature mapping (e.g., infrared cameras). Table 1 summarizes methods commonly applied to GW/SW problems, dividing them according to the general categories of measurement methodology (i.e., ground-based and waterborne geophysical temperature, hydraulic, chemical, and remote sensing methods) and indicating the scale of investigation (i.e., point, reach, or watershed), and information provided by the methods. Given the diversity of methods for GW/SW problems, it is challenging or impossible for researchers and environmental professionals to develop expertise—or even proficiency—in all of the methods listed in Table 1. New tools are needed to help researchers and practitioners select appropriate methods, challenge preconceived notions, and expand one's expertise and experience beyond those methods usually applied. As such, the target audience for the GW/SW-MST is environmental professionals with at least a cursory or undergraduate introductory level exposure to these methods. Therefore, the GW/SW-MST points this potential novice user to the appropriate tool(s) for their particular circumstances while providing descriptions of each method and citations for further education. The GW/SW-MST does not usurp the expert; rather it guides users to relevant resources (Kalbus et al. 2006; Rosenberry and LaBaugh 2008). The GW/SW-MST focuses on established and commonly used methods.

Selection of a method or combinations of methods must be based on site characteristics as well as study goals. Site conditions and project goals dictate, respectively, which methods or combination of methods will be feasible and help answer the salient project questions. Here, we present a spreadsheet-based GW/SW-Method Selection Tool (GW/SW-MST) to help practitioners identify methods for use in GW/SW and hyporheic studies.

Background

Field methods for GW/SW studies (Table 1) span ground-based and waterborne geophysics, temperature, hydraulic, chemical, and remote sensing measurements; these methods provide insight into properties and processes from the point scale to the watershed scale. Methods can provide quantitative assessments, i.e., numerical values, as in the case of vertical flux as measured by seepage meters (Duque et al. 2020; Rosenberry et al. 2020), or hydraulic conductivity as measured by slug tests (Butler 2019). In other cases, methods produce data that are indirectly related to hydrologic properties or processes of interest (Hyndman et al. 2007). Some methods are semi-quantitative, as in the case of fiber-optic distributed temperature sensing and thermal imaging; these produce quantitative measurements of temperature, which are then interpreted qualitatively for zones of focused groundwater discharge (e.g., Slater et al. 2010; Hare et al. 2015).

The potential of a given method, or combination of methods, to solve a particular problem depends on the information provided by the method as well as site conditions that may limit or preclude the use of the method at that site. The geology of a site may impose constraints on which methods can be used, for example, many point-scale methods (e.g., seepage meters, permeameters, piezometers) may be difficult or impossible to install in heavily armored beds. Seasonal and geographic constraints may also be important, for example, many temperature-based methods require a substantial contrast between GW and SW temperatures. To borrow a concept from the medical field, factors indicating the likely failure of a particular method can be thought of as "contraindications." In medicine, application of a particular medicine is contraindicated (precluded) by a particular patient's characteristics. Here, constraints arise from the physical properties of pore fluids in the bed, e.g., ground penetrating radar signals are attenuated by electrically conductive saline fluids. Rules to reject methods based on such contraindications are coded in the GW/SW-MST.

In some cases, study goals may require a combination of methods. For example, the vertical hydraulic conductivity of a streambed may be determined by combining measurements of vertical flux (e.g., from seepage meters or vertical temperature profiles) and head gradient (e.g., from piezometers screened at different depths). Such synergy resulting from various combinations of methods is coded in the GW/SW-MST, with spreadsheet output indicating combinations of methods in qualifier comments. Such synergies are also documented in the Appendix worksheets for different methods and different study goals, accessed by hyperlink from the various GW/SW-MST worksheets.

The GW/SW-MST is intended to help focus users on methods likely to support their goals at a particular site; however, the tool is necessarily simple and is not a substitute for careful literature review or guidance from subject matter experts. For additional background, we refer the reader to review papers and texts on temperature methods (e.g., Anderson 2005; Constantz 2008; Koch et al. 2016; Domanski et al. 2020), hydraulic methods (e.g., Rosenberry et al. 2016), geophysical methods (McLachlan et al. 2017), chemical tracer methods (Harvey and Wagner 2000; González-Pinzón et al. 2015), remote sensing methods (Vélez-Nicolás et al. 2021), and general GW/SW approaches (Harvey 2016; Conant Jr. et al. 2019).

Approach

The GW/SW-MST is a Microsoft Excel-based method selection tool similar in concept and operation to the Fractured-Rock Geophysical Toolbox Method Selection Tool (FRGT-MST) (Day-Lewis et al. 2016), which, of course, is for fractured-rock problems. Here, the GW/SW "toolbox," which comprises 32 methods, can be applied to one of three possible hydrologic setting types: (1) stream or river, (2) lake or wetland, and (3) coastal or estuary; these three settings were chosen as the most common settings where hydrologic studies have groundwater/surface-water components. For a particular hydrologic setting, the user answers a series of questions organized in two separate lists, one for project site

Table 1
Summary of Methods Commonly Applied to GW/SW Problems in Streams

Method	Information Provided	Scale
Ground-based geophysical methods		
FDEM—electromagnetic induction (frequency domain)	Bed material and structure; bed pore-fluid salinity/TDS variations	Point to watershed
TDEM—electromagnetic induction (time domain)	Bed material and structure; bed pore-fluid salinity/TDS variations	Point to watershed
Direct current (DC) electrical resistivity (ER)	Bed material and structure; bed pore-fluid salinity/TDS variations; conductive contaminant or tracer monitoring	Point to reach
IP—induced polarization (time domain)	Characterization of subsurface geology	Point to reach
SIP—spectral induced polarization	Bed material and structure	Reach
SP—self or spontaneous potential	GW/SW exchange	Reach to watershed
GPR—ground penetrating radar	Bed material and structure; bed pore-fluid salinity/TDS or gas-content variations	Reach to watershed
Seismic refraction	Depth to bedrock, geologic layers	Reach to watershed
Waterborne geophysical methods		
FDEM (floating)—electromagnetic induction (frequency domain)	Bed material and structure; bed pore-fluid salinity/TDS variations	Reach to watershed
TDEM (floating)—electromagnetic induction (time domain)	Bed material and structure; bed pore-fluid salinity/TDS variations	Reach to watershed
GPR (floating)—ground penetrating radar	Bed material and structure; bed pore-fluid salinity/TDS or gas-content variations	Reach to watershed
CRP—continuous resistivity profiling	Bed material and structure; bed pore-fluid salinity/TDS variations	Reach to watershed
IP—induced polarization (time domain)	Characterization of subsurface geology	Reach to watershed
SIP—spectral induced polarization	Bed material and structure	Reach
SP—self or spontaneous potential	GW/SW exchange	Reach to watershed
CSP—continuous seismic profiling	Bed material and structure; gas-content variations	Reach to watershed
Temperature methods		
Paired air and water temperature logging	Characterization of deep vs. shallow groundwater discharge zones	Point
Vertical bed temperature profiling	Specific discharge through the bed	Point
Spatial bed temperature mapping	Maps of areas of focused exchange	Point to reach
FODTS—fiber optic distributed temperature sensing	Profiles or maps of bed or water column temperature; zones of enhanced discharge; possible groundwater discharge	Point to watershed
Hydraulic methods		
Seepage meters	Vertical flux through bed; K if head gradient is known	Point
Differential gaging/seepage runs	Net loss/gain in flow for a stream reach	Reach to watershed
Darcy fluxes	Specific discharge through the bed	Point
Physical hydrograph separation	Estimate of baseflow	Reach to watershed
Chemical hydrograph separation	Estimate of baseflow	Reach to watershed
Chemical methods		
Injected tracer tests	Transport properties; groundwater discharge	Reach
Environmental tracers	Groundwater discharge; groundwater age	Point to watershed
Groundwater interface tracer tests	Longitudinal profiles of water column temperature; Zones of enhanced discharge; possible groundwater discharge	Point to reach
Remote sensing methods		
Thermal imaging	Surface temperatures; zones of enhanced discharge or bank seepage	Reach to watershed
Visible light imaging	Mapping hydrologic features and vegetation	Reach to watershed
Multi- and hyperspectral imaging	Mapping vegetative stress	Reach to watershed
LiDAR	Topography and bathymetry	Reach to watershed

parameters/characteristics and one for goals. The user answers the questions/statements for the project site parameters/characteristics and goals and based on the answers selected, the matrix “table” is populated with indicators for which methods support specified goals and are likely feasible at the site described. Due to the unique hydrologic conditions associated with the different surface water settings, the worksheets for the three settings differ slightly in terms of goal statements and project site parameters. Most goals and project site condition questions are common to all three settings, but the questions reflect important differences between settings in terms of flow conditions, salinity changes, and the frequency and nature of water-level changes (Winter et al. 1998).

In worksheets corresponding to each of the three hydrologic settings, logic formulas and conditional formatting are used to identify (1) methods that could potentially address goals (e.g., mapping bank seepage), and (2) methods rendered infeasible given user-specified site characteristics (e.g., seepage meter installation is problematic in armored beds). Generation of results for each surface water scenario setting matrix worksheet is outlined in 5 steps:

- *Step 1*: Select answers to questions about project goals. Logic function formulas and conditional formatting in applicable matrix table cells will determine if the matrix table cells under the “Method Contributes to Goal” section for a particular method is populated with a green checkmark (✓). The green checkmark (✓) indicates the method contributes to a specific project goal. A cell that is highlighted in yellow indicates that there is a qualifier comment for using that method under certain conditions or with certain precautions for that specific project goal.
- *Step 1b*: Based on answers to the questions about project goals, a statistical formula and conditional formatting will determine if a worksheet cell under the “Appropriate for Goals” section for a particular method is populated with either a black filled-in circle (●) or an open circle (○). A black filled-in circle indicates the method is “Likely Appropriate/Effective” and an open circle indicates the method is “Not Likely Appropriate/Effective” for the project goals.
- *Step 2*: Select answers to questions about project site parameters/conditions. Logic function formulas and conditional formatting in applicable matrix table cells will determine if the matrix table cells under the “Method Made Infeasible by Site Parameter” section for a particular method is populated with a red mark (✖). The red mark (✖) indicates the method is made infeasible by site-specific parameters/conditions. If no symbol is displayed for a cell, then the method is suitable for use at the project site. A cell that is highlighted in yellow indicates that there is a qualifier comment for using that method under certain conditions or with certain precautions for that specific project site-specific parameter/condition.
- *Step 2b*: Based on answers to the questions about project site parameters/conditions, a statistical formula and conditional formatting will determine if a worksheet cell under the “Effectiveness at Site” section for a particular method is populated with either a black filled-in circle (●) indicating “Likely Appropriate/Effective” for the project site parameters/conditions or an open circle (○) indicating “Not Likely Appropriate/Effective” for the project site parameters/conditions.
- *Step 3*: Based on the results for the “Appropriate for Goals” and “Effectiveness at Site” sections, a statistical formula and conditional formatting will determine if a worksheet cell under the overall “Suitable” section for a particular method is populated with either a green checkmark (✓) indicating the method is “Potentially Suitable” overall for the project or an red mark (✖) indicating the method is “Not Likely Suitable” overall for the project.

Note that overall method suitability is determined by a combination of whether a method is appropriate for goals and whether a method will be effective at a site. If a method contributes to goals but is made infeasible by site parameters, then the method is not likely to be suitable for the project.

The logic function formula used in the matrix table cells consists of the Excel IF function or a variation of it. This function allows one to make a logical comparison between two results with the first comparison result being True and the second comparison result being False. For example, =IF(Agoal = “Yes”,1,−1) evaluates if the answer to Goal A is yes, then return a 1 (i.e., True because the answer to Goal A was Yes), otherwise return a −1 (i.e., False because the answer to Goal A was No). Therefore, based on the answer selected to a specific question or statement, a numeric value of either 1 or −1 is assigned to the applicable matrix table cell by the resident logic function formula.

Conditional formatting rules are also assigned to the same matrix table cells that, based on their numeric value, will display a visual graphic to indicate whether a specific field data collection method either contributes to accomplishing that specific project goal or is made infeasible for use due to a specific project site parameter/characteristic. In some cases, an additional conditional formatting rule is also applied to matrix table cells changing the cell color to yellow as an indicator that a qualifier comment is present for that method. For example, if one of the goals is to estimate the hydraulic conductivity of a stream’s bed material the GW/SW-MST will indicate that the Vertical Bed Temperature Profiling, Seepage Meters, and Darcy Fluxes methods are applicable, with the qualifying comment that piezometers are also needed for this goal. These method-qualifier comments only appear when the applicable GW/SW-MST logic and conditional formatting rules have been triggered based on answers to the applicable question/statement. The user can view the logic as coded in the spreadsheet by simply clicking on cells and viewing the formulas. An example of the method selection logic

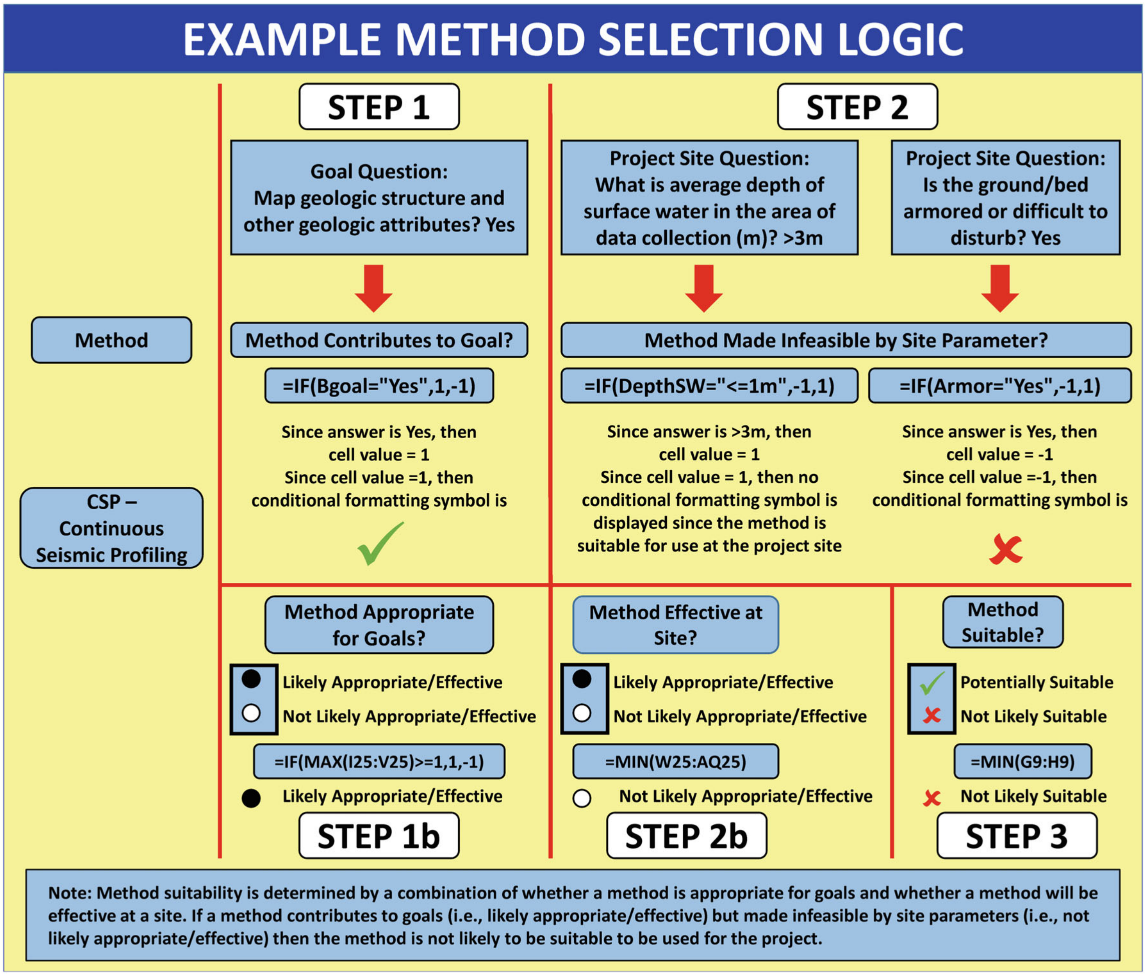

Figure 1. GW/SW-MST example method selection logic diagram.

with conditional formatting used in the GW/SW-MST is shown below in Figure 1.

Overall, the GW/SW-MST comprises nine types of worksheets: (1) introduction worksheet; (2) directions for using worksheet; (3) selecting the hydrologic setting worksheet; (4) index worksheet; (5) three separate matrix table worksheets for each of the three hydrologic settings; (6) methods technical references list worksheet; (7) geophysical resistivity/conductivity values worksheet; (8) separate worksheets for information slides for each of the 32 field data collection methods; and (9) separate methods qualifiers worksheets for each of the three hydrologic settings. Throughout these worksheets, hyperlinks are used to facilitate navigation. To simplify development of the GW/SW-MST, no Visual Basic for Applications (VBA) code or macros are used, thus minimizing potential security and installation issues.

Example

As distributed, the GW/SW-MST spreadsheet is populated with inputs describing a U.S. Geological Survey (USGS) study area on the Quashnet River, in Falmouth, Massachusetts, USA (Figure 2). The use of the Quashnet River provided a test for the logic that is coded in the spreadsheet. The coastal Quashnet River on Cape Cod has been the site of GW/SW exchange research for decades, in part due to its importance as a cold water brook trout habitat and fishery (Barlow and Hess 1993). The stream drains a glacial sand and gravel aquifer, but is underlain by discontinuous peat lenses, with persistent channel modifications from previous cranberry farming operations that create a complicated template of connectivity between the stream and aquifer (Briggs et al. 2018a). The average baseflow index determined near the outlet to Waquoit Bay (USGS gage 011058837; USGS 2021) is approximately 95%, indicating the dominance of groundwater discharge processes along this coastal stream (Briggs et al. 2020).

The USGS and others have recently used the Quashnet River as a natural laboratory for the advancement of several active and passive heat-based GW/SW exchange-related methods (Briggs et al. 2016, Briggs et al. 2014; Briggs et al. 2018b; Hare et al. 2015; Irvine et al. 2017; Koch et al. 2016; Rosenberry et al. 2016). These methods and others that are listed in the GW/SW-MST have helped support process-based research related to brook trout spawning habitat (Briggs et al. 2018a) and transport of emerging contaminants such as PFAS from groundwater

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Return to Select Scenario Setting

✓	Indicates method is potentially suitable
✗	Indicates method is not likely suitable
●	Indicates method is likely appropriate/effective
○	Indicates method is not likely appropriate/effective

Methods	Suitable	Appropriate for Goals	Effectiveness at Site	Method contributes to goal: A	B	C	D	E	F	G	H	I	J	K
Ground-based Geophysical Methods														
FDEM - Electromagnetic Induction (Frequency Domain)	✓	●	●		✓				✓	✓				
TDEM - Electromagnetic Induction (Time Domain)	✓	●	●		✓				✓	✓				
Direct Current (DC) Electrical Resistivity (ER)	✓	●	●	✓	✓				✓	✓				
IP - Induced Polarization (Time Domain)	✓	●	●		✓									
SIP - Spectral Induced Polarization	✓	●	●		✓									
SP - Self- or Spontaneous- Potential	✓	●	●	✓						✓	✓			
GPR - Ground Penetrating Radar	✓	●	●		✓									
Seismic Refraction	✓	●	●		✓									
Waterborne Geophysical Methods														
FDEM (Floating) - Electromagnetic Induction (Frequency Domain)	✓	●	●	✓	✓				✓					
TDEM (Floating) - Electromagnetic Induction (Time Domain)	✓	●	●	✓	✓				✓					
GPR (Floating) - Ground Penetrating Radar	✓	●	●	✓	✓									
CRP - Continuous Resistivity Profiling	✓	●	●	✓	✓				✓					
IP - Induced Polarization (Time Domain)	✗	●	○		✓									
SIP - Spectral Induced Polarization	✗	●	○		✓									
SP - Self- or Spontaneous- Potential	✓	●	●	✓							✓			
CSP - Continuous Seismic Profiling	✗	●	○		✓									
Temperature Methods														
Paired Air and Water Temperature Logging	✓	●	●	✓		✓								✓
Vertical Bed Temperature Profiling	✓	●	●	✓		✓				✓	✓	✓	✓	✓
Spatial Bed Temperature Mapping	✓	●	●	✓		✓					✓		✓	
FODTS - Fiber Optic Distributed Temperature Sensing	✓	●	●	✓		✓								
Hydraulic Methods														
Seepage Meters	✓	●	●	✓					✓		✓	✓	✓	
Differential Stream Gaging/Seepage Runs	✓	●	●	✓							✓			
Darcy Fluxes	✓	●	●	✓						✓	✓	✓	✓	
Physical Hydrograph Separation	✓	●	●								✓			✓
Chemical Hydrograph Separation	✓	●	●								✓			✓
Chemical Tests														
Injected Tracer Tests	✓	●	●	✓							✓		✓	
Environmental Tracer Tests	✓	●	●	✓					✓		✓		✓	✓
Groundwater Interface Tracer Tests	✓	●	●	✓					✓				✓	
Remote Sensing Methods														
Thermal Imaging	✓	●	●	✓		✓				✓				
Visible Light Imaging	✓	●	●		✓		✓			✓				
Multi- and Hyperspectral Imaging	✓	●	●	✓	✓		✓			✓				
LiDAR	✓	●	●		✓		✓							

Figure 2. Screen capture of the GW/SW-MST spreadsheet tool with partial example output of the Stream or River GW-SW Matrix worksheet based on the Quashnet River, in Falmouth, Cape Cod, MA. Available at https://doi.org/10.5066/P9YFJALF (Hammett et al. 2022).

to surface water (Briggs et al. 2020). However, important questions remain regarding the expected resiliency of cold-water habitat as the climate warms, the impact of rising sea levels on groundwater discharge along the stream, and contaminant transport from numerous upstream point sources. For the purposes of demonstration, we have assumed a range of possible goals for future GW/SW work along the Quashnet River and report the GW/SW-MST results in Figure 2.

Given the many goals for the Quashnet site, the GW/SW-MST identifies all methods as potentially contributing, but with many only being relevant to specific study goals, which is key information when conducting complex GW/SW process evaluations with multiple study objectives. To support the results of the GW/SW-MST, most of these methods have already been employed by the USGS in previous studies at the site with the exception of the hydraulic and chemical tracer methods. The use of hydraulic and chemical tracer methods at the Quashnet River represents an opportunity to gain additional insight on the GW/SW exchange mechanisms at the site.

Usage Recommendations

Understanding how the GW/SW-MST operates is essential to knowing how to effectively use it. Users should thoroughly familiarize themselves with the content, structure, and functionality of the tool. The GW/SW-MST includes a diverse toolbox of methods that vary in complexity—both to learn and to use. As indicated in the spreadsheet appendices, some methods require specialized equipment and training to perform and/or analyze results. As indicated previously, the GW/SW-MST serves as a starting point to help the user identify methods on the front end of research and site characterization planning. Communication with and guidance from subject matter experts in these methods and on planning a GW/SW interaction investigation will be critical to a successful field campaign.

The target audience envisioned for the GW/SW-MST is the working technical professional with varied experience in performing studies of the interaction between groundwater and surface water. By using the GW/SW-MST tool in consultation with, and mentoring by, experienced professionals, less experienced researchers and environmental professionals will be able to acquire and develop the necessary proficiency and knowledge in these methods. Furthermore, the GW/SW-MST can facilitate regulators and managers in identifying potential strategies to advance the state of the practice in groundwater/surface-water interaction investigations.

Limitations

The GW/SW-MST is intended to help focus users on methods likely to support their goals at a particular site; however, the tool is necessarily simple and is not a substitute for careful literature review or guidance from subject matter experts. Although the GW/SW-MST indicates multiple methods for consideration, it does not explicitly recommend sets of complementary methods; however, a combination of methods is commonly advantageous to achieve study goals.

The results of the GW/SW-MST are not the official recommendations of the USGS or EPA. The USGS and EPA provide no warranty, expressed or implied, as to the correctness of the furnished software or the suitability for any purpose. The software has been tested, but as with any software, there could be undetected errors. Users who find errors are asked to report them to the corresponding author.

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Supporting Information

The spreadsheet tool (Hammett et al. 2022) that accompanies this paper can be downloaded from https://doi.org/10.5066/P9YFJALF. The GW/SW-MST was not peer reviewed by Groundwater but was reviewed during USGS internal peer review process.

Authors' Note

None.

Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article. Supporting Information is generally *not* peer reviewed.

Appendix S1: Supporting Information

References

Anderson, M.P. 2005. Heat as a ground water tracer. *Groundwater* 43, no. 6: 951–968. https://doi.org/10.1111/j.1745-6584.2005.00052.x

Barlow, P.M., and K.M. Hess. 1993. Simulated hydrologic responses of the Quashnet River stream-aquifer system to proposed ground-water withdrawals, Cape Cod, Massachusetts. USGS Water-Resources Investigations Report 93-4064. https://doi.org/10.3133/wri934064.

Briggs, M.A., L.K. Lautz, S.F. Buckley, and J.W. Lane. 2014. Practical limitations on the use of diurnal temperature signals to quantify groundwater upwelling. *Journal of Hydrology* 519, no. 27: 1739–1751. https://doi.org/10.1016/j.jhydrol.2014.09.030

Briggs, M.A., S.F. Buckley, A.C. Bagtzoglou, D.D. Werkema, and J.W. Lane. 2016. Actively heated high-resolution fiber-optic-distributed temperature sensing to quantify streambed flow dynamics in zones of strong groundwater upwelling. *Water Resources Research* 52, no. 7: 5179–5194. https://doi.org/10.1002/2015WR018219

Briggs, M.A., J.W. Harvey, S.T. Hurley, D.O. Rosenberry, T. McCobb, D. Werkema, and J.W. Lane Jr. 2018a. Hydrogeochemical controls on brook trout spawning habitats in a coastal stream. *Hydrology and Earth System Sciences* 22, no. 12: 6383–6398. https://doi.org/10.5194/hess-22-6383-2018

Briggs, M.A., Z.C. Johnson, C.D. Snyder, N.P. Hitt, B.L. Kurylyk, L. Lautz, D.J. Irvine, S.T. Hurley, and J.W. Lane. 2018b. Inferring watershed hydraulics and cold-water habitat persistence using multi-year air and stream temperature signals. *Science of the Total Environment* 636, no. 15: 1117–1127. https://doi.org/10.1016/j.scitotenv.2018.04.344

Briggs, M.A., A.K. Tokranov, R.B. Hull, D.R. LeBlanc, A.B. Haynes, and J.W. Lane. 2020. Hillslope groundwater discharges provide localized stream ecosystem buffers from regional per- and polyfluoroalkyl substances contamination. *Hydrological Processes* 34, no. 10: 2281–2291. https://doi.org/10.1002/hyp.13752

Butler, J.J. 2019. *The Design, Performance, and Analysis of Slug Tests*, 2nd ed. New York: CRC Press ISBN: 978-1466595903, 280 p.

Conant, B. Jr., C.E. Robinson, M.J. Hinton, and H.A.J. Russell. 2019. A framework for conceptualizing groundwater-surface water interactions and identifying potential impacts on water quality, water quantity, and ecosystems. *Journal of Hydrology* 574: 609–627. https://doi.org/10.1016/j.jhydrol.2019.04.050

Constantz, J. 2008. Heat as a tracer to determine streambed water exchanges. *Water Resources Research* 44, no. 4: W00D10. https://doi.org/10.1029/2008WR006996

Day-Lewis, F., C. Johnson, L. Slater, J. Robinson, J. Williams, C. Boyden, D. Werkema, and J. Lane. 2016. A fractured rock geophysical toolbox method selection tool. *Groundwater* 54, no. 3: 315–316. https://doi.org/10.1111/gwat.12397

Domanski, M., D. Quinn, F.D. Day-Lewis, M.A. Briggs, D. Werkema, and J.W. Lane. 2020. DTSGUI: A python program to process and visualize fiber-optic distributed temperature sensing data. *Groundwater* 58, no. 5: 799–804. https://doi.org/10.1111/gwat.12974

Duque, C., C. Russoniello, and D. Rosenberry. 2020. History and evolution of seepage meters for quantifying flow between groundwater and surface water: Part 2 – Marine settings and submarine groundwater discharge. *Earth-Science Reviews* 204. https://doi.org/10.1016/j.earscirev.2020.103168

González-Pinzón, R., A.S. Ward, C.E. Hatch, A.N. Wlostowski, K. Singha, K., M.N. Gooseff, R. Haggerty, J.W. Harvey, O.A. Cirpka, and J.T. Brock. 2015. A field comparison of multiple techniques to quantify groundwater–surface-water interactions. *Freshwater Science* 34, no. 1: 139–160. https://doi.org/10.1086/679738.

Hammett, S., F.D. Day-Lewis, and B.R. Trottier. 2022. U.S. Geological Survey Software Release for the GW/SW-MST: A Groundwater/Surface-Water Method Selection Tool, v1.0.0. USGS Software Release. https://doi.org/10.5066/P9YFJALF.

Hare, D.K., M.A. Briggs, D.O. Rosenberry, D.F. Boutt, and J.W. Lane. 2015. A comparison of thermal infrared to fiber-optic distributed temperature sensing for evaluation of groundwater discharge to surface water. *Journal of Hydrology* 530: 153–166. https://doi.org/10.1016/j.jhydrol.2015.09.059

Harvey, J.W. 2016. Hydrologic exchange flows and their ecological consequences in river corridors. In *Streams in a Changing Environment*, ed. Jay Jones, and Emily Stanley, 1–84. London: Academic Press. https://doi.org/10.1016/B978-0-12-405890-3.00001-4

Harvey, J.W., and B.J. Wagner. 2000. Quantifying hydrologic interactions between streams and their subsurface hyporheic zones. In *Streams and Ground Waters*, ed. J.B. Jones, and P.J. Mulholland, 3–44. New York: Elsevier.

Hayashi, M., and D.O. Rosenberry. 2002. Effects of ground water exchange on the hydrology and ecology of surface water. *Groundwater* 40, no. 3: 309–316. https://doi.org/10.1111/j.1745-6584.2002.tb02659.x

Hyndman, D.W., F.D. Day-Lewis, and K. Singha (Eds). 2007. *Subsurface Hydrology: Data Integration for Properties and Processes*. Washington, D.C.: American Geophysical Union.

Irvine, D.J., M.A. Briggs, I. Cartwright, C.R. Scruggs, and L.K. Lautz. 2017. Improved vertical streambed flux estimation using multiple diurnal temperature methods in series. *Groundwater* 55, no. 1: 73–80. https://doi.org/10.1111/gwat.12436

Kalbus, E., F. Reinstorf, and M. Schirmer. 2006. Measuring methods for groundwater – Surface water interactions: A review. *Hydrology and Earth System Sciences* 10, no. 6: 873–887. https://doi.org/10.5194/hess-10-873-2006

Koch, F.W., E.B. Voytek, F.D. Day-Lewis, R. Healy, M.A. Briggs, J.W. Lane Jr., and D. Werkema. 2016. 1DTempPro V2: New features for inferring groundwater/surface-water exchange. *Groundwater* 54, no. 3: 434–439. https://doi.org/10.1111/gwat.12369

McLachlan, P.J., J.E. Chambers, S.S. Uhlemann, and A. Binley. 2017. Geophysical characterisation of the groundwater–surface water interface. *Advances in Water Resources* 109: 302–319. https://doi.org/10.1016/j.advwatres.2017.09.016

Rosenberry, D.O., M.A. Briggs, G. Delin, and D.K. Hare. 2016. Combined use of thermal methods and seepage meters to efficiently locate, quantify, and monitor focused groundwater discharge to a sand-bed stream. *Water Resources Research* 52, no. 6: 4486–4503. https://doi.org/10.1002/2016WR018808

Rosenberry, D.O., and J.W. LaBaugh. 2008. Field techniques for estimating water fluxes between surface water and ground water. USGS Techniques and Methods 4-D2.

Rosenberry, D.O., C. Duque, and D.R. Lee. 2020. History and evolution of seepage meters for quantifying flow between groundwater and surface water: Part 1 – Freshwater settings. *Earth-Science Reviews* 204: 103167. https://doi.org/10.1016/j.earscirev.2020.103167

Slater, L.D., D. Ntarlagiannis, F.D. Day-Lewis, K. Mwakanyamale, R.J. Versteeg, A. Ward, C. Strickland, C.D. Johnson, and J.W. Lane Jr. 2010. Use of electrical imaging and distributed temperature sensing methods to characterize surface water–groundwater exchange regulating uranium transport at the Hanford 300 Area, Washington. *Water Resources Research* 46, no. 10: W10533. https://doi.org/10.1029/2010WR009110

Vélez-Nicolás, M., S. García-López, L. Barbero, V. Ruiz-Ortiz, and Á. Sánchez-Bellón. 2021. Applications of unmanned aerial systems (UASs) in hydrology: A review. *Remote Sensing* 13, no. 7: 1359. https://doi.org/10.3390/rs13071359

U.S. Geological Survey (USGS). 2021. Data Inventory Page for Site 011058837—Quashnet River at Waquoit Village, MA. USGS web page. https://waterdata.usgs.gov/nwis/inventory/?site_no=011058837 (accessed October 12, 2021).

Winter, T.C., J.W. Harvey, O.L. Franke, and W.A. Alley. 1998. Ground water and surface water: A single resource. USGS Circular 1139. https://pubs.er.usgs.gov/publication/cir1139.