A review of methods for measuring groundwater-surface water exchange in braided rivers

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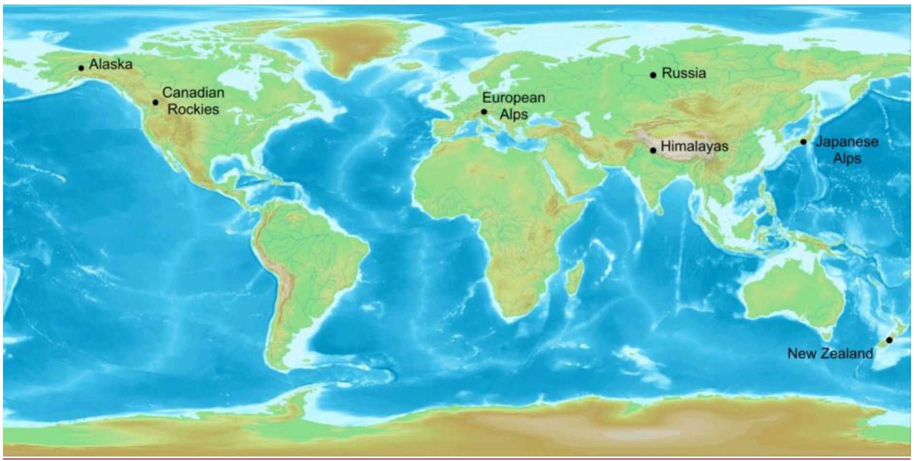
Abstract. Braided rivers, while uncommon internationally, are significant in terms of their unique ecosystems and as vital freshwater resources at locations where they occur. With an increasing awareness of the connected nature of surface water and groundwater, there have been many studies examining groundwater-surface water exchange in various types of waterbodies, but significantly less research has been conducted in braided rivers. Thus, there is 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 groundwater-surface water flow paths. This article provides an overview of characteristics specific to braided rivers, including a map showing the regions where braided rivers are ~~concentrated~~ mainly found at the global scale: Alaska, Canada, the Japanese and European Alps, the Himalayas, Russia and New Zealand. To the authors' knowledge, this is the first map of its kind. This is followed by a review of prior studies that have investigated groundwater-surface water interactions in braided rivers and their associated aquifers. The various methods used to characterise these processes are discussed with emphasis on their effectiveness in achieving the studies' objectives and their applicability in braided rivers. We also discuss additional methods that appear promising to apply in braided river settings. The aim is to provide guidance on methodologies most suitable for future work in braided rivers. In many cases, previous studies found a multi-method approach useful to produce more robust results and compare data collected at various scales. Ultimately, the most appropriate method(s) for a given study will be based on several factors, including the scale of interactions that need to be observed; site-~~-~~specific characteristics; budget; and time available. Given those considerations, we conclude that it is best to begin braided river studies with broad-scale methods such as airborne thermal imaging, geophysics, differential flow gauging or tracer analysis, and then focus the investigation using finer scale techniques such as groundwater well observations or temperature sensors. Given the challenges of working directly in braided rivers, there is considerable scope for the increased use of remote sensing techniques ~~and geophysics~~. There is also opportunity for new approaches to modelling braided rivers using integrated techniques that incorporate the ~~often~~ complex river bed terrain and geomorphology of braided rivers explicitly. We also identify a critical need to improve understanding of the role of hyporheic exchange in braided rivers; rates of recharge to/from braided rivers; and historical patterns of dry and low-flow periods in these rivers.

1 Introduction

Until recently, groundwater and surface water systems were often considered separately both in research and in the way they were managed as resources (Kalbus et al., 2006; Winter et al., 1998). However, understanding the interactions between groundwater and surface water is now recognised as crucial to effective water resource management (Brodie et al., 2007). These systems are connected, so the development or contamination of either groundwater or surface water will often affect the other (Rosenberry and LaBaugh, 2008). Pumping from wells that are hydraulically connected to surface water bodies can result in, for example, reduced flows in rivers or diminished lake levels, or cause surface water inflow to groundwater (Stefania et al., 2018). Locations where groundwater and surface water interact can serve as contaminant transport pathways (Chadwick et al., 2002). Groundwater seepage into surface water can provide important nutrients and temperature regulation for aquatic organisms (Hayashi and Rosenberry, 2002). Key questions in groundwater-surface water investigations are the location and flux of groundwater discharge to surface water bodies, and conversely, surface water recharge to groundwater. These questions can be considered at various spatial and temporal scales (Lovett, 2015).

This paper often refers to groundwater-surface water exchange, which in this context may include regional groundwater exchange with river water, as well as hyporheic zone exchange. ~~Scholars~~Researchers have defined the hyporheic zone and the exchange processes that occur there in many ways (e.g., Krause et al., 2011; Cardenas, 2015~~;2000~~). In the present paper, hyporheic exchange refers to downwelling or upwelling of water through the hyporheic zone, i.e., the saturated area between the streambed and shallow aquifer where stream water and shallow groundwater mix.

This article investigates the methods that have previously been used for examining groundwater-surface water exchange in braided rivers and discusses scope for new methods to be applied. Braided rivers are a highly dynamic type of river with meandering channels, wide bars and variable flow levels. Globally, braided rivers are relatively rare; they are mainly found in the Canadian Rockies, Alaska, the Himalayas, New Zealand, Russia and the European and Japanese Alps (Figure 1) (Tockner et al., 2006; Alexeevsky et al., 2013). There are instances of braided rivers at locations outside of these regions (e.g., the ~~Russia,~~ U.S., Scotland, Iceland, China, Poland, Belarus, Colombia, Congo, Brazil, Paraguay, Argentina, and the Touat Valley in Africa);~~,~~ however these locations are not shown in Figure 1 because, at a global scale, they are not where braided rivers are mainly found. The regions displayed in Figure 1 are regularly cited in literature on braided rivers as the main regions where this river type can be found (Hibbert and Brown, 2001; Tockner et al., 2006). Braided rivers generally occur in mountainous areas with a large sediment source (such as glacial outwash), high river discharge rates and a steep topographic gradient (Charlton, 2008). These high-energy environments enable the rivers to carry large sediment loads. When these rivers reach their capacity to carry sediment, they form gravel braids, which branch out and re-join, creating gravel islands and shallow bars (Figures 2 & 3). Bars and islands are often referred to as distinct features, with bars existing at periods of low flow, while islands are generally more permanent features that may be vegetated (Charlton, 2008). Braided rivers can completely change their geometry over a few decades. They undergo expansion and contraction phases in which their channels widen or narrow, depending on sediment supply and river flows (Piégay et al., 2006). The wetted channels of the river can shift, abandoning channels and re-occupying old channels (Charlton, 2008). Relatively erodible streambanks, which allow for wide channels to form and meander, are a key characteristic of braided rivers. These rivers generally have gravel beds but sand-bed rivers such as the Brahmaputra-Jamuna, which begins in the Himalayas and flows through India and Bangladesh (and is the world's largest braided river), can also form braided patterns (Sarker et al., 2014). The Brahmaputra-Jamuna is the only braided river in this review that is not a gravel-bed braided river. Also, it is important to note, the specific rivers discussed in this article are all braided rivers unless otherwise mentioned.



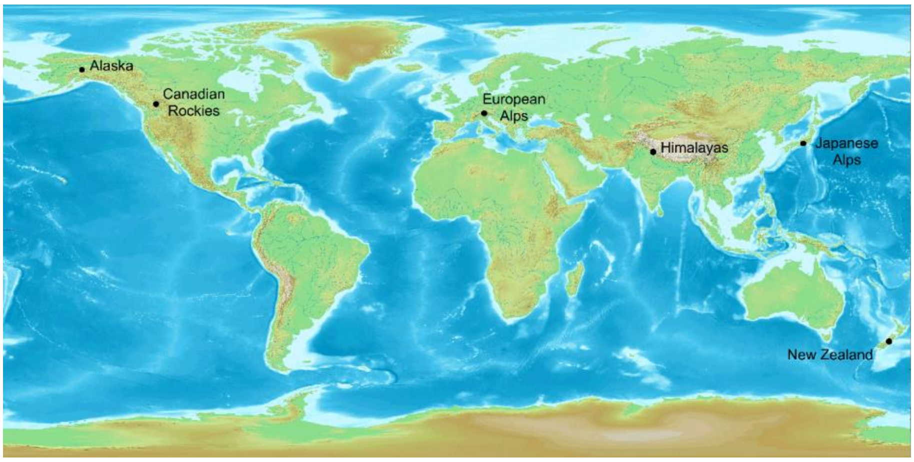


Figure 1. Locations where most braided rivers occur globally. Map base layer image attribution: “World Map-A non-Frame” is licensed under CC BY-SA 3.0.

Figure 2. Rakaia River in New Zealand displaying a classic braided pattern. Image reproduced with permission by Andrew Cooper.

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Figure 3. The Rakahuri/Ashley River in New Zealand displaying a typical braided river consisting of multiple channels, gravel bars and vegetated islands. Photo: Katie Coluccio.

Braided river deposits have formed extensive aquifers throughout the world including many in the regions shown in Figure 1 (Brown, 2001; Huggenberger and Regli, 2006). The complex depositional processes of braided rivers create heterogeneous aquifer properties (Huggenberger and Regli, 2006), and a significant portion of flow occurs in preferential flow paths formed by previous river flow channels (Close et al., 2014; Dann et al., 2008; White, 2009). The complexity of braided rivers and their underlying heterogeneous aquifers makes managing these systems in an integrated manner, that accounts for surface water-groundwater interaction, challenging. For example, there is significant uncertainty surrounding rates of groundwater recharge from large braided rivers in New Zealand, which complicates the sustainable allocation of water extraction rights from surface water and groundwater sources (Close et al., 2014). There is also limited knowledge of how hyporheic flow processes operate and how they impact river flow levels and water quality in braided rivers~~hyporheic exchange in braided rivers affects groundwater-surface water interactions~~. Braided rivers also often have reaches that become dry or have very low flows.~~, and t~~The historical patterns of these drying and low-flow periods, and the impact of groundwater-surface water exchange on this, is an area of research where improved knowledge is needed. For example, many irrigation schemes have artificially raised groundwater levels due to land surface recharge, or lowered groundwater levels due to abstraction in comparison to their pre-irrigation states. In some rivers this has affected their losing/gaining patterns (Burbery and Ritson, 2010; Riegler, 2012).

Braided rivers around the world have ecological, cultural, social, economic and recreational importance. Braided rivers provide habitat for many plant and animal species specifically adapted to survive in the dynamic, nutrient-poor environment of the rivers' gravel bars and their margins (Kilroy et al., 2004; Tockner et al., 2006). In New Zealand, the rivers are some of the last remaining native habitat on the heavily modified Canterbury Plains of the South Island, thus serving a vital ecological purpose for plant and animal species, many of which are critically endangered (Caruso, 2006; Williams and Wiser, 2004). Braided rivers and their associated aquifers are also important freshwater resources used for drinking water supplies, irrigation, stock water and hydropower. In many areas, these rivers hold significant cultural, social and recreational value for their importance for food gathering, boating and swimming, and as places of outstanding natural character.

However, braided rivers face pressure from many angles. In many places they are subject to damage from vehicles, gravel extraction, invasive plant species, development on river margins, damming, low-flow levels and poor water quality (Caruso, 2006; Larned et al., 2008; Tockner and Stanford, 2002). These factors can influence river processes in many ways, including altering the rate of sedimentation or changing the flow regime, which may impact various uses of these rivers, as well as riparian ecosystems (Piégay et al., 2006).

Much braided river research has focused on understanding their geomorphological structures and processes, such as sediment transport (e.g., Ashmore, 1993; Chalov and Alexeevsky, 2015; Huggenberger and Regli, 2006; Nicholas et al., 2006). The majority of studies up to the early 1990s consisted of laboratory-based modelling of the braiding process (e.g., Ashmore, 1982; Young and Davies, 1991) and field studies of small reaches of valley-confined systems (Ferguson et al., 1992). Beginning in the mid-1990s, there were advances in numerical models to estimate the braiding process in reaches, remote sensing, and the quantification of river morphology and morphological change using digital elevation models (e.g., Bernini et al., 2006; Copley and Moore, 1993; Doeschl et al., 2006; Huggenberger, 1993). This allowed, for the first time, the visualisation and analysis of the morphology of large braided rivers (e.g., Hicks et al., 2006; Huggenberger, 1993; Lane, 2006). A number of studies have looked at the surface water features of braided rivers (e.g., Davies et al., 1996; Meunier et al., 2006; Young and Warburton, 1996), as well as aquifers created by braided river deposits (e.g., Huber and Huggenberger, 2016; Pirot et al., 2015; Vienken et al., 2017). However, the connections between the two have been less explored. ~~To highlight the scarcity of studies examining groundwater-surface water interaction in braided rivers compared to other types of surface water bodies, a Web of Science search (on 8 February 2018) for “groundwater and surface water interactions” in lakes, estuaries and small streams produced 437, 73 and 204 results, respectively, compared to only six results for braided rivers (note that this database search does not reflect *all* studies conducted in braided rivers, only what was found in this key word search, but this significantly smaller number of results highlights the relative scarcity).~~

This article addresses this gap in the literature by reviewing methods previously used in braided rivers internationally to characterise groundwater-surface water interactions, as well as recommendations for new methods that can be applied in this type of river environment. The objective is to provide guidance for future braided river studies. As described in this section, braided rivers have many ~~unique ~~features that~~s, which~~ may make it difficult to apply techniques used in different river environments. While many of these features are found in other river types, they exist in a particular combination in braided rivers, which make it problematic to investigate groundwater-surface water exchange. The rapidly shifting channels of braided rivers make it difficult to establish, maintain and access study sites. The typical coarse gravel substrate makes it challenging to install instruments in the riverbed. Large braided rivers can be several kilometres wide, resulting in data collection across the width of the river difficult or impossible. The very permeable gravel streambeds are often highly gaining or losing in respect to groundwater, and these interactions can have large temporal variability~~ strength of these relationships can change seasonally or year to year~~. The mixed sand and gravel substrate makes it nearly impossible to take undisturbed samples for sediment structure analysis. The heterogeneous nature of the river substrate and structures—largely mixed sand and gravel, with some clay and silt layers, and open framework gravels—make upscaling point-scale data difficult. A significant portion of river flow occurs within the streambed; and in aquifers, the open framework gravels (i.e., paleo river channels) serve as preferential flow paths. In relation to the methods used in previous studies, this article examines the equipment and study design; cost; issues of temporal and spatial scales; and ultimately the techniques' effectiveness. For general overviews of methodologies not specific to braided river applications, refer to Kalbus et al. (2006); Brodie et al. (2007); Rosenberry and LaBaugh (2008);~~ and~~ Lovett (2015); Rosenberry et al. (2015); and Brunner et al. (2017).

2 Methodologies for assessing groundwater-surface water interactions in braided rivers

Various types of methods have been used to investigate groundwater-surface water exchange in braided rivers such as mass balance approaches; ~~natural and artificial tracers~~hydrochemical tracers; direct measurement of hydraulic properties; and modelling. Many of these studies employed multiple methods to meet their objectives. To thoroughly and clearly assess each method, the techniques, and their advantages and limitations will be discussed individually in the following section, and the discussion section will review the merits and limitations of multi-method studies. This information is then summarised in Table 1.

2.1 Water budgets

Some of the most commonly used methods for identifying gains and losses to braided rivers have been based on a mass balance approach. The underlying principle of this method is that any gain or loss of surface water can be related to the water source, therefore the groundwater component can be identified and quantified (Kalbus et al., 2006). Many of these mass balance approaches have used water budget~~sing~~ to separate groundwater and surface water components both on river-reach and catchment-wide scales.

~~2.1.1 River-reach water budgets~~

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River-reach water budgets involve estimating the net flux of seepage in a defined river reach by measuring stream discharge in cross-sections and then calculating the difference in flow between the cross-sections (Kalbus et al., 2006). If there is an increase or decrease in discharge, this can be considered as a gaining or losing reach, respectively, provided any surface inflows or outflows (e.g., tributary inflows, abstractions) are accurately quantified. Measurements should generally be taken in low flow conditions to eliminate the influence of recent rainfall (Brodie et al., 2007).

Several studies ~~on the South Island of New Zealand~~ have used river-reach water budgets to identify gaining and losing reaches of braided rivers. The Selwyn River in New Zealand, which has losing and gaining reaches, and annually dries in parts, has been the focus of several studies (Larned et al., 2008; Larned et al., 2015; Vincent, 2005). Both Larned et al. (2008) and Vincent (2005) ~~investigated the patterns of losing and gaining along the river by flow gauging at 19 sites between two permanent flow recorders on the river. The authors~~ used ~~this~~ flow gauging data to classify gaining and losing reaches of the river ~~as perennial, ephemeral or intermittent depending on the percentage of time that the river flowed and the source of the flow (i.e., ephemeral reaches in this study were sourced from runoff only, whereas intermittent reaches were groundwater sourced when the water table intersected the river channel and could also have a runoff component) (Larned et al., 2008)~~. ~~Larned et al. (2008) also compared flow at two sites on the river with data from 11 nearby groundwater wells for a five-year period to assess lag times between the two systems. In a subsequent study on the Selwyn River,~~ Larned et al. (2015) used a 30-year gauging record from two flow recorder sites on the river to calculate groundwater level lag times. ~~Vincent (2005) conducted an in-depth study of the hydrogeology of the upper Selwyn River catchment, which included concurrent flow gauging to estimate gains and losses from the river to groundwater.~~ In another study, Farrow (2016) characterised gaining and losing reaches of the four major rivers in the Ashley-Waimakariri zone in New Zealand using historic flow gauge records, however~~. The author~~ they cited the need for additional concurrent flow gauging under mean flow conditions to more accurately characterise long-term gaining and losing reaches. In an attempt to determine the causes of the perennial drying ~~of the North Branch~~ of the Ashburton River in New Zealand, Riegler (2012) conducted flow gauging along the river in conjunction with groundwater well measurements, mapping of dry reaches and regression analysis. ~~Despite the various methods used, the cause of drying in the North Branch could not be determined (Riegler, 2012). Burbery and~~

~~Ritson (2010) incorporated various methods such as flow gauging, piezometer surveys, hydrochemical sampling and stable isotope analysis with catchment water use data to characterise the groundwater and surface water interactions in the Orari River catchment on the South Island of New Zealand. The authors used the flow gauging data to classify gaining and losing reaches in four of the rivers in the catchment. They agreed with previous conclusions by Davey (2004) that in order to obtain a greater level of detail about groundwater-surface water connectivity at the local scale, shorter spaced flow gauging coupled with high-resolution piezometric surveys and aquifer pumping tests should be carried out (Burbery and Ritson, 2010). In a 2012 study of the Waimakariri River in the Canterbury region of New Zealand,~~ White et al. (2012) used a steady-state groundwater budget to estimate groundwater outflow from the riverbed based on the mean daily flow at a recorder site on the Waimakariri R~~r~~iver ~~between 1967-2009~~ and ~~seven-year~~ groundwater level observations in a monitoring well array beside the river. The authors found that river channel area rather than channel position was most important in their calculations~~.~~; ~~H~~however, they recommended that future research examine the effects of channel position and area on groundwater outflow ~~from the Waimakariri River~~. This is particularly relevant in braided rivers, as their channel positions often change.

~~Flow gauging has also been used outside of New Zealand to investigate groundwater-surface water interactions in braided rivers.~~ Both Simonds and Sinclair (2002) and Doering et al. (2013) used flow gauging as part of multi-method studies for estimating groundwater-surface water interactions in the Dungeness River (Washington State, U.S.) and Tagliamento River (northeastern Italy), respectively. These authors conducted concurrent gauging to calculate the net loss or gain of flow along river reaches and compare to data collected from other methods.

~~**2.1.2** Catchment-scale water budgets~~

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~~Some studies~~A smaller number of braided river studies (e.g., Burbery & Ritson (2010)) have used catchment-scale water budget calculations to estimate the inflow and outflow from braided river catchments and distinguish groundwater from surface water sources. The underlying relationship is provided below (modified from Scanlon et al. (2002)):

$$inflow = outflow \pm \Delta S \tag{1}$$

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Here, inflow is the sum of precipitation, surface water inflow and groundwater inflow. Outflow is comprised of actual evapotranspiration, surface water outflow and groundwater outflow. ΔS is the change in water storage in the catchment. This also considers artificial changes to water levels in the catchment such as industrial discharges to surface water or water abstraction.

Burbery and Ritson (2010) calculated a water budget for the Orari River catchment in Canterbury, New Zealand, which was ~~to aid in characterising groundwater-surface water interactions in the catchment. This model was~~ based on field observations from various methods including flow gauging and groundwater well observations, climate data and water use data. The authors used the flow gauging data to classify gaining and losing reaches in four of the rivers in the catchment. They noted that in order to obtain a greater level of detail about groundwater-surface water connectivity at the local scale, shorter spaced flow gauging coupled with high-resolution piezometric surveys and aquifer pumping tests should be carried out (Burbery and Ritson, 2010).~~The authors concluded that the model provides a good basic understanding of the Orari catchment, but a sensitivity analysis of the model should be carried out. They also recommended additional investigation of the deep groundwater system to better understand its hydraulic connection to shallow groundwater, as the authors believed deep upwelling groundwater might be supplying shallow groundwater.~~

~~In another study in Canterbury, New Zealand, Anderson (1994) calculated a regional groundwater budget for the area between the braided Selwyn and Rakaia rivers, which included a consideration of inflows and outflows to these rivers. Inputs to the water budget were rainfall, recharge from surface water estimated by flow gauging, sea water intrusion into the aquifer, inflow from other aquifers, leakage from stock water races and artificial recharge (i.e., land surface recharge from irrigation). Outputs were groundwater abstraction, groundwater-fed spring flow, river baseflow, groundwater discharge to the sea, flows to other aquifers and evapotranspiration. This water budget provided a useful indication of flows in and out of the groundwater system in the study area, but it is important to note that there were significant uncertainties with some parameters. For example, there were large uncertainties with river loss rates, and this study was done before groundwater abstraction was metered in this region (so actual use was not known).~~

~~2.1.3~~ Advantages and Limitations

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River-reach w~~Reach-scale w~~ater budgets are useful for identifying hotspots of river gains and losses at a broad scale. However, ~~Streamflow gauging provides more reliable information in relatively homogeneous environments (which braided rivers often are not, as discussed below).~~

~~t~~~~T~~here are several issues regarding the~~ir~~ effectiveness ~~of river-reach water budgets for characterising groundwater-surface water interactions~~ in braided rivers. As detailed in Section 1, these types of rivers are typically comprised of heterogeneous materials and thus there may be small-scale interactions of groundwater and surface water within reaches, of which flow gauging is poor at identifying (Hughes, 2006). For example, Larned et al. (2015) noted that lag time calculations can only highlight generalised flow paths, whereas predicting more specific groundwater flow paths or residence times would require studies using additional techniques such as tracers or potentiometric data. Also, accurate measurements of flow rates can be compromised by several factors including interference of macrophytes in the streambed, low flow, imprecise or shifting river margins, high sediment load, or unstable streambeds that permit parafluvial flow (i.e., flow in the area of riverbed that is to some extent annually scoured by flooding (Stanford, 2007)). As noted by Close et al. (2014), there is significant uncertainty around estimates of river to groundwater flows solely based on hydraulic measurements, particularly for large braided rivers, as these environments provide various challenges for accurate flow measurements. These systems are difficult to measure because precise flow gauging can only be carried out during low flows and measurement errors can be considerable (Close et al., 2014). ~~In larger rivers, often~~Often the measurement error is greater than the net exchange of groundwater and surface water (LaBaugh and Rosenberry, 2008).

Catchment water budgets can be a useful method at a larger scale but are generally not appropriate for assessing small-scale groundwater-surface water interactions, as the accuracy of recharge rates to or from rivers is limited by the accuracy of the measurement of the other components in the budget (Scanlon et al., 2002). They can be simple and quick to calculate, but this depends on how time consuming or expensive the data collection is. Also, this method can have low resolution because of the limited number of flow gauging stations on rivers (Kalbus et al., 2006). Thus, when calculating budgets for large catchments, the errors can be significant.

2.2 ~~Environmental tracers~~Hydrochemistry

There are various natural physical and chemical properties of groundwater and surface water that can serve as indications of interaction between the two systems. A variety of tracers have been used in braided rivers to investigate groundwater-surface water exchange including geochemical tracers such as conductivity, chloride or alkalinity; stable isotopes; and radioactive isotopes such as radon. At sites where there is a discernible difference between the groundwater and surface water concentrations of one of these parameters, the influence of groundwater or surface water may be able to be detected. ~~.~~This type of analysis assumes there is an evenly distributed groundwater concentration ~~discharge or recharge~~ between sampling locations and that there is complete mixing of water sourcese (Lovett, 2015). To separate surface water or groundwater components, mixing models based on conservation of mass are used (Kalbus et al., 2006), such as End Member Mixing Analysis (EMMA) or hydrograph separation. The methods presented below represent the majority of known braided river applications to date, and thus this is not a complete list of all tracers used in previous studies. Some additional tracers applied in braided river settings not discussed in detail here include dissolved oxygen (e.g., Larned et al., 2015; Rodgers et al., 2004), silica (e.g., Botting, 2010; Rodgers et al., 2004; Soulsby et al., 2004), nitrate (e.g., Burbery and Ritson, 2010; Larned et al., 2015; White et al., 2012) and sulphate (e.g., Acuña and Tockner, 2009; Botting, 2010).

2.2.1 Stable isotopes

Oxygen, which is a key component of water, naturally occurs in three~~wo~~ stable isotopic forms: mainly as oxygen-16 (^{16}O), and in smaller proportions as oxygen-17 (^{17}O) and oxygen-18 (^{18}O) (Sharp, 2007). Due to the difference in mass between the ~~two~~se isotopes, they undergo fractionation during evaporation and condensation (Taylor et al., 1989). The process is largely driven by temperature, humidity and salinity ~~and elevation~~, whereby precipitation is increasingly depleted in ^{18}O at ~~higher elevations and~~ colder temperatures (which tend to occur at higher elevations) ~~-~~(Sharp, 2007). The ratio of ^{16}O to ^{18}O (referred to as δ^{18}O) is used to identify the relative concentrations of the two most abundant stable oxygen isotopes. This allows for the identification of groundwater recharged by alpine sources and lowland rainfall (Burbery and Ritson, 2010) and can shed light on groundwater flow paths in aquifers.

Several studies have used δ^{18}O to characterise groundwater-surface water exchange in ~~New Zealand's~~ braided rivers and their associated aquifers. Blackstock (2011) ~~analysed δ^{18}O and δD (δD refers to the ratio of deuterium, a stable isotope of hydrogen) to identify groundwater flow paths and recharge sources in the Christchurch groundwater system. Blackstock (2011)~~ found their~~at the~~ isotopic model for the Christchurch, New Zealand groundwater system matched well with previous physical mass balance calculations ~~for the groundwater system~~ and that stable isotope analysis was useful, especially in shallow groundwater.~~,~~ ~~while recommending future studies of the system combine both stable isotopic and physical hydrological methods~~

~~(e.g., piezometric surveys).~~ Botting (2010) found that stable isotope analysis was the most effective technique for distinguishing surface water from groundwater amongst the multiple methods that they used (including hydrochemical sampling, pumping tests, and groundwater well observations) in a study of the north bank of the braided Wairau River in New Zealand. In addition, ~~carried out another stable isotope study, examining groundwater flow patterns and origins on the north bank of the braided Wairau River in the Marlborough region. In his multi-method study including δ^{18}O and δD analysis, hydrochemical sampling, pump tests, and groundwater well observations, he found that stable isotope analysis was the most effective technique for distinguishing surface water from groundwater.~~ Vincent (2005) successfully used δ^{18}O analysis to identify groundwater recharge sources in the ~~aimed to establish the relationship between surface water and groundwater in the~~ upper Selwyn River catchment. ~~using δ^{18}O analysis, flow gauging and groundwater well observations. The δ^{18}O analysis enabled the identification of groundwater recharge sources.~~

Burbery and Ritson (2010) used δ^{18}O analysis to determine alpine versus lowland recharge sources for groundwater in the Orari River catchment ~~in New Zealand~~. Of the various methods used in the study (which also included flow gauging, a catchment-scale water budget, chemical tracers and groundwater level observations), the authors found δ^{18}O analysis to be highly effective for understanding groundwater-surface water interactions in the catchment. Given δ^{18}O varies seasonally, they recommended sampling be carried out at various times during the year to obtain better temporal resolution, as well as on a long-term~~s~~ basis to consider climatic ~~n. Additionally, long-term sampling would allow climatic~~ variations ~~to be considered~~. ~~The authors also noted that to accurately understand water mixing in a catchment, δ^{18}O sampling must consider all end members (i.e., surface water, rain water, soil water and groundwater).~~

~~In a regional study of the depth and spatial variation of groundwater chemistry on the central Canterbury Plains in New Zealand,~~ Hanson and Abraham (2009) carried out δ^{18}O and other hydrochemical analyses along two transects across New Zealand's~~the~~ Canterbury P~~p~~lains. The authors found δ^{18}O to be the most reliable tracer to differentiate between land surface recharge and alpine river water ~~on the Canterbury Plains~~. However, they pointed out that a suite of tracers would be needed to characterise groundwater flow paths and groundwater recharge sources. They also noted that δ^{18}O can be significantly altered where alpine water is used for irrigation.

2.2.2 Radon

Radon-222 (Rn-222) is another useful tracer for identifying groundwater-surface water interactions. ~~Radon-222 (Rn-222),~~ It is a chemically and biologically inert radioactive gas~~, is~~ part of the Uranium-238 decay process and is present in nearly all rocks and soils (LaBaugh and Rosenberry, 2008). As water flows through rocks and soils it becomes enriched in Rn-222. In surface waters, radon quickly degasses, so groundwater generally has Rn-222 concentrations three to four orders of magnitude higher than surface waters, thus making it an effective tracer in many environments (Burnett et al., 2001). For example, an area of high radon concentrations in surface water would suggest groundwater inflow. It is a cost-effective, simple technique that is suitable for ~~studying large areas~~ study areas ranging in size (Martindale, 2015).

Rn-222 analysis can address many questions related to groundwater and surface water interactions. In a multi-method study in the braided Tagliamento River in northeast Italy, Acuña and Tockner (2009) used Rn-222 to assess the residence time of upwelling groundwater in the hyporheic zone. Moore (1997) analysed Rn-222~~radon~~ to estimate ~~and barium concentrations in the Bay of Bengal in Bangladesh at the mouth of the Brahmaputra River. In the Bay of Bengal, sediment deposited by the Brahmaputra River provides a significant source of radon and barium. This sediment is mainly deposited during high flows. Moore (1997) found that radon and barium concentrations were also high during low flows and concluded that this is due to~~ groundwater inflow to the Brahmaputra R~~r~~iver in the Bay of Bengal.

Close et al. (2014) used Rn-222 sampling to calculate the velocity of groundwater recharge from the Waimakariri River to groundwater in the Canterbury Plains in New Zealand using the ingrowth (i.e., the rate of build-up in a closed system) equation for Rn-222.~~assessed the effectiveness of Rn-222 analysis to characterise surface water recharge from the Waimakariri River to groundwater in the Canterbury Plains in New Zealand. While it is feasible in most cases to obtain in-stream water samples to measure groundwater inflow to surface water, sampling surface water outflow to groundwater is more complicated. A well network of sufficient size is needed to enable sampling of shallow groundwater at a suitable distance from the river (within 2 to 3 weeks of groundwater transport time) (Close et al., 2014). Close et al. (2014) used Rn-222 sampling to calculate the velocity of groundwater recharge in the aquifer using the ingrowth (i.e., the rate of build-up in a closed system) equation for Rn-222. Radon concentrations were measured in shallow groundwater wells near a reach of the river known to lose flow and compared with radon concentrations in the river. The study did not include a calculation of recharge fluxes, and the authors noted that to do this would require several known parameters (or~~

~~assumptions), including dimensions of the recharge area, whether recharge is constant along a particular reach and the effective porosity of the groundwater system. The authors also noted that estimations of groundwater velocities from wells located at regular intervals down a river could shed light on spatial variations in recharge volumes, which may help avoid uncertainties around estimating aquifer dimensions and properties.~~ The authors ~~also~~ recommended that a high-resolution study with closely spaced sampling sites could be useful for highlighting preferential flow paths in the riparian zone ~~(e.g., channels of open framework gravel)~~. In addition,

~~In another New Zealand-based study,~~ Close (2014) sampled Rn-222 amongst other hydrochemical parameters in the Wairau River in Marlborough and in groundwater wells within five kilometres of the river to better understand the groundwater-surface water interactions in the river and the amount and variability of recharge to the groundwater system.~~. The author also measured temperature, dissolved oxygen and pH, as these physicochemical properties are often distinct in groundwater and surface water.~~ Close (2014) found that temperature correlated well with the spatial distribution of the radon ~~. The author noted some recommendations for future radon studies including that the samples should be counted for longer during analysis (referring to liquid scintillation counting (LSC)), to reduce the analytical percentage error, which increases at low radon concentrations. Close (2014) also~~ but added that there could be significant errors with estimating groundwater flow paths due to local heterogeneity and the meandering nature of the alluvial deposition process in the area. Close (2014) recommended analysing temperature and data collected from piezometers in conjunction with radon to resolve these uncertainties.

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There are some limitations of Rn-222 analysis, as it requires several assumptions, including that stream water is well mixed downstream of groundwater discharge areas; water fluxes are constant; the radon activity in the stream water and groundwater are known and constant; and that there is no additional surface recharge from sources such as streams or stock water races (Kraemer and Genereux, 1998). It also may be difficult to distinguish between regional groundwater discharge and hyporheic zone exchange using radon analysis (Lovett, 2015; Martindale, 2015).

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2.2.3 Chloride

The chloride ion (Cl$^-$) can be used as an indicator for groundwater and surface water mixing in locations with sufficiently distinct chloride concentrations in groundwater and surface waters. For example, t~~T~~he groundwater s~~S~~urrounding the ~~braided~~ Bow River~~, which flows from~~ in the Canadian ~~Rocky Mountains through the~~ province of Alberta~~, the groundwater~~ has elevated levels of chloride from road salting. This allowed Cantafio and Ryan (2014) to measure~~d~~ chloride levels in an urban reach of the ~~Bow River~~ river and~~to~~ assess water quality impacts and baseflow sources ~~for the river~~. They found that nearly all river flow originates in the Rocky Mountains and there is little contribution from groundwater.

Chloride is frequently sampled amongst a suite of hydrochemical parameters to investigate groundwater and surface water interactions, as groundwater often becomes enriched in chloride as it passes through soil and rocks (Dommisse, 2006). Burbery and Ritson (2010) measured chloride concentrations in the Orari River catchment in New Zealand, specifically looking at chloride-to-sulphate ratios to delineate groundwater-surface water interactions and examine recharge sources in the catchment. They found that basic ion chemistry was useful for determining the extent of the Orari River water but noted that results can be complicated by hydrochemical changes due to land use activities. Several other studies measured chloride to determine recharge sources and quantities in braided rivers and their associated aquifers including Acuña and Tockner (2009), ~~also analysed chloride in the Tagliamento River in northeast Italy to better understand groundwater and surface water interactions. The authors used EMMA to determine the relative proportion of freshly infiltrated surface water in upwelling hyporheic zone water.~~ Larned et al. (2015), ~~also measured chloride along with several hydrochemical parameters to correlate groundwater and surface water mixing in the Selwyn River in New Zealand.~~ Botting (2010) and ~~analysed chloride ions in his study of groundwater flow patterns and origins on the North Bank of the Wairau River in the Marlborough region of New Zealand. Similarly,~~ Domisse (2006). ~~analysed chloride in order to characterise recharge sources on the Hinds-Rangitata plain in Canterbury, New Zealand.~~

2.2.4 A~~pH and a~~lkalinity

A~~pH and a~~lkalinity can serve as an effective indicator~~s~~ for determining catchment water sources. In a study of the River Feshie, ~~a braided river~~ in the Cairngorms in Scotland, Rodgers et al. (2004) used alkalinity as a tracer to investigate temporal changes in stream water hydrochemistry and characterise sources of river flow. ~~They collected in-stream samples fortnightly for one year and at a finer resolution during two rainfall events in this period.~~ The authors noted that Gran alkalinity is particularly useful as it serves as a directly measurable, close approximation to the acid neutralising capacity, which is considered a conservative chemical tracer. Gran plots are commonly used to determine alkalinity and acid neutralising capacity in water with low alkalinity or low conductivity. A Gran function plot identifies the point at which all alkalinity has been titrated in a strong acid-strong base titration (Rounds and Wilde, 2002). Rodgers et al. (2004) used EMMA to estimate different hydrological sources of River Feshie water. The authors were reasonably confident of their estimates because of the extensive temporal and spatial components of their study. Because of the relative simplicity and low cost of the Gran alkalinity method, these types of longer term and detailed spatial surveys are becoming increasingly feasible (Rodgers et al., 2004), though may be costly in terms of human resources required. ~~They also measured pH and correlated it with alkalinity levels in the stream water.~~

In another study in the Feshie catchment, Soulsby et al. (2004) conducted a geochemical tracer study to improve large-scale flow path understanding ~~in this 231 km^2 catchment~~. The authors carried out chemical-based hydrograph separations to separate baseflow from storm event sources. ~~They conducted flow gauging on a fortnightly basis for two years and used 10 years of flow data in their analysis. They collected water samples on a wide spatial scale at median flow levels.~~ They analysed for ~~pH and~~ Gran alkalinity ~~amongst other parameter~~, which~~s . T~~they noted was~~found these were~~ simple and inexpensive to measure. Alkalinity has ~~These methods have~~ proven to be a useful parameter in the United Kingdom (UK) ~~as they~~to distinguish between water sourced from acidic, organic soils (which are common in the UK at shallow depths) and deep, older groundwater. Soulsby et al. (2004) found their study provided valuable information at the sub-catchment scale, but more information was needed at finer spatial scales.

~~2.2.5~~ Advantages and Limitations

~~Environmental tracers~~Hydrochemistry can provide significant insight into both catchment-wide hydrology, as well as provide estimations of seepage flux on the point scale (Close, 2014; Dommisse, 2006; Lovett, 2015). Even considering catchment heterogeneity, some tracers can behave predictably enough to serve as effective tracers for studies of braided rivers (Soulsby et al., 2004). Environmental tracers are useful in settings where there is a sufficient difference between tracer concentrations in the groundwater and surface water, and some ~~tracers~~ parameters can be easily incorporated in long-term routine monitoring programs. Disadvantages of these methods include that hydrochemistry of the baseflow and storm event water composition may be too similar, or that hydrochemistry may not be constant in time or space (Genereux and Hooper, 1998). Importantly, various tracers such as dissolved oxygen, pH, nitrate and sulphate may be affected by biogeochemical processes, so to be effective, the tracers must be conservative at the scale of the investigation. Also, land use activities may alter

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Formatted: Indent: Left: 0 cm, Hanging: 1 cm, No bullets or numbering hydrochemistry in catchments, for example from fertiliser application or mixing of water sources through irrigation (Soulsby et al., 2004). Additionally, some low tracer concentrations may cause analysis errors (e.g., in the case of radon) (Close, 2014).

2.3 ~~Heat tracers~~Temperature studies

Temperature has been used in a number of studies~~, particularly in Europe, ~~to characterise groundwater-surface water interactions in braided rivers. In most locations, during winter and summer months, there is a discernible difference in groundwater and surface water temperatures. In general, groundwater temperature is more stable, whereas surface water temperatures change diurnally and seasonally (Kalbus et al., 2006). In summer, groundwater is typically colder than surface water, whereas in winter, groundwater is generally warmer. Heat tracer methods can be used to identify discharge and recharge zones as well as quantify the flux of water moving between groundwater and surface water systems (Andersen, 2005). There are various methods involving temperature sensing that range in complexity, scale and cost. One-off temperature readings can be taken using probes, or sensors and~~or~~ data loggers can gather time-series data both in-stream or in groundwater wells. Vertical and horizontal temperature profiles can also be measured by arranging sensors in a series either in-stream or in wells on river margins. Temperature profiles can be analysed using various methods such as VFLUX (Gordon et al., 2012) or the steady state approach (Schmidt et al., 2006). Some temperature methods, such as thermal infrared imaging and fibre-optic temperature sensing (both of which are discussed further in Section 4), are best suited for identifying patterns, such as temperature differences in surface water that may indicate areas of recharge or discharge. Other methods such as temperature depth profiles can be used to quantify the flux of water through the streambed.~~The studies discussed below demonstrate various applications of temperature measurement to characterise groundwater-surface water exchange.~~

The following studies demonstrate various applications of temperature measurement that have been used to characterise groundwater-surface water exchange in braided rivers. ~~Tonolla et al. (2010) investigated thermal heterogeneity in the braided river floodplains of the Roseg River in Switzerland and the Tagliamento River in Italy. They used thermal infrared imaging to identify surface temperature patterns at 12 to 15-minute intervals over 24-hour cycles. They took photos using an infrared camera with a measurement accuracy of ±0.5°C set up on a tripod at the rim of the mountains bordering the catchment. This allowed for higher spatial and temporal resolution images to be captured than if taken aerially. However, the authors noted that the large zenith angles of~~

~~the images may have impacted the temperature measurements and thus would need to be taken into consideration. The authors found that thermal infrared imagery is a powerful, non-invasive tool for understanding thermal heterogeneity in complex river systems. They also measured the vertical temperature distribution at 3 to 5-minute intervals in the top layer of unsaturated gravel deposits (1 cm spacing, 0-29 cm depth) on the two floodplains using thermocouples attached to PVC frames, which were buried in the sediment. They found that the temperature differences in the top 29 cm of unsaturated sediment varied almost as much as thermal variation across the entire floodplain.~~

~~In another study of the Tagliamento River, Acuña and Tockner (2009) investigated how groundwater and surface water interactions affect temperature changes in the river, a key factor in the health of ecosystems. Along four reaches of the river, they continuously measured temperature during the summer of 2007 and the winter of 2007-2008. They used other methods such as mini-piezometers to determine hydraulic gradient, and radon and chloride analysis to shed light on groundwater-surface water mixing. They found that there was minimal groundwater discharge to the river reaches, but they did find that there was considerable hyporheic zone upwelling, which influenced surface water temperatures and provided potential refuge for aquatic organisms.~~

~~Malard et al. (2001) investigated thermal heterogeneity in the Roseg River in Switzerland. They monitored surface water temperatures and measured the temperature in sediments using mini-piezometers (at 30 and 80 cm deep) for one year. They found that the direction and magnitude of surface water-groundwater exchanges significantly influenced the vertical pattern of water temperature (Malard et al., 2001). The authors also found that the groundwater source (e.g., shallow alluvial, deep or hillslope) resulted in very different effects on seasonal temperature changes in the hyporheic zone.~~

~~In another European Alps study,~~ Passadore et al. (2015) conducted thermal monitoring to characterise the temporal and spatial variability of streambed water fluxes in the Brenta River in Italy. They used heat as a tracer in conjunction with water level measurements and~~. Passadore et al. (2015)~~ found this combination of methods to be effective in estimating groundwater-surface water interactions. ~~They measured temperature and water levels both in the stream and on the riverbank using piezometers. They noted that this method requires continuous monitoring of water temperature and levels of the stream and groundwater.~~

Two studies of the Wairau River in Marlborough, New Zealand analysed temperature (Close, 2014; Close et al., 2016). Close (2014) measured temperature in the river and in groundwater wells located near the river to characterise river recharge to the aquifer. The author compared the data to Rn-222 analysis and found that the ~~measured~~ temperatures correlated well with the spatial distribution of radon. Close et al. (2016) ~~logged temperature in 17 groundwater wells in 15-minute intervals, using~~used the daily mean temperature~~ values~~s in groundwater wells to estimate the lag time between the river and the observation wells. ~~Close et al. (2016) used the average monthly temperatures in the wells as an input for a numeric model. They found that only qualitative conclusions could be drawn due to the relative nature of the recharge estimates (Close et al., 2016).~~

Lastly, Coluccio (2018) ~~demonstrated, for the first time, the use of~~used VFLUX to analyse diurnal temperature signal~~ analysis~~ s to characterise seepage through the streambed of a braided river. ~~Temperature probes with a series of evenly spaced temperature sensors were installed into the riverbed of the Ashburton River on the South Island of New Zealand.~~ The study determined the direction and magnitude of vertical seepage through the streambed using temperature probes in the Ashburton River in New Zealand. The results were compared with ~~chemical analysis~~hydrochemistry and water level measurements in the river and shallow groundwater to better inform the interpretation of the temperature data. Coluccio (2018) found that it was difficult to distinguish between shallow groundwater and hyporheic flow and also noted~~.~~ ~~The author also noted~~ that further studies would benefit from combining a point-scale method like temperature probe analysis with broader scale techniques. ~~(Coluccio, 2018).~~

~~2.3.1~~ Advantages and Limitations

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Heat tracers offer many techniques at varying spatial and temporal scales. Broad-scale methods like aerial thermal infrared imaging can be used to obtain large-scale data, and they can offer the advantage of remote collection of data in areas that are difficult to access. Point-scale techniques using temperature sensors ~~on the other hand~~ can indicate surface water-groundwater interactions at a specific location. Some methods of temperature analysis can also quantify seepage flux (e.g., using diurnal signal analysis~~, (see Coluccio, 2018)~~). The methods range in cost and complexity, and thus can be tailored to suit a study’s needs. There are some limitations including that a temperature gradient between groundwater and surface water might not always be present (e.g., this may be affected by environmental conditions such as season, wind, shade from vegetation or rapidly changing river levels) (Johnson, 2003). Also, for certain types of analysis, temperature needs to be measured continuously (Irvine et al., 2017).

2.4 ~~Hydraulic property measurement~~Darcy approach

~~Several studies have directly measured hydraulic properties to quantify flow between groundwater and surface water in braided rivers (e.g., Acuña and Tockner, 2009;Botting, 2010;Dommisse, 2006;Malard et al., 2001;Shu and Chen, 2002;Simonds and Sinclair, 2002). This has included direct groundwater level measurements in wells (Doering et al., 2013;Dommisse, 2006;Simonds and Sinclair, 2002;Vincent, 2005) and various well tests such as slug and pumping tests (Botting, 2010;Chen, 2007;Coluccio, 2018).~~

2.4.1 ~~Groundwater well observations~~Hydraulic gradient

Groundwater levels are often used to aid in the understanding of groundwater-surface water interactions, and there have been several studies conducted in braided rivers using this technique. Groundwater level data can be used to identify the hydraulic gradient (i.e., the difference in hydraulic head over a given distance) at a location, which can reveal groundwater discharge to a river and river recharge into an aquifer. The underlying principle is that if groundwater levels in a well are higher than the river level, the river is gaining (i.e., ~~because~~ groundwater is flowing into the river). Conversely, where river levels are higher than the groundwater level in a nearby well, the river is losing (i.e., ~~because~~ river water is flowing into groundwater). Groundwater levels are most typically measured using pressure transducers or electronic water level indicators.

The h~~H~~ydraulic gradient is calculated as $\Delta h/\Delta l$, where Δh [L] is the difference in hydraulic head [L] and Δl is the distance between the points where the hydraulic head was measured. Hydraulic gradient can be measured in the horizontal direction to characterise flows into or out of a river through the sides of the river. Here, Δh [L] is the difference between the groundwater level in a well at the edge of the river and a well a distance Δl [L] away from the edge of the river. Hydraulic gradient can also be measured in the vertical direction, to characterise vertical flows into or out of the river through the stream~~river~~ bed. In this case, Δh [L] is the difference between the groundwater level in an in-river piezometer and the river level at that location; and Δl [L] is the distance from the riverbed to the top of the well screen (Doering et al., 2013).

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Once the hydraulic gradient has been measured, the magnitude of groundwater flow into or out of a river can be estimated using the Darcy equation:

$$Q = -KA\frac{\Delta h}{\Delta l} \qquad (2)$$

Where Q [L^3/T] is the volume of flow; A [L^2] is the cross-sectional area perpendicular to flow through which the water passes; and K [L/T] is hydraulic conductivity (Schwartz and Zhang, 2003). For calculating the horizontal flow magnitude, a horizontal hydraulic conductivity of the surrounding aquifer is generally used. To calculate the vertical magnitude of flow, the vertical hydraulic conductivity of the streambed needs to be determined, as does the streambed area over which the water exchange occurs (Simonds and Sinclair, 2002).

In terms of specific methods that can be used for measurements, existing piezometers (i.e., monitoring wells) near rivers can be useful for conducting these types of studies, particularly given the often high cost of drilling new wells.~~In terms of specific methods that can be used for measurements, existing groundwater wells or piezometers near rivers can be useful for conducting these types of studies, particularly given the high cost of drilling new wells.~~ Please refer to a standard text such as Fetter (2001) for a definition of piezometers. Mini-piezometers, which are scaled-down versions of piezometers and typically installed no deeper than about two metres (Figures 4 & 5), have been previously used in studies of braided rivers (Acuña and Tockner, 2009; Doering et al., 2013; Malard et al., 2001). We recommend referring to the studies mentioned in this section for piezometer designs for braided river applications, as feasibility of installation into coarse gravel is one of the significant limitations of this technique, and not all designs would be effective in braided rivers for this reason.

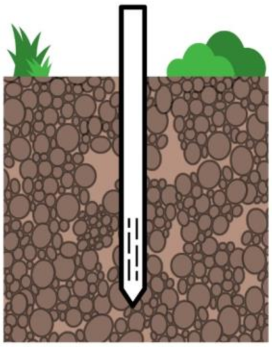

Figure 4. Conceptual diagram of a mini-piezometer (Coluccio, 2018).~~. Image source: Steve Coluccio~~

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Figure 5. Mini-piezometer installed on the bank of a braided river (Coluccio, 2018). ~~Image source: Katie Coluccio~~

Previous studies have examined the correlations between groundwater levels and river levels to establish the degree of connectedness of groundwater systems and braided rivers, for example, attempting to identify the causes of drying reaches and changes in long-term river flows. Prior studies have been carried out in catchments with substantial agricultural surface and/or groundwater abstraction for irrigation. Thus, the questions here are often whether abstraction has caused drying in rivers or decreases in river flows, and what effect future abstraction will have. These studies have often coupled groundwater level measurements with streamflow gauging and physicochemical sampling of river water and groundwater. Riegler (2012) ~~explored these questions in the North Branch of the Ashburton River in Canterbury, New Zealand, which has annually become dry in recent years. Reigler (2012)~~ examined groundwater levels, in conjunction with flow gauging, in the North Branch of the Ashburton River in Canterbury, New Zealand to attempt to correlate groundwater levels and decreased flow levels in the river. The study concluded that there were too many uncertainties, particularly around the complex behaviour of the groundwater system, to draw strong conclusions on the causes of the drying riverbed. Several other studies also investigated New Zealand braided rivers that are highly connected to groundwater using these methods (Larned et al., 2008; Larned et al., 2015; Vincent, 2005; Coluccio, 2018).

A multi-method study was carried out on the Dungeness River in Washington State in the U~~nited States~~ .S. to characterise groundwater-surface water interactions. Simonds and Sinclair (2002) installed~~ 27~~ mini-piezometers in the river in which they measured the vertical hydraulic gradient between the stream and water table. They also continuously monitored water levels and temperature in two well transects, providing data on the horizontal hydraulic gradient and temporal changes in groundwater-surface water flows. The authors also conducted flow gauging along “seepage runs” in the river to quantify the net gain or loss of flow over a reach. ~~This information was used to calibrate a model used to predict the impacts of land use change in the catchment.~~

Groundwater level measurements in mini-piezometers have also been applied in studies of European braided rivers. Malard et al. (2001) calculated the difference in hydraulic head between hyporheic water and surface water and between the parafluvial zone and the river using mini-piezometers in ~~their study of~~ the Roseg River in Switzerland. ~~They used a manometer in the piezometers to measure the water levels and calculate the vertical hydraulic gradient in piezometers installed in the river. For piezometers installed in the parafluvial zone, they calculated horizontal hydraulic gradient.~~ Acuña and Tockner (2009) also incorporated groundwater level observations into their multi-method study of the Tagliamento River in Italy. The used PVC mini-piezometers installed to a depth of 50 cm in four reaches of the river. They calculated vertical hydraulic gradient to determine the direction and intensity of surface and subsurface (i.e., hyporheic flow or groundwater) exchange in the streambed. In another study of the Tagliamento River, Doering et al. (2013) installed mini-piezometers along 10 transects in losing and gaining reaches of the river. Five mini-piezometers were installed horizontally across the river at each location and were used to calculate the vertical hydraulic gradient where the piezometers were installed.

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2.4.2 Hydraulic conductivity~~y tests~~

As detailed above, the hydraulic conductivity of riverbeds is needed to calculate the magnitude of flow through the riverbed. There have been a number of studies investigating the hydraulic conductivity of streambeds (e.g., Landon et al., 2001; Kelly and Murdoch, 2003), though few studies have been conducted in braided rivers. There are many well-established methods for calculating hydraulic conductivity of a porous medium, including grain size analysis, permeameter tests, slug and bail tests, and pumping tests (see Fetter, 2001).

In an early investigation of the permeability of gravel streambeds, Van't Woudt and Nicolle (1978) extracted gravel from the bed of the braided Waimakariri River in Canterbury, New Zealand. They conducted lab-based tests to determine hydraulic properties of the bed substrate such as porosity and infiltration rates. This study resulted in several conclusions about sub-surface flow in gravel-bed rivers including that fine sediments flowing through the gravels tend to create a low-permeability clogging layer along the margin of and below the riverbed. T~~Interestingly, t~~he authors also found horizontal permeability to be far higher than vertical permeability (30:1), but it is difficult, if not impossible, to draw conclusions about horizontal and vertical conductivities once the sediment is disturbed.

Cheng et al. (2010) carried out a study to determine the statistical distribution of streambed vertical hydraulic conductivity at 18 sites along a 300-km reach of the Platte River in Nebraska. They conducted in-situ permeameter tests using falling head tests and found that vertical hydraulic conductivity was normally distributed at all but one of their study sites.

In a study on the n~~N~~orth b~~B~~ank of the Wairau River in Marlborough, New Zealand, Botting (2010) conducted pumping tests ~~(along with stable isotope and hydrochemical analysis, geomorphological mapping, and groundwater level observations)~~ to determine groundwater flow paths and origins. The pumping tests were of limited use however, because the pumping did not successfully lower the groundwater levels, most likely due to the high transmissivity of the aquifer.

On the Ashburton River in New Zealand, Coluccio (2018) conducted slug tests in mini-piezometers installed on the margins of the river. ~~Due to the high permeability of the sediments, a pneumatic slug testing device (Michell, 2017)was used so that the water level in the wells could be effectively lowered and the removal of the slug could be carefully controlled. Air was pumped into the well to lower the water level and then instantaneously removed to begin the rising head test. A data logger that took more than one reading per second was necessary to record a sufficient number of data points for analysis.~~ The hydraulic conductivity values calculated from the slug tests were on the low end of the range for expected hydraulic conductivity values in this area, which may have been a reflection of the tests being conducted in localised areas of finer sediments, highlighting the limits of using this point-scale method in heterogeneous environments (Coluccio, 2018).

~~2.4.3~~ Advantages and Limitations

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There are various benefits and drawbacks of the methods described in this section. Use of existing groundwater wells may be very useful in a study, but the installation of new deep wells generally comes at a high cost. Mini-piezometers offer an inexpensive and simple method for obtaining groundwater level and pressure data (Lee and Cherry, 1978). They are easy and quick to install in most locations, and the analysis of their measurements is generally straightforward (Brodie et al., 2007). They can be used in small-scale applications and in detailed surveys in heterogeneous environments (Fritz et al., 2016). However, measurements at a study site must be taken at the same time to be representative of similar flow conditions (Kalbus et al., 2006). Another important factor to consider is that many data loggers require a certain diameter well. In previous studies, groundwater level observations have rarely been used in isolation and typically have been coupled with other methods.

The heterogeneous composition of braided rivers complicates the estimation of the hydraulic conductivity of streambeds on a reach or catchment scale. Hydraulic conductivity can vary significantly across an area, even with small changes in sediment composition, thus it is difficult to extrapolate values to represent a large area (Brodie et al., 2007). With grain size analysis, the structure and stratification of the sediment are destroyed during analysis, so the conductivity value does not represent the vertical or horizontal conductivity (Cheng and Chen, 2007) and does not provide any information on preferential pathways (Brunner et al., 2017). This issue is particularly problematic in gravel-bed braided rivers where there is high anisotropy and a large portion of sub-surface flow occurs in preferential channels (Dann et al., 2008). Similarly, when conducting permeameter tests it is difficult to transport sediment samples without disturbing their structure (Kalbus et al., 2006). In particular, taking undisturbed cores of sediments containing unconsolidated gravel, as most braided rivers do, is nearly impossible. However, these tests can be used as a preliminary~~imary~~ estimation before conducting further tests. Also, there is the potential for freeze coring, which allows for an intact sediment sample, but there are limitations, such as in rivers with warm water or compacted cobbles (Brunner et al., 2017). Slug tests are quick and simple to carry out and a significant advantage is that they only require one well. Pumping tests on the other hand require a pumping well and an observation well, which can be cost prohibitive. Pumping test results provide average hydraulic conductivity values across a larger area than for slug tests, thus their results may be less sensitive to heterogeneous conditions (Kalbus et al., 2006), whereas slug tests provide information only about the location where the well is installed.

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2.5 Modelling

Computer modelling is often used for the estimation of exchange between surface water and groundwater as a complement to field measurements. Such computer models have become irreplaceable tools to gain insight into real-world surface water-groundwater issues ranging from system understanding at the local or regional scale to future projections for management purposes. The complexity of numerical hydrological models used for this purpose range from simple conceptual models that treat subsurface compartments (i.e., groundwater) as reservoirs where inflows or outflows are specified, to highly complex integrated models that have a more realistic physical coupling between surface water and groundwater. MODFLOW (Harbaugh, 2005) is the most commonly used numerical model to simulate surface water-groundwater interactions (Furman, 2008; Barlow and Harbaugh, 2006). As pointed out by Wöhling et al. (2018), MODFLOW is considered to be a good compromise between integrated and conceptual modelling approaches. ~~Several packages are available within MODFLOW for simulating surface water-groundwater interaction including the River Package (RIV) (McDonald and Harbaugh, 1984), the Stream Package (STR1) (Prudic, 1989), the Streamflow-Routing Package (SFR1) (Prudic et al., 2004), and the Streamflow-Routing 2 Package (SFR2) (Niswonger and Prudic, 2005). Common to all of these packages, is that flows to or from the river are calculated as the product of streambed hydraulic conductance (a lumped parameter summarising the geometry of the river and the clogging layer, which in practice generally acts as a calibration parameter), and the difference between the hydraulic head in the river and hydraulic head of the groundwater. In the case where the groundwater head is below the base of the river (i.e., the groundwater and river are disconnected), flows from the river are the product of the hydraulic conductance and the difference between the hydraulic head of the river and the elevation of the river bed bottom. Further details of the application and limitations of the MODFLOW packages can be found in (Brunner et al., 2009;Brunner et al., 2010) and will not be repeated here.~~ Several packages are available in MODFLOW for simulating surface water-groundwater interaction and further details about the application and limitations of these can be found in Brunner et al. (2009) and (2010).

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While the modelling of braided rivers is not new, it has been done more often from a geomorphological perspective (e.g., Ashmore, 1993; Copley and Moore, 1993; Meunier et al., 2006; Williams et al., 2016). Nevertheless, a number of published studies detail modelling of braided rivers for the purposes of understanding flow dynamics and pumping impacts (e.g., Baalousha, 2012; Chen, 2007; Passadore et al., 2015; Scott and Thorley, 2009; Shu and Chen, 2002; Wilson and Wohling, 2015; Wohling et al., 2018)~~(e.g., Shu and Chen,~~

~~2002; Chen 2007; Passadore et al., 2015; Scott and Thorley, 2009; Baalousha, 2012; Wilson and Wöhling, 2015; Wöhling et al., 2018)..~~

~~. Shu and Chen (2002) developed a transient MODFLOW model to understand the spatial and seasonal variation in surface water-groundwater exchange for the braided Platte River, in Nebraska, USA, one of the most well-known braided rivers in the United States. Shu and Chen (2002) also simulated pumping from over 1000 wells to better understand the relationship between seasonal pumping from irrigation wells and river levels. Simulation results suggested that continued over-extraction of groundwater in the region would gradually increase losses from the river. In a subsequent study, Chen (2007) developed a numeric model using the Galerkin finite-element method to assess the impact of the riparian vegetation on baseflow interception and increased river water infiltration in the Platte River.~~

~~Passadore et al. (2015) developed a three-dimensional groundwater flow model for the large and complex Central Veneto aquifer in northeast Italy, which is highly connected to the braided Brenta River. The authors calibrated the model using historic observation data from groundwater wells. They first created a conceptual geologic model, which was used to set up a finite-element numeric model. They used aquifer parameter inputs (e.g., hydraulic conductivity, transmissivity) based on field observations and carried out a steady-state calibration based on observations from 100 wells. The authors provide no detail regarding the manner in which the Brenta River was implemented in the model but note that fluxes from the river to the underlying aquifer are an important component of aquifer recharge.~~

~~Ramanathan et al. (2010) examined the heterogeneity in braided river deposits using the geometric-based simulation method, and the resulting model can be used to simulate fluid flow. Their model incorporated typical braided river features such as areas of lower permeability, high permeability structures such as open-framework gravels, and channel shifting dynamics.~~

~~There are several braided river studies conducted in New Zealand that involved modelling groundwater-surface water exchange. In the Canterbury region, Anderson (1994) and Scott and Thorley (2009) developed a relatively simple steady-state MODFLOW model,s for the purpose of improving understanding of regional-scale water budgets, which included gains and losses from the braided Rakaia, Selwyn and Waimakariri Rivers. In Hawkes Bay, Baalousha (2012) used MODFLOW to characterise groundwater-surface water interactions in the~~

~~Ruataniwha Basin, which contains several braided rivers~~ and found ~~.~~ t~~The modelling~~ to ~~indicated that the braided rivers in this region gain much more than they lose.~~ Wilson and Wöhling (2015) attempted to improve the understanding of Wairau River recharge into the Wairau aquifer in Marlborough, New Zealand, using a ~~.~~ ~~They used flow gauging and groundwater level observations to calibrate a~~ steady-state MODFLOW model and ~~.~~ ~~The river was modelled using~~ the SFR2 package. The authors noted groundwater monitoring records and pump testing showed the aquifer to be more complex and stratified than previously thought, indicating that groundwater monitoring sites were likely only representative of local conditions. This finding ~~further highlights~~underscores the difficulties of modelling highly heterogeneous, complex river systems and their associated aquifers. This was further highlighted by Close et al. (2016) who used the Wilson and Wöhling (2015) MODFLOW model as a basis for a study using heat as a tracer in the Wairau aquifer. ~~Close et al. (2016) simulated thermal transport using MT3DMS in MODFLOW, which is incompatible with the SFR package, used in the original model, so they used the STR package. They compared results in the flow model to their thermal transport model and found that the transport model produced higher recharge rates on average and that it did not provide "unique insight" into the model parameters, unlike the flow model, which was based on river flow and groundwater levels.~~ Close et al. (2016) ~~also~~ found that ~~model calibration fit the observed flow and groundwater levels well but not the observed groundwater temperatures, indicating the aquifer was more heterogeneous than captured in the model. This~~ including heterogeneity was ~~an~~ important when calibrating the model to observed ~~consideration to fit the model to the~~ temperature data.

In a subsequent study of the Wairau Plain aquifer and the Wairau River, Wöhling et al. (2018) developed a transient MODFLOW model that was calibrated using targeted field observations as well as "soft" information from experts of the local water authority. The uncertainty of simulated river-aquifer exchange flows was evaluated using Null Space Monte Carlo methods. The study suggested that the river is hydraulically perched (losing) above the regional water table in its upper reaches and is gaining in the downstream section. It was found that despite large river discharge rates (i.e., regularly reaching 1000 m^3/s), the net exchange of flow rarely exceeded 12 m^3/s and seemed to be limited by the physical constraints of unit-gradient flux under disconnected rivers. An important finding for the management of the aquifer was that changes in aquifer storage are mainly affected by the frequency and duration of low-flow periods in the river.

~~2.5.1~~ Advantages and Limitations

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Field methods are often time consuming and expensive, and they may not be at the targeted spatial or temporal scale. Therefore, the estimation of exchange between braided rivers and groundwater is often complemented by hydrological modelling. MODFLOW is commonly used to model surface water-groundwater interaction, including in braided rivers. Complex flow channel geometry, which changes over time, is not explicitly incorporated into modelling efforts, at least in the studies identified by the authors listed above. As such, the impact of complex and temporally variable flow channel geometry on surface water-groundwater exchange is not well understood. More complex integrated modelling approaches than that possible using the MODFLOW suite of packages is likely required to incorporate this level of detail. A future integrated approach that considers channel geometry in a more physically realistic manner may be facilitated by the recent development of braided river terrain models (e.g., Williams et al., 2016) and methods for simulating the heterogeneity of braid~~i~~ed river sediments (e.g., Ramanathan et al., 2010)~~(e.g., Ramanathan et al., 2010)~~.

3 Discussion

There are many factors to consider when selecting the appropriate method(s) for studying groundwater-surface water interactions~~vestigations~~, and there are special considerations relevant to braided river environments. The most appropriate method will depend on physical and hydrological conditions in the setting and scale of interaction to be measured (LaBaugh and Rosenberry, 2008). As a result of this review of studies investigating groundwater-surface water exchange in braided rivers, a summary table has been developed (Table 1) that ~~outlines~~ summarises the literature discussed in this paper and the advantages and disadvantages of the various methods used in these studies.

Table 1. Advantages and disadvantages of various methodologies for ~~estimating~~ measuring groundwater-surface water interactions in braided rivers

Method	**Advantages**	**Disadvantages**	**Applications of these methods in braided rivers***
~~River-reach water~~Water budgets	• Better s~~S~~uit~~abl~~e~~e ~~d for relatively homogeneous aquifers • Good for large-scale studies • Useful for identifying hotspots of river gains and losses • Can be simple and relatively quick to calculate	• Errors can be greater than the amount of groundwater-surface water flux • Not well suited for sub-reach scale • Not very accurate in highly heterogeneous systems • Does not consider streambed throughflow • Multiple sites on a river must be gauged concurrently • Errors can be significant in large catchments • Uncertainties of land surface recharge and offshore flow rates can result in errors • Can be expensive and time consuming depending on how data is collected	Acuña & Tockner (2009); ~~Aitchison-Earl & Ritson (2013)~~ Burbery & Ritson (2010); Doering et al. (2013); Farrow (2016); Larned et al. (2008); Larned et al. (2015); Riegler (2012); Simonds & Sinclair (2002); Soulsby et al. (2004); White et al. (2012)~~; Williams & Aitchison-Earl (2006)~~
~~Catchment-scale water budgets~~	~~• Good for large-scale studies~~ ~~• Simple and can be relatively quick~~	~~• Errors can be significant in large catchments~~ ~~• Uncertainties of land surface recharge and offshore flow rates can result in errors~~ ~~• Can be expensive and time consuming depending on how data is collected~~	~~Anderson (1994); Burbery & Ritson (2010)~~
~~Environmental tracers~~Hydrochemistry ~~(e.g., radon, stable isotopes, chloride, etc.)~~	• Good for environments where there is a sufficient difference between tracer concentrations in groundwater and surface water • Useful for identifying interactions on a large scale • Some ~~tracers~~ parameters can easily be included in long-term, routine sampling ~~(e.g., pH, alkalinity, dissolved oxygen)~~ • • Some tracers ~~C~~can be used to quantify seepage rates	• Analysis errors can be an issue when concentrations are low (e.g., radon) • Groundwater and surface water concentrations may be too close to differentiate ~~• Land use activities may cause hydrochemical changes~~ • Concentrations may not be temporally or spatially consistent • Some tracers (e.g., dissolved oxygen, nitrate) may be affected by biogeochemical processes, so they need to be conservative on the scale of the investigation	Acuña & Tockner (2009); Blackstock (2011); Botting (2010); Burbery & Ritson (2010); Cantafio & Ryan (2014); Close (2014); Close et al. (2014); Coluccio (2018); Doering et al. (2013) Domisse (2006); Guggenmos (2011); Larned et al. (2015); Malard et al. (2001); Moore (1997); Rodgers et al. (2004); Soulsby et al. (2004); Vincent (2005)
~~Heat tracers~~Temperature studies	• Variety of methods ranging in complexity, cost, scale	• Often needs to be measured continuously • Need a sufficient temperature difference between groundwater and surface water	Acuña & Tockner (2009); Close (2014); Close et al. (2016); Coluccio (2018);

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	• Can be used for both locating areas of discharge/recharge and quantifying flux • Aerial surveys can be faster than in-stream surveys	• May be less effective in periods of high river flows	Doering et al. (2013); Lovett et al. (2015); Malard et al. (2001); Passadore et al. (2015) ~~; Tonolla et al. (2010)~~
Modelling	• Acts as a database for field data • Can assist researchers to develop intuition about physical processes and refine their conceptual models • Useful for carrying out regional-scale assessments for management purposes, such as determining streamflow depletion associated with pumping • MODFLOW packages widely accepted for numerical simulation and intuitive to apply~~.~~ • MODFLOW packages considered a good compromise between a simple conceptual modelling approach and a more complex integrated approach~~.~~	• Some models have high computational and time requirements • Various assumptions required that may not reflect actual hydraulic processes or aquifer properties	~~Anderson (1994);~~Baalousha (2012); Chen (2007); Close et al. (2016); Passadore et al. (2015); ~~Ramanathan et al. (2010);~~ Scott & Thorley (2009); Shu & Chen (2002); Wilson & Wöhling (2015); Wöhling et al. (2018)
~~Hydraulic Property Measurement~~Darcy approach	• P~~Mini p~~iezometers ~~are~~ are typically easy and quick to install • Wells can be installed in-stream or on land • Can also use existing well networks • Can be used in small-scale or regional applications • Can be used to survey heterogeneous areas • Piezometer measurements are straightforward to analyse	• Deep groundwater wells are expensive to install • All measurements at a study site must be taken at the same time • Hydraulic conductivity can significantly vary spatially, thus difficult to extrapolate to represent a large area	Acuña & Tockner (2009); ~~Aitchison-Earl & Ritson (2013)~~ Botting (2010); Burbery & Ritson (2010); Chen (2007); Cheng et al. (2010); Coluccio (2018); Doering et al. (2013); Domisse (2006); Larned et al. (2008); Larned et al. (2015); Malard et al. (2001); Passadore et al. (2015); Riegler (2012); Shu & Chen (2002); Simonds & Sinclair (2002); Van’t Woudt & Nicolle (1978); Vincent (2005); ~~Williams & Aitchison-Earl (2006);~~ Wilson &

			Wöhling (2015); Wöhling et al. (2018)

*Note: some studies referenced in this table were not discussed in the text.

The objectives of a~~the~~ study will influence which methods are most applicable. If only qualitative information about groundwater-surface water exchange is required, this could be obtained by methods such as mapping the locations of wet and dry reaches of a river, or identifying where there is mixing between groundwater and surface water based on chemical or heat tracers. Alternatively, if quantitative data is needed, such as the rate of groundwater seepage into a surface water body, this may be obtained by measuring Rn-222, analysing temperature signals, or by calculating the hydraulic gradient. Researchers have developed flux quantification techniques for some of the methods discussed in this paper (e.g., for temperature analysis see Gordon et al., 2012), but it is important to consider inputs required to calculate seepage through a streambed, such as streambed hydraulic conductivity (see section 2.4). If direct water samples are needed, tools to consider could include groundwater wells or mini-piezometers. Water samples and flux rates can also be obtained using seepage meters, a common method used for estimating groundwater-surface water interactions typically based on the design proposed by Lee (1977). However, it does not appear that these devices have been previously used in gravel-bed braided rivers. Seepage meters have various limitations as discussed in previous studies (e.g., Kelly and Murdoch, 2003; Brodie et al., 2009; Cey et al., 1998), which indicate their application in braided rivers would be difficult and less effective than other methods.

It is important to match the scale of the data required with the methods being used. This should include the consideration of both spatial and temporal scales. If regional or catchment-scale information is desired, methods such as pumping tests, flow gauging, stable isotope analysis~~,~~ and ~~solute tracers and chemical analysis~~hydrochemical tracers are among the most applicable methods. Remote sensing techniques such as airborne thermal infrared imaging and geophysics may also prove useful to apply in braided river settings for gathering data on a large scale, as these methods have been used in braided rivers for geomorphological studies (e.g., Huber and Huggenberger, 2016) and for investigating groundwater-surface water exchange in other settings (McLachlan et al., 2017). We discuss these approaches in Section 4. It is important to recognise that it may be difficult to accurately characterise groundwater-surface water interactions in highly heterogeneous environments based on broad-scale methods. At the reach scale, oxygen-18 or radon analysis could be appropriate methods (Lovett, 2015). At a point scale, streambed piezometers and temperature profiles can be useful. With finer resolution methods, there may be issues with up-scaling the data because many closely spaced measurements are needed, and it is difficult to distinguish between groundwater discharge and hyporheic zone flow (Lovett, 2015). While point-scale data may be desired, it may be impractical to carry out the large number of measurements necessary on a wider scale (such as in a large river). Using a combination of broad and point-scale techniques at a single study site may help overcome the limitations of the individual techniques, particularly in heterogeneous environments (Kalbus et al., 2006). Temporal scale variabilities are also important to consider. The magnitude and direction of groundwater-surface water interactions may change in response to factors such as river flow levels (Rosenberry and LaBaugh, 2008). Some methods may require that all sampling be completed within a short time period so that the data is representative of similar conditions. For instance, concurrent flow gauging, where the flow in reaches on a river are gauged on the same day, will generally produce a more reliable representation of baseflow conditions compared to gauging carried out over multiple days, as flow levels can change daily (Farrow, 2016). Temperature profiling on the other hand may need to be continuous over a period of time to remove the influence of diurnal fluctuations (Passadore et al., 2015) depending on the method of analysis. In addition to temperature, many parameters can be collected as time series (e.g., water levels, hydrochemistry), which may be very useful for interpreting temporal changes in groundwater-surface water exchange.

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~~Conceptualisation and quantification of hydrogeological systems is generally associated with a degree of uncertainty. The degree of accuracy of measurements can vary based on many factors including sampling protocol, lab analysis, assumptions required (e.g., aquifer properties) or the nature of the method chosen. The degree of accuracy dictated by the study objectives and the study object should be carefully considered when choosing the appropriate methods. Likewise, the level of accuracy and confidence in results should be discussed in conjunction with study results.~~

Site-specific characteristics will largely determine the most appropriate methods to use. The geology, topography, hydrochemistry, hydrology and hydrogeology of the study site will need to be considered. Factors such as geologic complexity, chemical components of the soils and surface and ground waters, aquifer properties, and climate should be taken into account. Inputs and outputs to groundwater and surface water may need to be considered, such as abstraction for irrigation or industrial discharges. There are various practical considerations such as the availability of groundwater wells, river access and feasibility of techniques. For example, large braided rivers with high flows and deep channels may prove difficult to access directly. There is also a reasonable risk of the loss or damage of equipment installed in braided riverbeds due to floodwaters or sediment movement~~ during storms~~. These practical considerations underline the potential benefits of remote techniques to collect data in this type of river.

As with any study, the available resources will influence the types of methods selected. Techniques vary in cost depending on materials needed, installation requirements or analysis methods. Mini-piezometers, for example, are on the inexpensive end of this range, while airborne thermal imaging is a more expensive method, though its cost may be reduced by using Unmanned Aerial Vehicles (UAVs). Time is a key consideration, and this can range widely. While simple and relatively inexpensive, some field techniques, such as streamflow gauging or piezometer measurements, may be time consuming to carry out given the large number of measurements required to obtain a representative sample, especially in heterogeneous environments like braided rivers. If many replicate samples are required to obtain representative data for an area, it may be cheaper to use remote sensing or another broad-scale method. Analysis requirements should be considered when evaluating the merits of particular methods. Some chemical sampling for example may require expensive lab analysis and then subsequent statistical analysis, whereas other methods such as flow gauging require minimal processing of data. The availability of data relevant to the study site will be important to consider. For example, aquifer properties may need to be known to carry out calculations or modelling. Or, historical sampling records may be needed to compare long-term trends.

Despite these various considerations involved in choosing the appropriate methods for carrying out investigations of groundwater-surface water interactions, according to Landon (2001), the number of measurements made may be more important for obtaining accurate data than the type of methods chosen given the spatial variability in hydraulic conductivity of streambeds. Also, as demonstrated in the various studies discussed in this review, rarely did researchers rely on a single method to explore groundwater-surface water interactions. As Kalbus et al. (2006) conclude in their comprehensive review of methodologies, the most accurate results for estimating fluxes between groundwater and surface water may be achieved by combining multiple methods at various scales. A multi-method approach may also help overcome the challenges of working in heterogeneous braided river environments. ~~Indeed, most of the studies presented in this article used more than one technique to investigate questions relating to groundwater-surface water exchange.~~

~~3.1~~4Key gaps and possibilities

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This paper has highlighted that there are currently gaps in the knowledge of how groundwater and surface water interact in braided rivers. ~~One of the most significant gaps in our understanding relates to hyporheic exchange.~~ ~~We have~~There is limited understanding of how hyporheic flow processes operate, and how they impact river flow levels and water quality in braided rivers. The hyporheic zone has been highlighted as a significant area for ecological processes in rivers (Febria et al., 2011; Krause et al., 2011; Malard et al., 2001), but as Kalbus et al. (2006) note, it can be difficult to differentiate between hyporheic exchange and groundwater discharge. In addition, despite the contributions of the studies discussed here, the recharge rates to and from braided rivers continue to be a source of question for water scientists and managers, as this has implications for both water quality and quantity. Measuring seepage rates is still difficult in many gravel-bed braided rivers, and often there is significant uncertainty in the data collected. Lastly, there is still much scope for research on identifying historical patterns of dry and low-flow periods in braided river reaches. This is often an area of significant concern for communities that are seeking answers on the correlations between dry or low-flow periods, and current and historical water use practices and climate.

There is also room for improvement in the methods available to carry out these investigations. Refinement of techniques that allow for direct measurements of physical or chemical properties in braided rivers would be helpful. While the studies presented here have employed some direct methods, there is still a need for techniques that can be used in braided rivers with coarse gravel substrate, wide active riverbeds, ~~fluctuating flow levels,~~ and shifting channels and gravel bars. Methods that can better capture the heterogeneous properties of braided rivers would be ideal. ~~Previous studies discussed in this~~The present paper has~~ve~~ shown the promise of using environmental tracers such as Rn-222 and stable isotopes, as well as heat tracers in these settings. Additional techniques that allow for indirect measurements would also be beneficial, ~~in braided rivers~~ given the difficulty of working directly in braided rivers. Geophysical methods (discussed in more detail below) have been used in many other river environments to gather information about hydrogeologic systems that can then be inferred to better understand groundwater-surface water exchange. There is also scope for more remote collection of data, and Carbonneau and Piégay (2012) review a range of technique for use in rivers, while Marcus (2012) provides an overview of remote sensing specifically in gravel-bed rivers. There is a significant amount of freely available satellite data (e.g., via the Sentinel satellites, https://sentinel.esa.int/web/sentinel/home) that may be useful in braided river studies. Unmanned aerial vehicles have become more affordable and advanced in recent years,

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allowing for remote collection of a range of data on rivers such as thermal infrared, multispectral and hyperspectral imaging, and photogrammetry (Pai et al., 2017).

Artificial dye, chemical (e.g., salt) or bacterial tracers are often useful for shedding light on processes such as groundwater velocity and flow paths or hyporheic zone flow (Flury and Wai, 2003). They have been used in other types of rivers to investigate groundwater-surface water exchange (e.g., Binley et al., 2013; Ferreira et al., 2018; Stoner et al., 2013; Knöll and Scheytt, 2018; González-Pinzón et al., 2015). Several studies have used rhodamine dye in a New Zealand well array installed in an alluvial aquifer ~~(2008)~~deposited by braided rivers to estimate hydraulic properties and examine groundwater flow paths (e.g., Close et al., 2002; Dann et al., 2008; Sarris et al., 2018). For artificial tracer tests to be time and cost effective, some prior knowledge of water flow paths and velocities is necessary (Close et al., 2002). ~~(2013)~~

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There is scope to use other temperature methods than those described in section 2.3, such as fibre-optic distributed temperature sensing (FODTS) (Busato et al., 2019; Klinkenberg, 2015; Lovett et al., 2015; Meijer, 2015; Rosenberry et al., 2016; Mwakanyamale et al., 2012) or active heat pulse methods (see Briggs et al., 2016; Banks et al., 2018). Collection of temperature profiles was briefly mentioned in section 2.3 in the study conducted by Coluccio (2018), which used 1-D temperature profiles. However, there are several ways temperature profiles can be collected (1-D, 2-D, 3-D), as well as a range of analysis methods that can be used, as demonstrated in several previous studies ~~with~~in non-braided river settings (Briggs et al., 2014; Gordon et al., 2013; Naranjo and Turcotte, 2015; Rosenberry et al., 2016). ~~, and these methods could be applied in braided rivers. It would be very interesting to apply 3-D temperature arrays in a braided river to help understand flow dynamics in multiple directions, such as the technique applied in Banks et al. (2018).~~ There is also considerable scope for applying thermal infrared (TIR) imaging in braided rivers. Handcock et al. (2012) provide a comprehensive review of the use of TIR imaging in rivers. Using TIR imaging to highlight temperature differences in a braided streambed may be particularly useful for qualitatively identifying locations of groundwater inflow to rivers. TIR data can be collected remotely (by UAV, helicopter or fixed wing plane), on the ground or by satellite, and there are important considerations with each category (e.g., cost, scale of data collected). TIR imaging has been used in several river environments to identify groundwater-surface water interactions (e.g., Culbertson et al., 2013; Eschbach et al., 2017; Hare et al., 2015; Liu et al., 2016; Lovett et al., 2015; Rautio et al., 2018) but does not appear to have been applied in braided rivers to any great extent for this purpose.

There have been many advances in geophysical techniques in recent years, and ~~for the most part,~~ these methods do not appear to have been applied in braided river settings for investigations of groundwater-surface water exchange. McLachlan et al. (2017) provide a thorough recent review of geophysical methods for characterising the groundwater-surface water interface such as electrical resistivity tomography (ERT); ground penetrating radar (GPR); seismic methods; and forward and inverse geophysical modelling. These methods allow for river systems to be characterised where factors such as geological, hydrological and biogeochemical heterogeneity make it difficult to make direct measurements (McLachlan et al., 2017). A recent study by Busato et al. (2019), demonstrates the use of ERT and FODTS in a rocky stream with poorly sorted substrate, which may provide useful learnings for braided rivers. Examples of studies in other types of river environments that used geophysics to characterise the groundwater-surface water interface include Singha et al. (2008), Binley et al. (2013) and Steelman et al. (2017). Geophysical data can also be collected remotely in airborne electromagnetic surveys such as in Harrington et al. (2014). As McLachlan et al. (2017) note, geophysical techniques should be used to complement data collected by other hydrological and biogeochemical methods.

~~Given the challenges of working directly in braided rivers, there is considerable scope for the use of remote techniques, such as thermal infrared imaging and geophysics, to collect data on these rivers. (Cardenas et al., 2008;Lovett et al., 2015)~~

As discussed in the modelling section of this paper, there is also opportunity for new approaches to modelling of braided rivers. Brunner et al. (2017) note that there have been recent advances in hydrologic modelling that incorporate both surface and sub-surface water flow, and there is certainly room to apply some of these techniques to braided river settings. There are software packages that have been applied elsewhere such as HydroGeoSphere (e.g., Gilfedder et al., 2019; Goderniaux et al., 2009; Tang et al., 2017) and MIKE-SHE (e.g., Butts et al., n.d.; House et al., 2016; Bandini et al., 2017) that appear promising to try in addition to MODFLOW, which has been traditionally used in braided river modelling of the groundwater-surface water interface.

5 Summary

Braided rivers are unique and dynamic river environments that serve important ecological, cultural, recreational and freshwater resource functions. A critical aspect of their effective management is understanding groundwater and surface water interactions in these rivers and their associated aquifers. This article provides an overview of characteristics specific to braided rivers, which include~~s~~ multiple meandering channels that often shift; temporary and semi-permanent bars and islands; wide active riverbed areas; heterogeneous and (typically) mixed sand and gravel streambeds; and ~~dynamic flow levels~~a significant portion of river flow that occurs within the streambed. We present a map showing the regions where braided rivers are ~~concentrated~~ mainly found at the global scale: Alaska, Canada, the Japanese and European Alps, the Himalayas, Russia and New Zealand. To the authors' knowledge, this is the first map of its kind. Our review of prior ~~surface water-groundwater interactions~~ studies of surface water-groundwater interactions in braided rivers showed that most studies have been recent (in the past 10-20 years), and they have investigated a range of questions including calculating seepage rates to/from braided rivers; estimating time lags between rivers and groundwater; and looking at the implications of groundwater-surface water exchange on ecological processes. We also investigated the effectiveness of the various methods used in the studies identified in this review in terms of achieving the studies' objectives and their applicability in braided rivers. A table has been produced summarising these findings and shows that there is a variety of available methods ranging in cost and scale.

Lastly, this article explored the various considerations one may make when choosing appropriate techniques for investigating groundwater-surface water exchange in braided rivers. While the methods selected will ultimately depend on a number of factors (e.g., budget and time requirements; spatial and temporal scales; data inputs required; and site-specific characteristics), we conclude that the most effective approach will likely involve the initial use of broad-scale approaches such as airborne thermal imaging, geophysics, fibre-optic temperature sensing, differential flow gauging, catchment water budgets or hydrochemistry~~tracers~~. Finer scale methods such as groundwater well observations, small-scale tracer studies and temperature sensors can then be used to explore hot spots of exchange or specific areas of interest. The use of multiple methods at varying spatial scales at a single study site may help overcome the uncertainties associated with data gathered in~~ these~~ heterogeneous, dynamic braided river environments. Given the challenges of working directly in braided rivers, there is considerable scope for the increased use of remote sensing techniques and geophysics. There is also scope for new approaches to modelling braided rivers using integrated techniques that incorporate the often~~-~~complex river bed terrain and geomorphology of braided rivers explicitly. There is presently limited understanding of the role of how~~the~~ hyporheic zone processes operate and impact braided rivers~~in surface water-groundwater exchange in braided rivers,~~; recharge rates to and from braided rivers;~~,~~ and historic drying and low-flow trends in braided rivers, and thus future research is needed in these areas.

Author contribution

The project was instigated by LM. KC carried out the literature review that formed the content of this manuscript and wrote the initial manuscript draft. KC and LM revised the manuscript together.

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<u>Reply to Reviewer # 1</u>

We thank Reviewer #1 for the helpful review and have responded to each comment below. All line numbers in our responses refer to the revised marked manuscript.

General Comments

1. The manuscript "A review of methods for measuring groundwater-surface water exchange in braided rivers" by Katie Coluccio and Leanne Kaye Morgan is a review paper. As the title suggests it is about measuring methods for groundwater-surface water exchange in braided rivers. In general, the manuscript is informative, provides an overview about the current literature, is well structured and well written.

<u>Response:</u> We thank the reviewer for these positive comments.

2. However, some sections are lengthy and might be shortened.

<u>Response:</u> We have shortened the descriptions of the literature as suggested in Comment #6, which has resulted in approximately 2,800 words being deleted. However, text has been added as a result of addressing the various comments by both reviewers, particularly in respect to discussing additional methods that could be used in braided rivers to investigate groundwater-surface water exchange.

3. Furthermore, as indicated in the major comments below important information, definitions etc. is missing.

<u>Response:</u> We thank the review for pointing out these omissions. As detailed below (in response to comments #8, 9, 11, 12, 13, 16, 17, 18, 19, 22, 23, 24, 26, and 27), we have addressed this in the revised manuscript.

4. In general the authors could think a little bit more outside of the box. They are very focused on the methods that have been used in studies of groundwater-surface water interactions in braided rivers. But there are several similar groundwater-surface water interfaces and as part of a scientific paper I would expect the authors to consider additional *methods that might be adapted to braided rivers in future in addition to simply summarising the literature available at present.*

Response: In the revised manuscript we have discussed (in Section 4 "Key gaps and possibilities") additional methods that have not yet been applied in braided rivers but show potential. Here we have included additional temperature methods such as fibre-optic temperature sensing, active heat pulse methods and thermal infrared imaging; artificial tracers (such as dye, salt and bacterial tracers); remote collection of data via satellite imaging and unmanned aerial vehicles; geophysical techniques; and modelling packages (i.e., HydroGeoSphere and MIKE-SHE).

5. I think the manuscript can be published after revision.

Response: Thank you.

Major comments

6. Entire manuscript: Try to shorten your manuscript and avoid lengthy descriptions of the literature, e.g. L173-L213, L216-242, L289-325, L328-L379, L382-402, L533-603, L606-L640, L667-L739.

Response: We agree that the manuscript would benefit from more concise descriptions of the literature and have shortened sections at L204-214, 220-229, 256-276, 280-284, 336-352, 360-365, 384-387, 392-407, 412-417, 445-452, 457-459, 467-476, 512-543, 548-564, 585-589, 641-643, 655-656, 661-663, 694-695, 700-704, 749-760, 768-803, and 808-816. This has resulted in the deleting approximately 2,800 words from the original manuscript.

7. L60 & entire manuscript: Suggest also methods that have been successfully used at other groundwater-surface water interfaces and that might be adapted to braided rivers and might be used in braided rivers in future. Reporting only what has already been done in braided rivers is a little bit thin.

Response: Thank you for the suggestion. Please refer to our response to Comment #4.

8. L64 & Fig. 1 & L882: I strongly recommend adding all additional instances of braided rivers outside of the major regions. You might use different symbols for major regions with braided rivers and single instances.

Response: When initially creating Fig. 1, we had considered attempting to include all instances of braided rivers globally, as suggested. However, we decided against this for a few reasons. Mainly, we were concerned that stating we had accounted for "all" braided rivers would run the risk of missing some rivers and in so doing being factually incorrect. Secondly, we felt that highlighting the locations where most braided rivers occur would be most useful to readers, as this indicates where most of the braided rivers research has been conducted. In an attempt to account for instances of braided rivers outside of the major regions, in the revised manuscript, we have added a sentence at L72 noting that braided rivers also occur in small numbers in the U.S., Scotland, Iceland, China, Poland, Belarus, Colombia, Congo, Brazil, Paraguay, Argentina, and the Touat Valley in Africa. Also, we have added Russia to Fig. 1 based on comments in studies by Chalov & Alexeevsky (2015) and Alexeevsky et al. (2013) about the high number of braided rivers in that country.

9. L100f; L791f, L855: I think there is a need for clear definitions of "groundwater-surface water interactions" and of "hyporheic exchange". Often, the term "groundwater-surface water interaction" is used in literature in a wide sense including hyporheic exchange as one process of groundwater-surface water interactions. However, according to line 100f you consider both as separate processes with some impacts on each other.

Response: Thank you for highlighting this, and we agree that this is an area where more clarity would be helpful. We have added the following text to the revised manuscript at L60: "This paper often refers to groundwater-surface water exchange, which in this context may include regional groundwater exchange with river water, as well as hyporheic zone exchange. Researchers have defined the hyporheic zone and the exchange processes that occur there in many ways (e.g., Krause et al., 2011; Cardenas, 2015). In the present paper, hyporheic exchange refers to downwelling or upwelling of water through the hyporheic zone, i.e., the saturated area between the streambed and shallow aquifer where stream water and shallow groundwater mix.

10. L134ff: Even though I agree that there is little research about groundwater-surface water interactions in braided rivers your "Web of Science" search is meaningless. I tried to reproduce it. First of all "groundwater and surface water interactions" with "…" results in much smaller numbers than the ones reported by you, e.g. only three papers for lakes instead *of 437 reported by you. Repeating the search without "…" resulted in approximately the numbers reported by you. However, having a closer look at those papers revealed that most of the hits are not about groundwater-surface water interactions at all but that the separate words of the phrase are used in separate sentences and in different context. Furthermore, at many of the interfaces mentioned by you (lakes, ocean, stream) specific terms are used, e.g. "lacustrine groundwater discharge", "submarine groundwater discharge" and "hyporheic zone" instead of "groundwater and surface water interactions". Sometimes the word "interactions" is substituted by "exchange" or by "interfaces". Also, there are different spellings for "groundwater" such as "ground water". I am quite sure that the largest number of studies focusing on groundwater-surface water interactions is about stream, followed by (coastal) oceans followed by lakes and finally by braided rivers. You might also have a look at review papers focusing on the different interfaces. There are several of them. I recommend either deleting lines 134-139 or repeating this literature search with a set of different keywords to get a more comprehensive overview of the literature of interest.*

Response: Thank you for highlighting this issue, and we agree that deleting these lines would improve the manuscript. They have been removed from the revised manuscript (L150–155).

11. L158ff: From my experience budgets are often quite error-prone because accurate measurements of river discharge are challenging. Often changes in river discharge between stations are much smaller than the error inherent to the measurements. You should mention this shortcoming more clearly than only in lines 261-263.

Response: Indeed, this is an important factor to consider. Additional to L297, we have mentioned this limitation in Table 1 (under Water Budgets), so we believe this limitation has been adequately addressed.

12. L272ff/L284ff: I think it is important to introduce here also the concept that tracers need to be conservative (on the scale of the investigation). In this context, I doubt that dissolved oxygen (L284), nitrate (L285), sulphate (L286) and pH (L404) are useful tracers. pH might be acceptable in the context of alkanity but that also needs more discussion. The concentrations of oxygen, nitrate, sulfate and H+ will be altered due to many different biogeochemical processes. They might be used under certain circumstances and on small *scales on which little turnover takes place. But this is something very critical. If you list these compounds you need to discuss them critically.*

<u>Response:</u> Thank you for the comments here and we agree with your point that tracers need to be conservative, and this is an important consideration to make when selecting parameters to measure. In the revised manuscript, we have added comments to this effect in the Advantages & Limitations section of Section 2.2 as well as in the Hydrochemistry section of Table 1. We think that these parameters are still worthy of discussion as they have been used in several previous studies to varying degrees of success.

13. L272ff: In addition to environmental tracers I recommend to discuss also artificial tracers that might be added to the system. There are multiple studies using artificial tracers and I am quite sure that the also have been used in braided rivers. However, even if not they are an option that should be considered.

<u>Response:</u> In Section 4 of the revised manuscript, we have added a paragraph on the use of artificial tracers such as dyes, salt and bacteria. Here, we have cited several studies conducted in non-braided river environments: Binley et al., 2013; Ferreira et al., 2018; Stoner et al., 2013; Knöll and Scheytt, 2018; González-Pinzón et al., 2015. We have also cited several studies that used artificial tracers to characterise alluvial aquifer properties in a well array in New Zealand: Close et al., 2002; Dann et al., 2008; Sarris et al., 2018.

14. L457-468: I don't see any connection of this paragraph to the topic groundwater-surface water interactions. Therefore, I recommend deleting this paragraph.

<u>Response:</u> Thank you for highlighting this, and we agree that this study was not specifically related to investigating groundwater-surface water interactions, and thus we have removed it from the revised manuscript (at L516-528).

15. L469-484: The topic of the present review is measurement methods for groundwater-surface water interactions. Thus, these two paragraphs don't fit to the topic of the review paper. They are about impacts of groundwater and surface water on temperature (and ecological consequences) but not how to use measurements to identify groundwater-surface water interactions.

Response: Thank you for the constructive comments on these studies. We have deleted these two paragraphs (L529-543). The two studies mentioned in these paragraphs (i.e., Acuna and Tockner, 2009; Malard et al., 2001) used multiple methods to assess groundwater-surface water exchange, and thus we feel that these are useful references to include, albeit now only in Table 1 within the revised manuscript.

16. L502ff: I think it is important to measure temperature depth profiles as you do in this paragraph. However, you should go into a little bit more detail here and also mention typical evaluation methods for temperature depth profiles such as the steady state approach (e.g. C. Schmidt, M. Bayer-Raich, and M. Schirmer. Characterization of spatial heterogeneity of groundwater-stream water interactions using multiple depth streambed temperature measurements at the reach scale. Hydrology and Earth System Sciences 10:849-859, 2006) or VFLUX.

Response: We agree that it would be useful to include some more detail on how temperature depth profiles may be analysed. VFLUX was used in the Coluccio (2018) study, and a note in this regard has been added to the revised manuscript at L561. Both VFLUX and the steady state method used by Schmidt et al. (2006) have also been mentioned at L507-508 in the revised manuscript.

17. L443ff: I think at one point in this subchapter you should clearly differentiate between methods that are used to determine fluxes (e.g. temperature depth profiles) and methods for pattern identification (aerial TIR, fo-DTS). This applies also to lines 513-515. TIR is a method for pattern identification. However, you need to describe this already before and not only in Advantages and Limitations. See also comment regarding this topic below.

Response: This is a very good suggestion, thank you. In the revised manuscript we have noted this difference in temperature methods at the beginning of section 2.3 (L508-512).

18. L443ff: Furthermore, you should briefly mention typical approaches to measure temperature and in this paragraph you should also include fibre-optic distributed temperature sensing even if it has not been used in braided rivers yet.

Response: We agree that it would be useful to have a brief explanation of typical approaches to measuring temperature while noting which ones are used for pattern recognition or flux estimates (as per the comment above). We have briefly mentioned fibre-optic DTS in the beginning of section 2.3 (L509) and discussed it further in section 4 (L982-983), as well as included relevant references.

19. L443ff: You could also consider adding temperature methods that don't rely on natural temperature differences but use temperature as an active tracer, e.g. active (heated) DTS, heat-pulse sensors etc.

Response: Thank you for the suggestion, and we agree that it would be useful to include active heat tracers (such as the 3D heat pulse array used in Banks et al. (2018)) in the revised manuscript. To our knowledge, these methods have not yet been used in a braided river setting, but they do have potential and thus may be beneficial for readers. We have included these methods in section 4 of the revised manuscript (L984).

20. L524: "Hydraulic property measurements" is no suitable chapter headline for the subchapter "Groundwater observation wells"! Alternatives might be "2.4 Flow-net analysis" or "2.4 Darcy approach". I would call 2.4.1 "Hydraulic gradients" and 2.4.2 "Hydraulic conductivity".

Response: Thank you for the suggestions and we have amended the section headings to the following:

2.4 Darcy approach

2.4.1 Hydraulic gradient

2.4.2 Hydraulic conductivity

Advantages and Limitations

21. L525ff: The second sentence of the paragraph is wrong: The groundwater level/hydraulic gradient is no hydraulic property. Hydraulic properties are the hydraulic conductivity, the porosity etc. The rest of the paragraph belongs to 2.4.2.

Response: Thank you for highlighting this. We have deleted L585-589 as these points are covered in sections 2.4.1 and 2.4.2. This has also served to shorten the manuscript.

22. L559ff: You use the terms well, piezometer and mini-piezometer but I have not seen a definition of those terms. Consider to include also other designs, e.g. M. O. Rivett, R. Ellis, R. B. Greswell, R. S. Ward, R. S. Roche, M. G. Cleverly, C. Walker, D. Conran, P. J. Fitzgerald, T. Willcox, and J. Dowle. Cost-effective mini drive-point piezometers and multilevel samplers for monitoring the hyporheic zone. Quarterly Journal of Engineering Geology and Hydrogeology 41:49-60, 2008. However, in this paragraph with its focus on groundwater level measurements either sufficient diameter for a logger or an electric contact gauge is useful even though some scientists used innovative approaches for very small diameters (transparent tubes, suction to increase water level differences to an easily visible height, colored strings ...) Also, you should consider describing at least in brief typical installation techniques for the different designs and different depth depending on substrate quality. Furthermore, report at least in one sentence how water tables are measured/logged.

Response: In L619-623 we intended “groundwater well” and “piezometer” to be synonymous. To clarify this, we have modified the sentence to read: “In terms of specific methods that can be used for measurements, existing piezometers (i.e., monitoring wells) near rivers can be useful for conducting these types of studies, particularly given the high cost of drilling new wells.” At L623 we have added the sentence: “Please refer to standard text such as Fetter (2001) for a definition of piezometers”. In L623-625 we have defined “mini-piezometers” as “scaled-down versions of piezometers and typically installed no deeper than about two metres”. With respect we prefer not to include reference to installation methods as these are detailed in the cited references. Also, for the sake of brevity, we prefer not to detail other piezometer designs.

In the revised manuscript, we have commented in the Advantages and Limitations section of 2.4 about the need to consider the diameter of wells being used with downhole equipment such as loggers. Also, at the beginning of section 2.4.1 we have briefly detailed the way in which water levels are typically measured.

23. L605ff: Consider to add also in brief the use of geophysics to characterize the subsurface pattern (together with some core for calibration of geophysical methods).

<u>Response:</u> This is a good suggestion, thank you. In the revised manuscript, we have discussed new methods for use in braided rivers in section 4. For the sake of brevity, we discuss geophysics in that section (L1002-1014).

24. L642ff: Mention that loggers require a certain diameter of wells/piezometers as a further disadvantage.

<u>Response:</u> At L716-717 we now include the following: "Another important factor to consider is that many data loggers require a certain diameter well."

25. Table 1: You have split the first method (water budget) into two budget methods. Why haven't you also split the following methods as in the text (e.g. environmental tracers, heat tracers, …). In fact heat tracers are also an environmental tracer. Why are River reach budgets suitable only for relatively homogenous aquifers? Remove pH and DO from environmental tracers (see corresponding comments above). As far as I understand the table and its table capitations it is about methods for quantifying water fluxes. The point "Aerial surveys can be faster than in-stream surveys" does not fit. This is a method for pattern identification and not for flux determination. As described above I doubt that "Hydraulic Property Measurement" is an adequate headline for this type of method. I don't think that this applies only to minipiezometers. Piezometers are also easy and quick to install. In general other authors have grouped their methods into three categories and I think this would be advantageous here as well:

+ point methods to estimate fluxes at a discrete location

+ methods for pattern identification don't yield numbers for fluxes but can help to identify representative sites and the most extreme sites to conduct the point methods at the most interesting sites. Under certain circumstances also transfer functions possible that combine methods for pattern identification and point methods

+ integrating methods over large areas that result in total fluxes, but without any information about local fluxes or distribution of patterns.

<u>Response:</u> Thank you for your thorough comments on Table 1. The intention of this table was to summarise all the methods discussed in the review, both for identifying patterns and for estimating fluxes. Perhaps the table title has created the confusion here, so we have amended

the title to read “Advantages and disadvantages of various methodologies for **measuring** groundwater-surface water interactions in braided rivers”.

We are not convinced that organising the methods according to scale of measurement would be helpful as there would be overlap amongst methods (i.e., some methods could be used at multiple scales, see Fig. 1 in Kalbus et al. (2006)). We have revised the categories for Table 1 to: Water budgets, Hydrochemistry, Temperature studies, Darcy approach and Modelling.

26. L783ff: Please keep the three points above in mind. Remote sensing is not gathering the same information as the point methods mentioned in L781-783! The same applies to Line 870-872.
<u>Response:</u> Thank you for highlighting that we may need more clarity around scales of measurement. However, we are not sure why there is confusion here. Depending on how they are carried out, the methods mentioned in L870-871 (pumping tests, flow gauging, stable isotope analysis and hydrochemical tracers) can provide broad spatial scale information, as can TIR imaging, geophysical methods and satellite data. As we mentioned in the response to comment #25 above, many of these methods can be used to collect data at various scales, while some indeed are point methods only (e.g. permeameter tests or 1-D temperature profiles).

27. L797f: Please mention here also that time series that might be recorded with loggers can be very useful to gain system understanding because groundwater-surface water interactions might vary with time and even the flow direction might reverse over time.
<u>Response:</u> Indeed, this is an important point to make. In this section of the manuscript, we intended to illustrate this with the example of temperature time series data in L890-891, but in the revised manuscript we have added an additional sentence here to make it clearer that time series data for a range of parameters can be very useful to observe changes in groundwater-surface water interactions over time. The added sentence at L892 reads: “In addition to temperature, many parameters can be collected as time series (e.g., water levels, hydrochemistry), which may be very useful for interpreting temporal changes in groundwater-surface water exchange.”

28. L849: It is definitely strange to have a subchapter 3.1 but no 3.2. Also, it is confusing that the introduction before 3.1 is about 5 pages long and 3.1 less than 1 page long.

Response: Thank you for highlighting this. We have changed the numbering of Section 3.1 (Key gaps and possibilities) to Section 4.

MINOR COMMENTS

29. L48: Cite also Winter et al. (1998) (https://pubs.usgs.gov/circ/circ1139/)

Response: Thank you for the relevant suggestion. This reference has been added to the revised manuscript (L48).

30. L102f: Why is improved knowledge of historical patterns needed? In addition, can you please cite a reference.

Response: Better knowledge of historic states and patterns of braided rivers would be very helpful for understanding the implications of modifications to natural systems in order to set water allocation limits and minimum flow levels in rivers (Riegler, 2012; Burbery et al., 2010). For example, many irrigation schemes have artificially raised groundwater levels due to land surface recharge, or lowered groundwater levels due to abstraction in comparison to their natural (pre-irrigation) states. In some rivers this has affected the losing/gaining patterns. A comment in this regard (with references) has been added to the revised manuscript.

31. L118: A more scientific reference would be great here.

Response: The reference has been replaced at L134 by references to Caruso (2006); Larned et al. (2008); Tockner and Stanford (2002), which are all peer-reviewed publications in international journals.

32. L147: Consider adding Rosenberry et al. (2015) (https://onlinelibrary.wiley.com/doi/full/10.1002/hyp.10403)

Response: This is a very useful reference, and we have added it to the revised manuscript, along with Brunner et al. 2017, which is a useful review of the latest advances in methods for characterising and modelling river and groundwater interactions and specifically mentions braided streams in some parts.

33. L279: I think what is much more important than evenly distributed groundwater discharge or recharge is an even groundwater concentration.

Response: Thank you for the suggestion, and we agree that amending the wording would be more accurate. The wording at L313-315 has been changed to "This type of analysis assumes there is an evenly distributed groundwater concentration between sampling locations and that there is complete mixing of water sources."

34. L289ff: Please correct: there are three stable oxygen isotopes including O-17!

Response: Thank you for highlighting this oversight. Oxygen-17 has been added to this discussion of stable oxygen isotopes at L326.

35. L291f: "The process is largely driven by temperature, whereby … at higher elevation due to colder temperatures" The process is not driven by elevation but the elevation effect is a result of decreasing temperatures with increasing depth. In case you really want to mention processes in addition to temperature you can add humidity and salinity as further processes.

Response: Thanks for pointing this out. At L328, we have amended this sentence to read: "The process is largely driven by temperature, humidity and salinity, whereby precipitation is increasingly depleted in ^{18}O at colder temperatures (which tend to occur at higher elevations) (Sharp, 2007)".

36. L519: I think the most important point that should be measured here is season!

Response: Thank you, this has been added to the revised manuscript at L580.

37. L560: Only deep wells/piezometers are expensive.

Response: Agreed. We have amended the text to reflect that cost of installing wells or piezometers may only be prohibitively high in some situations.

38. L565: Isn't this also a conceptual diagram of a well?

Response: As detailed in our response to comment #22 above, we have modified the text at L619 so that it is clear that we consider piezometers to be monitoring wells. We have also made it clear that mini-piezometers are small versions of piezometers at L624. In light of this we think that the labelling of this figure as a conceptual diagram of a mini-piezometer is no longer confusing.

39. L656: You might want to mention that it is nearly impossible to take undisturbed cores/rings for KSat analysis if the sediment contains coarse gravel as this is the case in most braided streams.

Response: Thank you. We have added a sentence to this effect at L728: "In particular, taking undisturbed cores of sediments containing gravel, as most braided rivers do, is nearly impossible."

40. L 674: "interactions" instead of "interaction"

Response: Thank you. The text has been amended at L747.

41. L687: Delete: "and will not be repeated here."

Response: Thank you. This text has been deleted at L760.

42. L704: "They used" instead of "The used"

Response: The text at L783 has now been removed.

43. L754: You are not investigating groundwater and surface water but their interactions:

"… for investigation of groundwater-surface water interactions, and there …"

Response: Thank you for recognising this error. The text has been amended at L842 to: "There are many factors to consider when selecting the appropriate method(s) for studying groundwater-surface water interactions."

44. L764: "a study" instead of "the study"

Response: Thank you. This change has been made at L852.

45. L808: "by the study objective and the study object

Response: The text at L899 has now been removed.

46. L820: Only during storms???

Response: This is a fair point. Our intention in specifically mentioning storms was to highlight mass sediment movement during flood events, but indeed, sediment transport at other times may equally damage equipment. The mention of storms at L911 has been removed.

47. L851: "One of the most …" – I do not understand this sentence.

Response: In the revised manuscript we have amended L942-944 to the following: "There is limited understanding of how hyporheic flow processes operate, and how they impact river flow levels and water quality in braided rivers."

48. L854: Consider adding here S. Krause, D. M. Hannah, J. H. Fleckenstein, C. M. Heppell, D. Kaeser, R. Pickup, G. Pinay, A. L. Robertson, and P. J. Wood. Interdisciplinary perspectives on processes in the hyporheic zone. Ecohydrology 4 (4):481-499, 2011.

Response: This is an excellent suggested reference and has been added at L62 and L945.

49.   L869: the present paper

Response: This suggested text has been added at L960.

50.   L895: You might add here DTS and geophysics

Response: We agree, and we have added fibre-optic DTS and geophysics at L1049.

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<u>Reply to Reviewer #2</u>

We thank Reviewer #2 for the helpful review and have responded to each comment below. All line numbers in our responses refer to the revised marked manuscript.

1. While the paper points out challenges in measuring gw-sw interaction, including a nice summary table by method, the challenges do not link up with the specific issues in braided rivers. In other words, the challenges would apply to all river types. For instance, the authors mention how heterogeneity makes it difficult to measure flow. While braided streams may be more heterogeneous (however that is defined), all streams would benefit from methods that address heterogeneity. I would have liked to see how the cross-sectional heterogeneity (in contrast to along reach) impacts measurement techniques. That said, Genereux's group has some papers illustrating both along-reach and cross section variation in streambed K, so even this aspect is not unique to braided rivers. The advantages and disadvantages sections list challenges that would apply to other stream types as well. The abstract and conclusions emphasize the need for multiple methods and consideration of scale in selecting methods, but again these recommendations apply to any river type. Without details about why a particular method works elsewhere but not on braided rivers, the paper lacks focus. It does not suffice to say a method is "more difficult" when it is difficult in a variety of river settings.

<u>Response:</u> Thank you for the constructive feedback. We agree that many of the challenges of conducting studies in braided rivers are also present in other river environments. However, in braided rivers these challenges tend to occur to a larger degree. We have attempted to convey this within the introduction and particularly in the paragraph at L151. However, we agree that this point can be made with greater clarity and we have revised the introduction in order to do so.

During the process of writing the review paper, we critically examined all published studies we could find on measuring groundwater-surface water interactions in braided rivers. We looked at all of the techniques used in these studies and attempted to summarise for the reader what was effective and what was not. In terms of a particular method that works elsewhere but likely not in a gravel-bed braided river, we specifically mention seepage meters in L862-867. However, we believe we can improve the manuscript in this respect, for example we can discuss how there have been various designs of mini-piezometers used in rivers, but many of these designs would be unlikely to be effective in gravel-bed braided rivers, which is why we point the reader to studies where they have been deployed successfully. Flow gauging for calculating catchment or reach-scale water budgets is another method that may be effective in other river environments but is very challenging in braided rivers. For example, because of the errors associated with flow gauging, it is very difficult to estimate losses or gains in reaches with a sufficient degree of accuracy. Flow gauging does not differentiate between groundwater inflow and hyporheic water re-emerging in streams, and given the significant portion of flow in braided rivers that occurs within the riverbed, this is an important issue to consider. As another example, it is very difficult to take undisturbed core samples for hydraulic conductivity tests when the river substrate contains coarse gravels, as gravel-bed braided rivers do.

2. The paper provides a map of locations with braided streams, but does not justify why these locations are included and not others. The definition of what "concentrated" means in terms of distribution of braided streams is not provided. There is a list of braided streams in the US on https://commons.wikimedia.org/wiki/Category:Braided_rivers_in_the_United_States_by_state*, which suggested that braided rivers are important in the US too, yet no sites there are listed. To list the map as a significant feature of the paper ("to the authors' knowledge, this is the first map of its kind") but provide no details on how the map was generated is frustrating to the reader.*

Response: Thank you for your feedback on Fig. 1. We agree that the term "concentrated" is ambiguous and we have replaced it in the text at L27, L70 and L1034 with "mainly found". This conforms to wording used in our justification for only displaying a selection of regions where braided rivers occur, at L71-75: "There are instances of braided rivers at locations outside of these regions (e.g., the U.S., Scotland, Iceland, China, Poland, Belarus, Colombia, Congo, Brazil, Paraguay, Argentina, and the Touat Valley in Africa); however these locations are not shown in Figure 1 because, at a global scale, they are not where braided rivers are mainly found." To further justify our selection of locations displayed, we have added the following sentence to the manuscript at L75: "The regions displayed in Figure 1 are regularly cited in literature on braided rivers as the main regions where this river type can be found (e.g., Tockner et al., 2006; Hibbert & Brown, 2001)." We have added Russia to Fig. 1 based on comments in studies (Chalov & Alexeevsky (2015), Alexeevsky et al. (2013)) about the high number of braided rivers in the country.

In regard to braided rivers in the United States, we respectfully point to L72, where we did mention the U.S. containing braided rivers. Thank you for pointing to the Wikipedia link (https://commons.wikimedia.org/wiki/Category:Braided_rivers_in_the_United_States_by_state), however it does not appear that this is a reliable authority on instances of braided rivers in the U.S. The webpage is a list of user-generated images that have included tags with the wording “braided river”, however many of the images shown here do not appear to be of braided rivers (e.g. on the pages for Alabama, Virginia, Utah and Massachusetts).

3. The word “hyporheic” only appears in the abstract and end of the paper, not in the main body. This mention in the abstract should be removed since it is not a topic covered in the paper. It is probably better left to another paper as the issues in measuring hyporheic flow differ significantly.

Response: Thank you for your comment, however the term “hyporheic” was mentioned 16 times throughout the original manuscript, and it was specifically discussed in conjunction with several of the cited studies. We believe this review would be significantly lacking if we did not include information on hyporheic flow processes. As we have noted at L113, issues surrounding hyporheic zone processes are of great importance in the management of braided rivers. There is a significant amount of river flow that occurs within the hyporheic zone in braided rivers. Further, as highlighted at L426, L568, L880 and L946, it is often difficult to distinguish between regional groundwater discharge into rivers and re-emerging river water from the hyporheic zone. While this is an issue that would be faced in other river environments, it is likely that this is more of an issue in braided rivers which 1) have highly permeable river bed strata, and 2) have a significant amount of river flow that occurs within the streambed. As Reviewer #1 highlighted (see comment #9), we need to clarify what we mean by hyporheic flow and the hyporheic zone, as well as better explain the related research gaps. We have addressed this at L60-65 and L113-114.

4. The modeling discussion is focused too much on MODFLOW. The description of MODFLOW packages can be found elsewhere and there are other models that incorporate *groundwater-surface water interaction that could be discussed. For example, a recent special issue in Groundwater on integrated modeling included a paper on streambed heterogeneity. There is also a recent review paper on modeling gw-sw interaction in Reviews of Geophysics that provides a broader view. The abstract mentions the need for new approaches in modeling, but the paper does not provide sufficient direction to justify this as a conclusion of the paper. The conclusion the models need more data and more sensitivity analysis has been stated many times before.*

Response: In the review we focused on MODFLOW as this is the code that most previous studies have used to model groundwater-surface water exchange in braided rivers. We agree that the description of MODFLOW packages can be found elsewhere and in the revised manuscript we have removed these details. Sentences from L749-760 have been replaced with the following: “Several packages are available in MODFLOW for simulating surface water-groundwater interaction and further details about the application and limitations of these can be found in Brunner et al. (2009, 2010).”

We agree that it would be helpful to include specific recommendations on new approaches to modelling including codes (such as HydroGeoSphere) and methods such as those detailed in Brunner et al. (2017). We have addressed this in section 4 of the revised manuscript at L955-L1025.

5. I was surprised that fiber optic temperature systems (also known as DTS for distributed temperature systems) and geophysics were not discussed. These methods have been mentioned in other reviews and provide broader coverage which might benefit braided streams. I found it odd to bring up thermal imaging for the first time in the discussion section rather than in the review of methods, especially since it is mentioned in the abstract and it is one of the more promising techniques for heterogeneous systems. An example of the benefits of thermal imaging might provide an interesting figure.

Response: Thank you for your suggestions. We agree that the manuscript would benefit from discussing geophysical techniques and DTS as possible methods to apply in braided rivers. In section 4, we have added more detail on additional methods that can be applied in braided rivers.

6. On the topic of figures, the figures were lacking in illustrative examples of applications. There was a map, but the other figures were photos or diagrams and didn't show quantitative challenges or opportunities. In other words, I think it would help the readers' understanding to include data figures.

Response: For the sake of brevity, we have decided not to add additional figures to the manuscript.

7. One place that the paper focuses on braided streams is the literature review of methods. The paper summarizes applications in braided streams and the table of methods lists braided stream citations. However, the literature summary sections of the paper are a bit dry. They list highlights of each paper one after another. I think some of these papers could be describing non-braided streams and the reader would not know. This type of literature review needs to be briefer and provide synthesis of issues specific to the problem identified. In addition, a significant number of references (estimated 25% based on the first page of the bibliography) are not readily available literature but reports or theses (typically from NZ). Many readers will not have ready access and the focus on one region is not justified.

Response: We agree that it would be beneficial to shorten the sections that discuss prior literature, and we have addressed this in the revised manuscript by deleting sections at L204-214, 220-229, 256-276, 280-284, 336-352, 360-365, 384-387, 392-407, 412-417, 445-452, 457-459, 467-476, 512-543, 548-564, 585-589, 641-643, 655-656, 661-663, 694-695, 700-704, 749-760, 768-803, and 808-816.

We endeavoured to make it clear through the introduction that the review focuses on braided rivers, so that if there were other types of rivers discussed, we would specifically note this. We have added a sentence to this effect in the introduction at L90: "it is important to note, the specific rivers discussed in this article are all braided rivers unless otherwise mentioned".

In regard to technical reports and theses that have been cited, the referencing requirements for the journal's publisher did not stipulate for URLs to be included with these reference types. However, based on the reviewer's recommendation and for the benefit of readers, we have included URLs where relevant in the reference list of the revised manuscript. We have also removed the following references that are not publicly available: Anderson (2004), Davey (2004), Aitchison-Earl & Ritson (2013), Williams & Aitchison-Earl (2006).

We realise that there is a heavy weighting on studies conducted in New Zealand and this is not intentional by any means. The vast majority of published studies on this topic that we were able to find were based in New Zealand. In fact we chose not to discuss several New Zealand studies in the methods section as we felt studies from this country were over-represented. Through the process of gathering literature, we did consider possible reasons for the apparent over-representation of New Zealand studies. We considered that search engine results may have been weighted to display New Zealand studies as the authors were based in New Zealand. To assess whether this was the case, in addition to more general searches, we specifically searched for literature in countries or regions (e.g., Italy) where braided rivers are common. This search method produced some, but not many, additional relevant references. Further, the majority of search engines used were via scientific indexing sites (e.g., Web of Science), which to the authors' knowledge, do not tailor search results in the way that Google does. We do acknowledge that we are likely to have missed literature published in languages other than English, but this issue is likely not unique to our review.

8. It can be difficult to meet the standards of a review article. In the end, I ask myself whether I would give this paper to colleagues to read, or just keep recommending Kalbus et al. or LaBaugh and Rosenberry as review papers on the topic. I do not think there is enough new material here for me to consider this paper to be an update on the earlier papers. If revising, I would recommend a very short review paper, which introduces Table 1 and gives the reader the reference list for readers to select topics on their own (rather than the one line summaries of each paper). The shorter paper also needs to provide the reader with an approach to braided streams that is distinctly different than other streams – this message will take additional synthesis and thus I would consider it to be a new paper rather than a resubmission. Hence, I am recommending rejection and significant redirection for any new submittal.

Response: We are grateful to the reviewer for their constructive comments. While there have been a number of review papers on surface water-groundwater interaction, none have focused on braided rivers previously and this is the gap we are wanting to address. We would argue that braided rivers have features that are unique enough to warrant a review paper that focuses on this river type specifically. As detailed above, we have revised the introduction to clarify the unique characteristics of braided rivers (L157-173). We have shortened the review of previous studies in Section 3 and increased our use of Table 1 to provide guidance to the reader, as suggested. Also, we have expanded section 4 to enhance the novelty of the paper by suggesting emerging and promising techniques being used in other environments and that are likely to have application in braided rivers.

We have had very positive feedback on this manuscript from numerous groundwater researchers and managers within our networks and we hope that by using the guidance provided by the reviewer we have addressed the reviewer’s concerns within the revised manuscript.

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