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Conceptualising surface water-groundwater exchange in braided river systems

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Abstract. Braided rivers can provide substantial recharge to regional aquifers, with flow exchange between surface water and groundwater occurring at a range of spatial and temporal scales. However, the difficulty of measuring and modelling these complex and dynamic river systems has hampered process understanding and the upscaling necessary to quantify these fluxes. This is due to an incomplete understanding of the hydrogeological structures which control river-groundwater exchange. In this paper, we present a new conceptualisation of subsurface processes in braided rivers based on observations of the main losing reaches of three braided rivers in New Zealand.

The conceptual model is based on a range of data including: lidar, bathymetry, coring, particle size distribution, groundwater, temperature monitoring, radon-222, electrical resistivity tomography, and fibre optic cables. The combined results indicate that sediments within the recently active river braidplain are distinctive, with sediments that are poorly consolidated and better sorted compared to adjacent deposits from the historical braidplain, which become successively consolidated and intermixed with flood silt deposits due to overbank flow. A distinct sedimentary unconformity, combined with the presence of geomorphologically distinct lateral boundaries, suggests that a "braidplain aquifer" forms within the active river braidplain through the process of sediment mobilisation during flood events.

This braidplain aquifer concept introduces a shallow storage reservoir to the river system, which is distinct from the regional aquifer system, and mediates the exchange of flow between individual river channels and the regional aquifer. The implication of the new concept is that surface water-groundwater exchange occurs at two spatial scales. The first is hyporheic and parafluvial exchange between the river and braidplain aquifer. The second is exchange between the braidplain aquifer and regional aquifer system. Exchange at both scales is influenced by the state of hydraulic connection between the respective water bodies. This conceptualisation acknowledges braided rivers as whole "river systems", consisting of channels, and gravel aquifer.

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This work has important implications for understanding how changes in river management (e.g., surface water extraction, bank modification and gravel extraction) and morphology may impact groundwater recharge, and potentially river flow, temperature attenuation, and ecological resilience during dry conditions.

1 Introduction

This study is motivated by the need to understand processes and quantify losses from braided river systems to alluvial aquifers. In New Zealand more than 150 river systems are thought to have braided reaches (Brower et al., in press), which provide a substantial component of recharge to alluvial aquifers. For example, in the case of the Wairau Aquifer, it has been estimated recharge is sourced almost exclusively from the Wairau River (Wöhling et al. 2018).

Braided rivers are spatially complex, dynamic hydrologic environments which are not easily measured using field techniques or represented by numerical models. The determination of flow exchanges between the river and groundwater in such a hydrologically complex and morphologically dynamic environment is difficult because of their spatial and temporal flow complexity, numerous and changing number of channels, dynamic bathymetry, coarse substrate, and tendency for loss of field installations during high flow events. The complexity of this challenge demands a collaborative effort that leverages the strengths of a diverse range of disciplines to develop a comprehensive and holistic understanding of the problem.

Many authors have studied surface-aquifer exchanges, and several reviews have been conducted on available techniques for measuring exchanges for alluvial rivers in general (Kalbus et al. 2006, González-Pinzón et al. 2015, Brunner et al. 2017), ephemeral rivers at different spatial scales (Banks et al., 2011, Shanafield and Cook 2014), and braided rivers (Coluccio and Morgan, 2019). Based on these reviews, there is a tendency for previous studies to focus on quantifying exchange fluxes prior to understanding the hydrological processes that influence the exchange. Ward and Packman (2019) suggest that despite the large amount of research on river-groundwater exchanges, an accurate predictive, transferable understanding of the river corridor is lacking. Indeed, a conceptualisation of how braided rivers relate to their underlying groundwater systems is lacking (Coluccio and Morgan, 2019). This has led to ambiguity in what measured exchanges represent, and some difficulty in trying to represent braided rivers within aquifer scale models.

The aim of this paper is to formulate a conceptualisation of braided river exchange processes at both the local (reach) and sub-catchment (aquifer) scale. This conceptualisation provides a framework for both providing context for field measurements of flow exchange to be interpreted, and the potential for representation of local scale processes in sub-catchment models. Incorporating these local scale processes is vital to predict how changes in the river system can impact groundwater recharge. The conceptualisation presented here was developed based on field observations but, for clarity of explanation, we introduce the conceptual framework first and then present the supporting evidence. Our working definition for hyporheic exchange is local bed-scale interaction that occurs within a single channel (e.g., a single riffle), whereas parafluvial exchange occurs between individual channels at larger scales (across a bar or further). We also distinguish between a river as a series of wetted channels, and a "river system", which consists of wetted channels plus subsurface flow through the associated braidplain gravels. “Braidplain” refers to the lateral extent occupied by the river braids, old bar surfaces and abandoned channels (Warburton, 1996; Gray et al., 2016; Brower et al., in press). The extent of wetted channels and recently reworked bed material (bare gravel) at a given point in time defines the “active braidplain”, which also has potential to shift laterally. Lateral adjustment of the active braidplain may be limited by hillslope margins, terraces or, in managed rivers, by rock revetments or artificial stop banks (levees) which are typically protected with vegetative buffers. We refer to the extent within which our study rivers can currently adjust as the “contemporary braidplain”, acknowledging that in two of our study rivers (Wairau and Ngaruroro) the contemporary braidplain margins are controlled by engineered flood defences which have narrowed the natural braidplain such that almost the entire contemporary braidplain is active.

2 Overview of existing hydrological concepts

The prevailing conceptualisation for gravel bed rivers in general consists of a surface channel with an associated bed with some hydraulic resistance (Schälchli 1992, Wu and Huang 2000) which exchanges water with an associated fluvial or alluvial aquifer (Stanford and Ward 1993, Poole and Berman 2001). Within the alluvial aquifer lies a hyporheic zone which functions as an interface between groundwater and surface waters (Stanford and Ward 1993, Poole and Berman 2001, Boano et al. 2014). The extent of the hyporheic zone is defined by its function or process of interest, which can be physical, chemical, biological, or a combination of functions (Ward 2015). Accordingly, the vertical or lateral boundaries of the hyporheic zone are transient and flexible, and not easily defined spatially (White 1993, Boulton et al. 1998, Ward 2015). From a hydrological perspective, the hyporheic zone has been defined as the extent to which surface water enters the high porosity subsurface beneath and lateral to a stream and returns to the stream surface farther downstream (Harvey and Wagner, 2000). Authors have suggested the hyporheic zone as extending from the upper few centimeters of sediment (Boulton et al. 1998, Sophocleous 2002) to larger scales (km^3) constituting a hyporheic corridor (Stanford and Ward 1993). Valett at al. (1996) predict the extent of the hyporheic zone to be related to catchment lithology, with interaction being more extensive in sites with higher alluvial hydraulic conductivity, whereas Boano et al. (2008) predict the infiltration depth to be related to bedform for any given hydraulic conductivity.

An additional, ecological, concept is that of a riparian zone (Steiger et al. 2005). This extends river margins beyond the active channel to include the biosphere supported by and including recent fluvial landforms and inundated or saturated by bank discharge (Hupp and Osterkamp 1996). Other authors have considered the presence of a parafluvial zone situated between the hyporheic zone (beneath the river channel) and riparian zone (Holmes et al. 1994) which accommodates longer flow paths within the alluvium adjacent to the stream (Bourke et al. 2014, Cartwright and Hoffmann 2016). Our interpretation of the parafluvial zone is that it constitutes exchange flow within the alluvial aquifer at spatial and temporal scales beyond what is considered hyporheic.

From a hydrological perspective of braided rivers, the framework that emerges from the prevailing concepts is one where river-groundwater exchange occurs within an alluvial aquifer which conveys both hyporheic and parafluvial flowpaths. The

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proportion of these flowpath components theoretically depends on the degree to which there is net loss or gain in river channel flow. However, the interpretation of river-groundwater exchanges becomes challenging in a braided river which comprises multiple channels within an alluvial aquifer. Harvey and Gooseff (2015), Barthel and Banzhaf (2016) and Ward and Packman (2019) propose that exchange fluxes be considered at different spatial scales: point, local, sub-catchment, and regional. Following this approach, exchange within individual river braids or channels can be considered to occur at the point-scale, and the sum of all braids within a river reach as a local-scale interaction. While process understanding can be observed and fluxes quantified at the point and local scale, it is imperative to enable an upscaling of observed processes so that fluxes can be estimated for at least the sub-catchment (aquifer) scale.

Previous work on subsurface structure in braided rivers has tended to focus on the role of bed material heterogeneity. A significant body of literature exists to describe braided river deposits via morphology (Huber and Huggenberger 2015), sedimentology (Huggenberger and Regli 2006, Theel et al. 2020), geophysics (Pirot et al. 2019), and modelling approaches (Pirot et al. 2014; 2015, Brunner et al. 2017). To date, no conceptual model has been posed for how a braided river and its associated braidplain gravels (alluvial aquifer) relate to those of the underlying regional aquifer. While the structural components of river-groundwater interaction have been identified by previous authors (e.g. Poole and Berman 2001, Steiger et al. 2005), the identification of clear spatial boundaries between structural elements has been missing. From a hydrological perspective of understanding surface water-groundwater interaction, this creates a problem of where the river system ends, and where the regional groundwater system begins. The uncertainty related to this lack of spatial definition transfers to the interpretation of field data, whether a sample is representative of river channel flow, alluvial aquifer (hyporheic or parafluvial zones), or regional groundwater. Consequently, representation of braided rivers in numerical models is problematic since their complexity is not readily captured by a simple conceptualisation. Water exchanges can potentially be simulated realistically using a fully coupled hydrological model such as HydroGeoSphere (Therrien et al. 2010, Brunner and Simmons 2012). However, the data required to parametrise such a model, and the computational demands of the detailed mesh required to simulate exchanges in braided rivers make this approach only suitable for point and local scale studies. Furthermore, braided river morphology is so dynamic that a new bed morphology would be required following each significant flood event. This limits the use of fully integrated 3D models in braided rivers to periods of stable bathymetry.

The simple river structure offered by the Streamflow-Routing (SFR, Niswonger and Prudic, 2005) and River (Harbaugh, 2005) packages in MODFLOW represent the river as a flux boundary condition with vertical flow impedance in the bed expressed by a lumped parameter termed 'streambed conductance'. Previous authors have shown that the concept of a streambed resistance concentrating all pressure losses, as implemented in MODFLOW, is questionable in many cases (Anderson 2005, Rushton 2007, Morel-Seytoux et al. 2018, Di Ciacca et al. 2019). Moreover, even if such a streambed exists, a major physical issue with a lumped parameter approach is that streambed conductance values in the field are not homogenous, but vary spatially (Cardenas and Zlotnik 2003, Zhou et al. 2014, Pryshlak et al. 2015, Laube et al. 2018) and temporally (Levy et al., 2011, Wu et al. 2015). In a braided river, bed material typically consists of a heterogeneous mixture of cobbles, gravels, and sands, which can have similar characteristics to alluvial sediments located several metres beneath the bed. Therefore, the streambed conductance concept seems inappropriate to represent surface water-groundwater exchange in braided river systems.

Different modelling approaches have been trialled to represent braided rivers in New Zealand. White et al. (2012) carried out a steady state water balance approach to determine flow losses for a reach of the Waimakariri River. Exchanges between individual channels and the adjacent alluvial aquifer were determined via mass balance, although the subsurface components of the exchange were not explicitly described. An alternative approach by Wöhling et al. (2018, 2020) simulated dynamic Wairau River exchanges at the sub-catchment scale using MODFLOW. In this case, the braided nature of the river was not considered, and the river was represented by the SFR package using a stage-width-flow relationship derived from a representative channel morphology. While this model fitted river flux and groundwater level data well, the approach employed a streambed conductance model, which is difficult to reconcile with the river morphology and bed sediment seen in the field. A particular drawback of the SFR package is its inability to represent the hyporheic or parafluvial exchange fluxes observed at the point or local scale. While the Waimakariri and Wairau modelling studies are relatively comprehensive, in both cases, an understanding of subsurface structure is missing from the river representation. This lack of knowledge about the structural controls on subsurface flow in the braided river environment needs clarification to understand what measured and modelled river-groundwater exchanges represent. In doing this, a more physically realistic method for representing braided rivers in numerical surface water-groundwater flow models may be achieved.

3 Proposed Conceptualisation

A conceptual framework is proposed which captures the key elements of water exchanges in a braided river system. This conceptualisation builds on the previous work of Fox and Durnford (2003) and Brunner et al. (2009a and b) and recognises that the hydrological controls on river-groundwater exchange occur at two distinct interfaces within a braidplain system. Specifically, these two exchange processes can be summarised as:

1. River channel ↔ braidplain aquifer (hyporheic and/or parafluvial exchange)
2. Braidplain aquifer ↔ regional aquifer (“river system” - groundwater exchange)

The first exchange interface is within the active braidplain, and occurs between individual river channels (braids) and the local shallow water-table in the river bed sediments, and occurs at the point or local scale. We term the water stored within these river bed sediments the “braidplain aquifer” (BPA), which facilitates hyporheic and parafluvial flow. Individual braids can be in hydraulic connection (gaining or losing), disconnection, or a transitional state relative to the BPA. At the active braidplain interface, all possible river exchange processes can occur regardless of the hydraulic relationship between the BPA and surrounding regional water table. The second exchange interface occurs at both the local (reach) and sub-catchment (aquifer) scale, between the BPA and regional water table. Central to this conceptualisation is the presence of a distinct BPA immediately beneath the river surface which facilitates exchange at these two interfaces. A similar term “braided-river aquifer” has been used by previous authors (Pirot et al. 2015), although we have not found an associated definition. The BPA functions as a

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storage medium to exchange water between the river and regional aquifer in braided river systems. Direct exchange of water between the river and regional aquifer can only occur if the river channel is in direct contact with the regional aquifer (i.e., where the surface water extends to the boundary of the BPA, for example where a channel follows the lateral margin of the BPA, or there is a connection at the base of a deep scour pool). A key feature of the BPA is its extremely high transmissivity, which is a product of the highly dynamic nature of braided rivers. Bedload transport during flood events causes braids to form, migrate, and be abandoned; processes that re-work the river bed sediments (Bristow and Best, 1993; Reinfelds and Nanson, 1993). This reworking process strips most fine sediment (silts and clays) from the river bed, as the shear stresses during floods are too high for these size fractions to be deposited except in vegetated areas and backwaters. The result is a braidplain deposit of high transmissivity lag gravels. High transmissivity combined with the relatively large bed slope of braided rivers and the presence of multiple braids for water exchange produces a groundwater flow path which is sub-parallel to the contemporary braidplain, regardless of the regional groundwater flow direction.

Conceptual diagrams have been drawn for situations where the BPA is hydraulically disconnected from (Fig. 1a), and connected to (Fig. 1b) the regional aquifer. The first case (Fig. 1a) consists of three functional lithological layers representing a BPA which is hydraulically disconnected from an underlying regional aquifer by an unsaturated zone. In this case, water moves vertically from the BPA to the regional aquifer under a unit hydraulic gradient. A minimum of three layers is required for an unsaturated zone to develop (Fox and Durnford, 2003), and there must be a sufficient transmissivity contrast between the impeding horizon and underlying sediments (Brunner et al., 2009a and b). It should be noted that braided river deposits are lithologically variable and complex, and in most cases only two functional layers are required due to stratification in the underlying sediments.

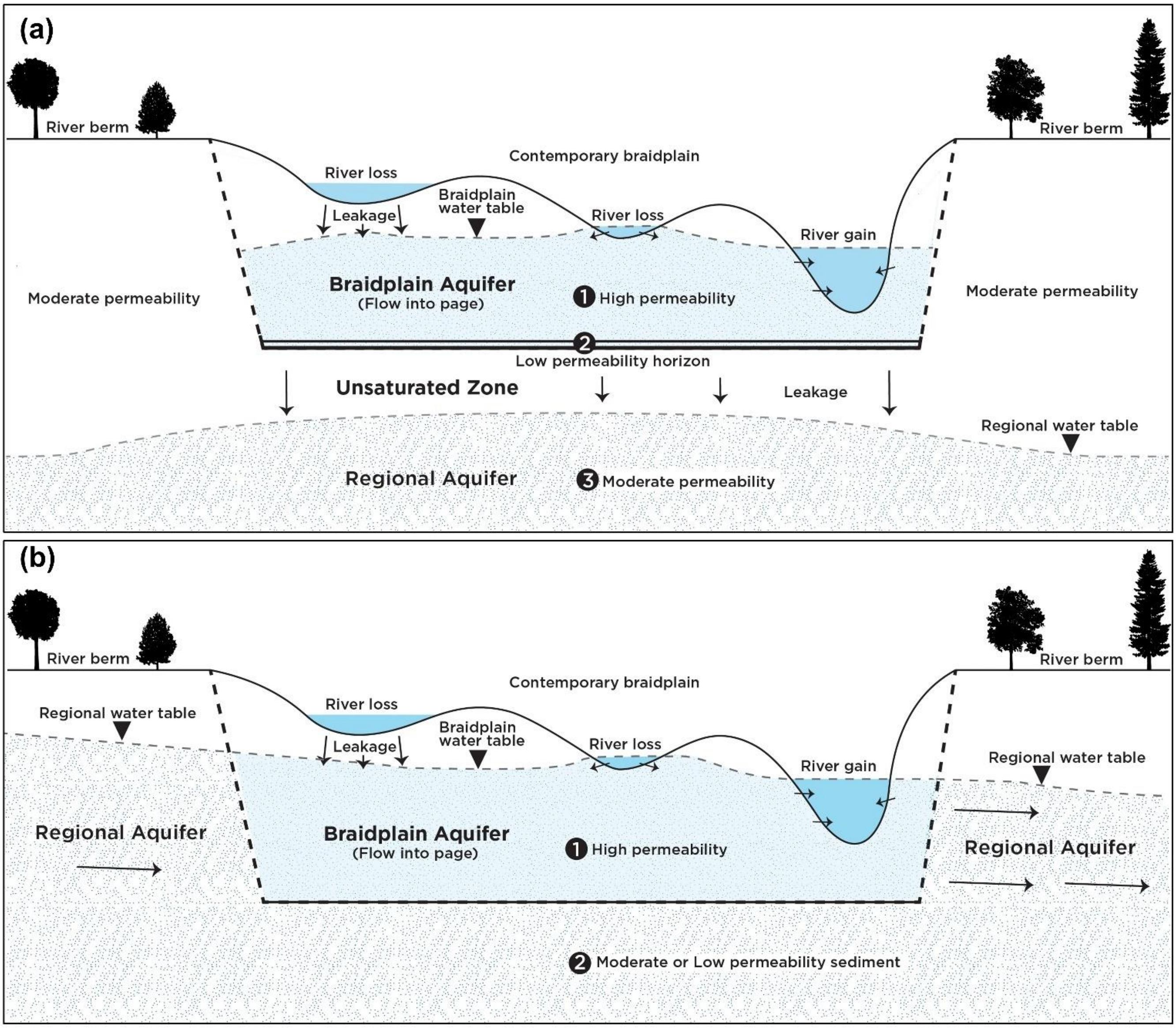

Figure 1: Conceptualisation for a braidplain aquifer which is (a) hydraulically disconnected from or transitional with the regional groundwater system, and (b) hydraulically connected to the regional groundwater system.

A hydraulically disconnected river system setting shares features in common with intermittent or ephemeral rivers (Shanafield et al. 2021). Infiltration to the regional aquifer is regulated by the vertical resistance of lower permeability sediments and the hydraulic head in the BPA. If the BPA is fully saturated across the contemporary braidplain, the rate of infiltration to the regional aquifer will be steady because the braidplain has reached a maximum wetted area. In this condition, some minor temporal infiltration variability will occur due to changing water levels in the BPA. Under ephemeral conditions, the saturated

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extent of the BPA decreases longitudinally, and locally laterally, during drying phases in response to extended periods of low river flow. The combined reduction in head and saturated area of wetted braidplain result in considerably less infiltration to the regional aquifer (Di Ciacca et al. 2023).

The second case is a setting where the river is hydraulically connected to the regional aquifer system (Fig. 1b). A minimum of two lithological units are present, a high transmissivity BPA and regional aquifer (1) overlying less permeable sediments (2) which impede vertical flow. The combination of these two factors creates an anisotropy, with preferential flow in the lateral direction. Hydraulically gaining conditions will occur in situations where regional water levels are elevated by low permeability boundaries (i.e., the presence of bedrock) on one or both sides of the river, or at middle to distal positions on alluvial fans where regional groundwater levels are closer to the land surface. For a hydraulically connected river system (braids + BPA), the hydraulic gradient is no longer vertical, as it is for the hydraulically disconnected scenario, but variable, with the exchange rate governed by the relative hydraulic gradient between the braidplain and regional aquifers. Thus, groundwater inflow to the BPA or discharge to the regional aquifer can occur laterally along both margins of the braidplain, as well as vertically through BPA base. The setting can also be asymmetric, with inflow on one margin, and outflow on the other (as shown in Fig. 1b), with the total river system water balance being gaining or losing or having no flow along one margin due to the presence of bedrock. While the hydraulically connected situation is simpler structurally, relative to the disconnected situation, exchange between the braidplain and regional aquifers is more complex. In this case (Fig. 1b), water exchange is governed by the hydraulic gradient between the two aquifers, the transmissivity of both aquifers, and the vertical hydraulic conductivity of the underlying sediments. Once water exits the BPA in a losing reach, it will not return unless it is re-routed back to the river system by a reversal of the hydraulic gradient.

In both settings, the braidplain gravels have a higher transmissivity than both the adjacent and underlying sediments, because of repeated reworking of the braidplain gravels during high flow events. Hyporheic and parafluvial flow occurs within these highly transmissive BPA sediments, subparallel to the river flow direction, with individual braids acting as recharge or discharge boundaries. As such, the local hydraulic gradient and groundwater flux are largely influenced by river bathymetry.

4 Locations and methods for concept validation

4.1 Catchment descriptions

The conceptualisation presented here is founded on field observations of the main losing reaches of three braided rivers in the drier eastern part of New Zealand (Fig. 2). These are, from north to south, the Ngaruroro (a), Wairau (b), and the Waikirikiri (c, also known as the Selwyn). These study areas were selected to take advantage of the potential for hydrological separation afforded by dominantly losing river reaches. The downward hydraulic gradient, and potential hydrological separation between channel, bed gravels and regional aquifer enables the possibility for different structural and hydrological components to be identified. Summary hydrological and geomorphological statistics for the three study sites and their source catchments are shown in Table 1.

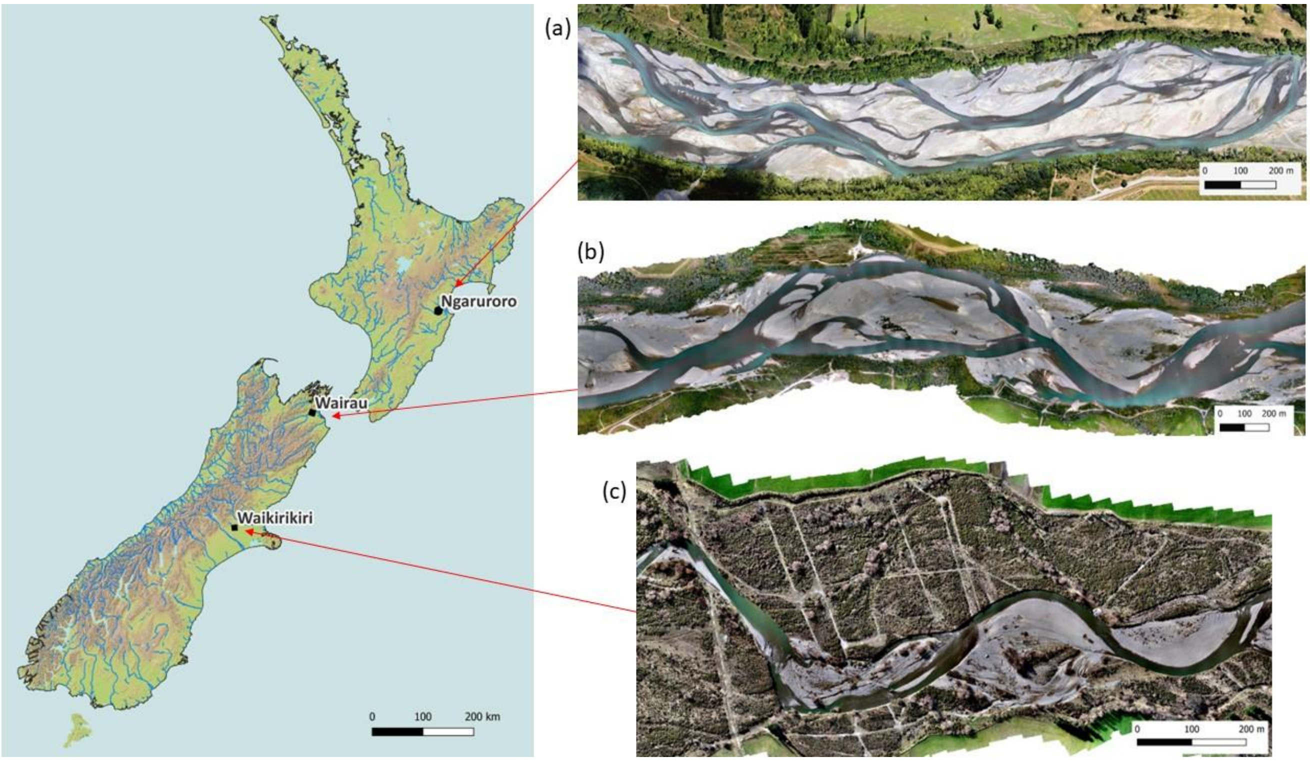

Figure 2: Location of the three study rivers and their aerial images

The Ngaruroro River is 164 km long, and has its headwaters in the Kaweka, Kaimanawa, and Ruahine ranges on the main divide of the North Island. The 3-km long study reach is located at the margin of the Heretaunga plain between Roy's Hill and Fernhill and is the main recharge source for the Heretaunga alluvial aquifer system (Dravid and Brown, 1997). A long-term flow monitoring site at Fernhill (70 years), situated at the lower end of our study reach, has recorded a mean flow of 40 $m^3.s^{-1}$ and mean annual peak flow of 1546 $m^3.s^{-1}$. The Ngaruroro study reach is in a natural depositional zone within the catchment (i.e., bedload into the reach exceeds that leaving the reach). This reach typically has 3 braids, with the active braidplain confined between willow plantings.

The Wairau River (Wöhling et al., 2018 and 2020) is 170 km long, and has its headwaters in the alpine Spencer Range on the main divide of the South Island. As such, the Wairau receives considerable source water from rain at higher elevations, producing a mean flow of 100 $m^3.s^{-1}$, and high mean annual peak flow of 1911 $m^3.s^{-1}$ (63 years of record at SH1). The Wairau River is also "flashy", with over ten events exceeding three times the median flow annually (FRE3, Booker 2013). The 2.2 km long study reach is in the middle section of the Wairau Plain, between Jeffries and Giffords roads. This study reach typically has 2 braids and the active braidplain is confined between engineered rock revetments and groynes. Bedload flux into and out of this reach is approximately equal (bedload transfer zone).

The Waikirikiri River has its headwaters in the foothills of the Southern alps and receives considerably less runoff than the other rivers. The 1 km long study reach is situated near Hororata where the river leaves the foothills and crosses the western margin of the Canterbury Plain. A long-term (58 years) flow monitoring site located upstream of the study reach at Whitecliffs shows a mean annual flow of 4.5 $m^3.s^{-1}$, and peak annual flow of 28 $m^3.s^{-1}$. The Waikirikiri River is also the least "flashy" with an average of only one event each year exceeding a flow of three times the median flow. As a result of its lower flow and high transmission losses, the Waikiriri River is subject to intermittent flow within our study reach (Larned et al., 2008; Di Ciacca et al., 2023). The Waikirikiri study reach is naturally incised between Pleistocene terraces, with no engineered flood controls. The active braidplain, which typically has 1 to 2 braids, can freely adjust between these contemporary braidplain margins, however, relatively dense exotic vegetation covers much of the contemporary braidplain.

Table 1. Characteristics of the three study catchments. Mean values are given unless stated otherwise. FRE3 is the annual number of events exceeding three times the median flow. Bed material grain size is near surface but excludes the armour.

	Ngaruroro	Wairau	Waikirikiri
Study reach length (m)	3000	2200	1000
Contemporary braidplain width in study reach (m)	300	400	460
Active braidplain width in study reach (m)	300	400	55
Braiding index in study reach	2.95	1.96	1.56
Reach slope ($m.m^{-1}$)	0.003	0.003	0.006
Catchment Area (km^2)	1930	3320	250
Catchment rainfall ($mm.y^{-1}$)	1414	1543	1045
Catchment potential evapotranspiration ($mm.y^{-1}$)	722	693	750
Annual low flow ($m^3.s^{-1}$)	1.2	9.9	0.97
Median flow ($m^3.s^{-1}$)	23.1	61	2.35
Mean flow ($m^3.s^{-1}$)	40	100	4.5
Annual peak flow ($m^3.s^{-1}$)	1546	1911	28.3
FRE3	6.1	10.7	1.1
River loss at study reach ($m^3.s^{-1}.km^{-1}$)	~0.6	≥0.2	0.25-0.65

All three rivers share a similar bedload lithology dominated by Jurassic greywacke. In the study reaches, the Ngaruroro is bounded to the north by Pliocene siltstone and limestone (Lee et al. 2011), while the Wairau is bounded to the north by schist (Begg and Johnston 2000). These two rivers lose water southwards, the river losing reaches being the primary source of recharge for the alluvial aquifers hosted by Holocene gravels. In the Waikirikiri study reach, the river is bounded by Pleistocene glacial outwash gravels (Forsyth et al. 2008). These gravels form the surface expression of a large, stratified aquifer system hosted by a composite of alluvial fans which underlies the Canterbury Plains. The Ngaruroro and Waikirikiri study reaches are both situated close to the apex of the river system's alluvial fan (close to where the rivers emerge from the foothills). Both the

Wairau and Ngaruroro are affected by gravel extraction, which has lowered the mean active braidplain bed elevation in the river recharge reaches by approximately a metre since the 1980’s (Gardner and Sharma 2016, Measures 2012). The varying physical environments, flow regimes, bed adjustment trajectories, and degree of lateral confinement result in different rates of bed reworking for each river. In particular, the Waikirikiri reworks its bed less frequently than the Ngaruroro and Wairau.

4.1 Field data collection

Investigations in the study reaches involved the collection of a variety of data types (Table 2). Each method and data type has advantages and disadvantages and is scale and process dependant (Gonzalez-Pinzon et al., 2015; Brunner et al., 2017). Stage and temperature recorders were established in the study reaches but were difficult to maintain due to repeated destruction by flood flows and frequent bed movement in the study reaches. Flow rating was carried out at the top of the reach for the Waikirikiri River, and permanent rated flow sites located downstream were used for the Ngaruroro and Wairau. A series of flow loss gauging surveys were undertaken at multiple transects within all three study reaches across a range of discharges to estimate transmission losses. Due to the difficulty of measuring flow in the larger rivers (and the related large measurement uncertainty), the most comprehensive set of flow loss surveys was carried out on the Waikirikiri (Di Ciacca et al., 2023).

Table 2. Type and number of measurements undertaken in the three study reaches

	Ngaruroro	**Wairau**	**Waikirikiri**
Study reach length (m)	3000	2200	1000
Contemporary braidplain width in study reach (m)	300	400	460
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River loss at study reach (m^{3}.s^{-1}.km^{-1})	~0.6	≥0.2	0.25-0.65

Piezometers were installed at different depths to provide a time series of water levels and temperature, and to enable sampling for radon-222 analysis. The piezometers were installed with 50mm diameter PVC with 1 to 2m length screens of slotted casing with a geotextile sock and sand pack around the screen, and cement grout around the overlying casing. A sump was used to collect downward percolating water in situations where pore water pressure was below saturation. Drilling methods involved a mix of rotary and sonic drilling, the former being used to install the piezometer network. Sonic drilling with a Geoprobe 8140LC (76.2mm diameter core) was carried out to collect cores for detailed logging and sediment analysis (grainsize and porosity). The sonic drilling method is not ideal as it can be difficult to get good core recovery, particularly in coarser or loose near-surface sediments. As a result, the core record is incomplete, however, there is currently no better method available to extract several meters of core from coarse riverbed deposits. Because core recovery was variable, data from individual drillholes are fragmented, and sediment analysis was only carried out on the most intact cores (0.1-1.2 m in length), with samples taken for grainsize and porosity analysis. Near-surface bed material grain size distribution and porosity were measured using manual excavation sieving combined with a detailed photogrammetry method to calculate excavation volume (Montgomery et al. under review). Particle size distribution was characterised by fitting Gompertz and Weibull curves (Bayat et al. 2015) to the sieved sediment data, and summary statistics determined via the method of Folk and Ward (1957).

The base of the BPA was identified in two ways. The first method was by mapping surface morphology, since the deepest areas of pools represent the scouring depth that has occurred during flooding. Surface and bed morphology was captured using remote sensing (photogrammetry, LiDAR, and bathymetry). The second method was through observations in drill core with good core recovery, where sediments beneath the BPA are characterised by more cohesion and a finer matrix. To enable data to be compared, contacts between the braidplain gravels and underling sediments (depositional unconformity) have been expressed as depth below a detrended surface representing cross-section mean contemporary braidplain surface elevation. This datum was chosen because of the spatially variable and temporally dynamic river bed levels.

Samples for radon-222 analysis were collected in 250 ml bottles in the Waikirikiri (Songola 2022) and Wairau reaches from riffles, at different depths in pools, and from purged piezometers. Analysis for radon activity was conducted with a RAD7 (Durridge 2020a), RAD H2O (Durridge 2020b), and active DRYSTIK (Durridge 2021) in a closed loop system, with the results adjusted for decay since the time of sampling.

Geophysical methods were also used to image the subsurface, including passive (DTS) and active (ADTS) distributed temperature sensing (Banks et al., 2022), electrical resistivity tomography (ERT), transient electromagnetic (tTEM) and electromagnetic induction (DualEM421). The tracks prepared for tTEM and DualEm surveys are evident in the aerial photos shown on Fig. 3. SkyTEM data were also available for the Ngaruroro area (Rawlinson et al. 2021). Of the geophysical methods employed, DTS/ADTS, and ERT were the most successful methods for delineating sediment structure and saturation associated with the river. The resistivity of New Zealand braided river gravels is too high (>400 Ωm) for electromagnetic methods to be effective, including SkyTEM, which provided insufficient definition in the near surface (<10m).

5.0 Field observations

A hydraulically disconnected river-regional aquifer system has been identified from drilling and monitoring data in the Waikirikiri study reach (Banks et al. 2022, Di Ciacca et al. 2023), and at the upper part of the Ngaruroro study reach. A hydraulically connected river-regional aquifer system is observed in the Wairau study reach, and in the lower part of the Ngaruroro study reach. Evidence for the proposed conceptualisation is provided below based on data type. Data referred to in the text and figures is shown spatially in Fig. 3. Points where the base of the BPA has been observed in cores, or inferred via deep pools are identified.

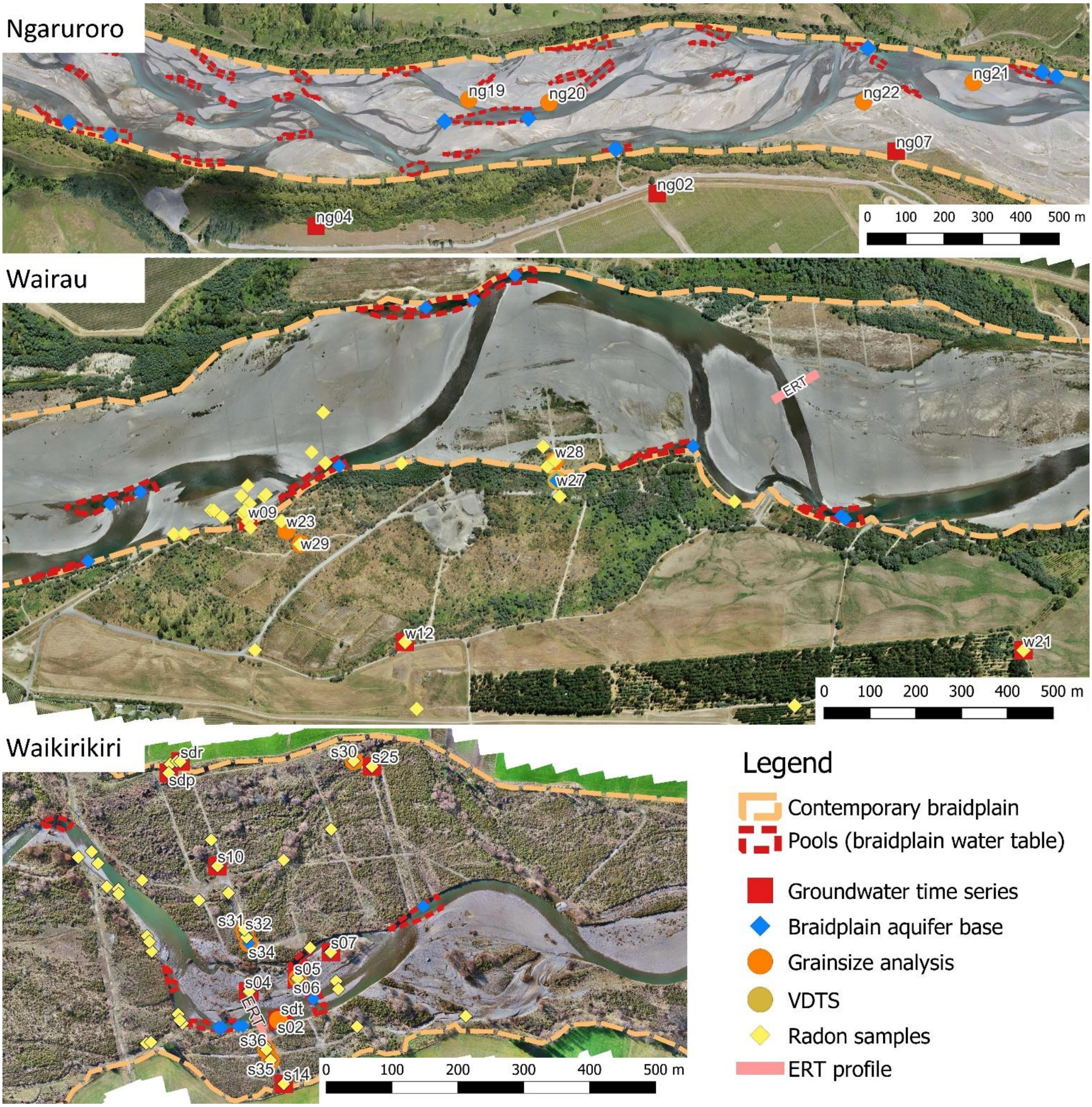

Figure 3: Map of data sources referred to in the text at each of the three study sites

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5.1 Geology and geomorphology

The BPA lateral extent in our three sites is identified geomorphologically as being at the contemporary braidplain margins (orange dashed lines in Fig. 3). The contemporary braidplain margins in our study reaches are either artificially confined by rock armouring or willow planting for flood protection (Wairau and Ngaruroro), or by terrace boundaries (Waikirikiri). These relatively static lateral controls result in the abutment of relatively loose (recently active) braidplain gravels against older, more poorly sorted sediments. In the Wairau and Ngaruroro rivers the artificial lateral controls are sufficiently narrow that the entire contemporary braidplain is regularly reworked (i.e., the active braidplain margins and contemporary braidplain margins are essentially the same). In the Waikirikiri, the active braidplain is narrower than the contemporary braidplain and the active braidplain can adjust laterally, reworking the contemporary braidplain gravels.

In all three braided rivers, deep pools form at the toe of riffles. In the Wairau and Ngaruroro, these are amplified at the braidplain margins where river flow is reflected by rock armouring or willow plantings that limit lateral erosion and enhance bed scour. These pools are zones where the BPA discharges to the river. Parafluvial seeps are commonly observed in these locations, which have higher radon-222 activities and summer temperatures that are cooler than adjacent river braids. The surface expression of the BPA can be seen in abandoned channels where the braidplain surface topography drops below the braidplain water table and exposes groundwater (static pools or flowing springs). These areas are demarked by dashed red lines on Fig. 3.

The depositional unconformity at the BPA base in recovered cores was observed at 1.7-2.0 m depth beneath the mean bed level of the contemporary braidplain in the Ngaruroro study reach, 4.3-5.0 m depth in the Wairau, and 2.1-3.7 m depth in the Waikirikiri. The greater depth in the Wairau River is unsurprising, as this river has the highest flood flows and is tightly confined by engineering works, resulting in greater depths of bed reworking. At the Waikirikiri site, the contact of the depositional unconformity was seen as a change from grey-brown postglacial sandy gravels to yellow-brown clay-rich glacial outwash gravels (Fig. 4). During drilling and completion of the groundwater monitoring wells, a drop in the water level with depth below the glacial contact was observed. Six cores were drilled just beneath the unconformity at various locations within the contemporary braidplain margins to investigate the saturation status beneath the braidplain gravels. These holes were drilled through the low permeability contact layer until an apparent increase in permeability was encountered, at which point the water level in the drillhole dropped significantly. Piezometers screened beneath the base of the BPA and above the regional water table showed low and unvarying water levels, indicating unsaturated or variably saturated conditions (Fig. 6).

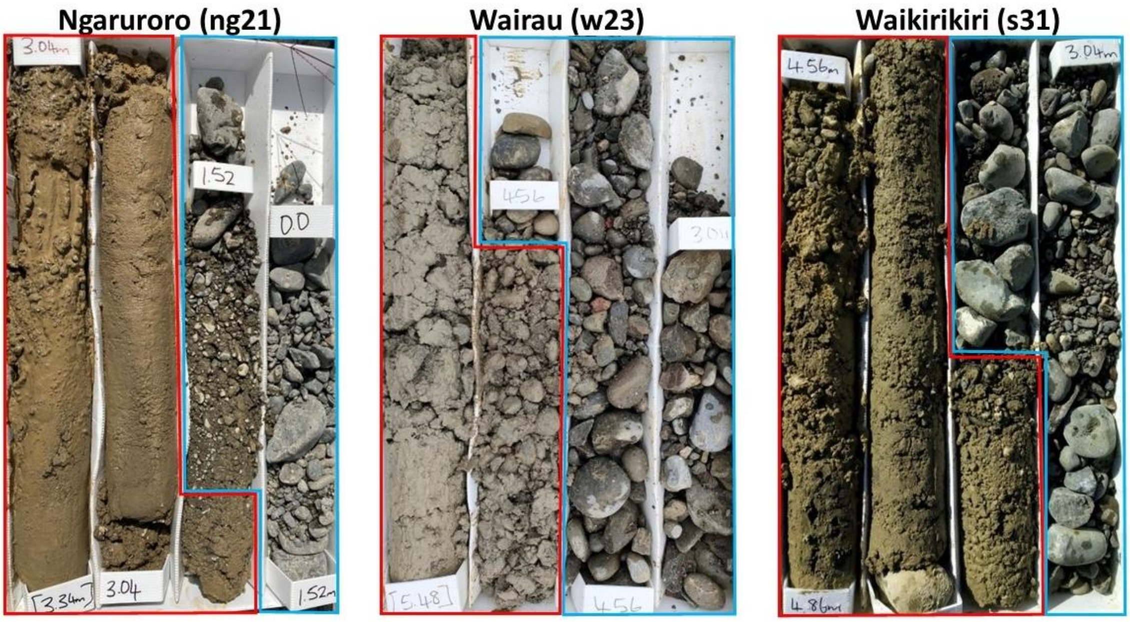

Figure 4: Representative core samples across the unconformity at the three study sites (blue=braidplain gravels, red=underlying very poorly sorted consolidated gravels)

At the Wairau River study site, the base of the BPA is visible as a change from grey-brown sandy clast supported gravel to more cohesive and poorly sorted gravel with increasing proportions of silt and clay. Just beneath this unconformity is a more prominent contact with yellow brown silty clay-bound gravel associated with old outwash fan deposits along the Richmond Range (not shown on Fig. 4, but evident on Fig. 10). Note that some of the Wairau core holes were positioned on the berms (outside of what we are referring to as the contemporary braidplain), where the active braidplain was located prior to river re-alignment in the 1960s. The river can no longer mobilise sediments on these berms due to rock armouring of the banks leaving a recent remnant braidplain gravel deposit beneath the southern berm. This deposit is both spatially and vertically separate from the contemporary braidplain (the mean bed level of the contemporary braidplain is approximately 2m below the berms).

In the Ngaruroro study site, the unconformity at base of the BPA is more gradational, manifesting as an increase in silt and clay content between 1.7 and 2.0 m depth visible within bore logs (Fig. 4) and particle size distribution (Fig. 5). As with the Waikirikiri River, a drop in the water table was observed while drilling beneath this lower permeability unconformity. The less-distinct base to the BPA in the Ngaruroro study reach is likely because the reach is depositional, so the underlying gravels were deposited relatively recently compared to the other study reaches.

Particle size distribution summary statistics of core samples collected by sonic drilling and bed excavation are shown in Fig. 5, with classifications according to the Folk and Ward (1957) scale. A relationship between sorting and grainsize is apparent at each site, with poorer sorting corresponding to an increase in the finer fraction. Shallow braidplain gravels are overall poorly sorted (1-2, data mean: Ngaruroro 1.98, Wairau 1.90, Waikirikiri 1.96), whereas the underlying gravels tend to be very poorly sorted (2-4, data mean: Ngaruroro 2.88, Wairau 2.28, Waikirikiri 2.60). The grainsize of the braidplain gravels is generally coarser (mean: Ngaruroro -4.76, Wairau -4.23, Waikirikiri -3.55) than the underlying very poorly sorted sediments (mean: Ngaruroro -1.64, Wairau -3.54, Waikirikiri -2.69).

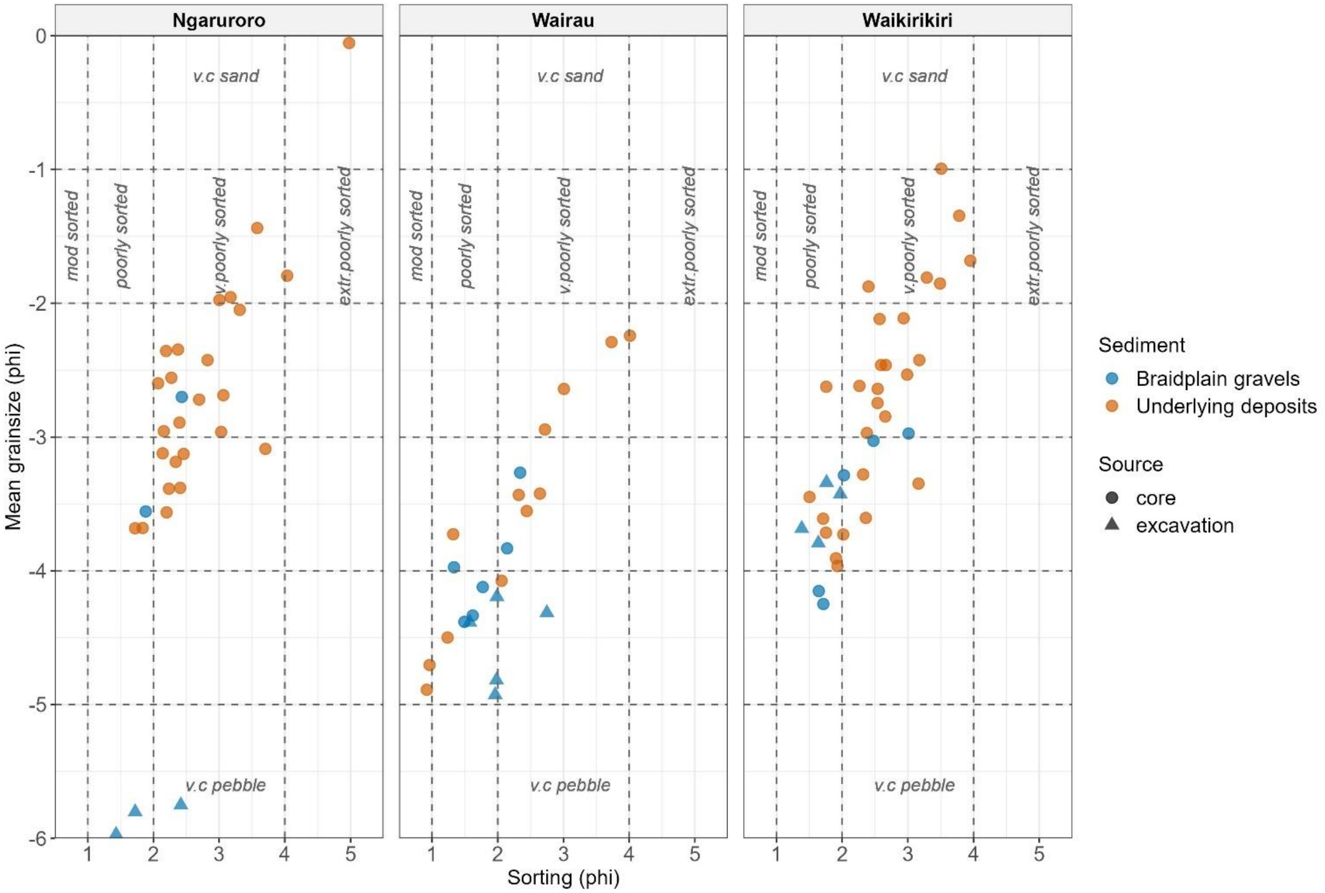

Figure 5: Grainsize analyses and sorting indices from samples beneath the three study reaches. Dashed lines are breaks for grainsize and sorting indices (after Folk and Ward 1957).

Core recovery at all sites was typically poor in the contemporary braidplain gravels, which mostly consist of loose gravel and cobbles, with a high proportion of sand but only a trace of silt and clay. Because of this, some of the braidplain gravel samples have been sourced from samples manually excavated from the braidplain subsurface (Fig. 5). These excavated samples exclude the surface armour common in gravel bed rivers. For the Wairau data set there is no clear separation in the particle size distribution between braidplain and underlying gravels. Wairau sediments are coarser than the other two sites, because of the high-energy of this river system. The coarseness of the sediments greatly hampers core recovery, so it is possible that the lack of separation is an artefact of the loss of finer fractions in some samples during drilling.

5.2 Water levels and temperature monitoring

Hydraulic heads within the braidplain aquifer are dynamic and fluctuate in response to changes in river stage. Figure 6 shows heads for the Waikirikiri field site, where the base of the BPA is at approximately 207 m elevation, and the regional water table is >13 m below the unconformity. The variably saturated zone (pore water pressure below saturation) is at least 10 m thick. For a river system that is hydraulically connected to the regional aquifer, the pressure response outside of the BPA is also dynamic and shows a similar response to the BPA (Fig. 7). For a river system with a hydraulic disconnection, the variably saturated zone attenuates the pressure fluctuations in the regional aquifer (Fig. 6). The relative water level depth and hydraulic response in the regional aquifer can therefore provide a useful test for hydraulic connectivity between the two aquifer systems.

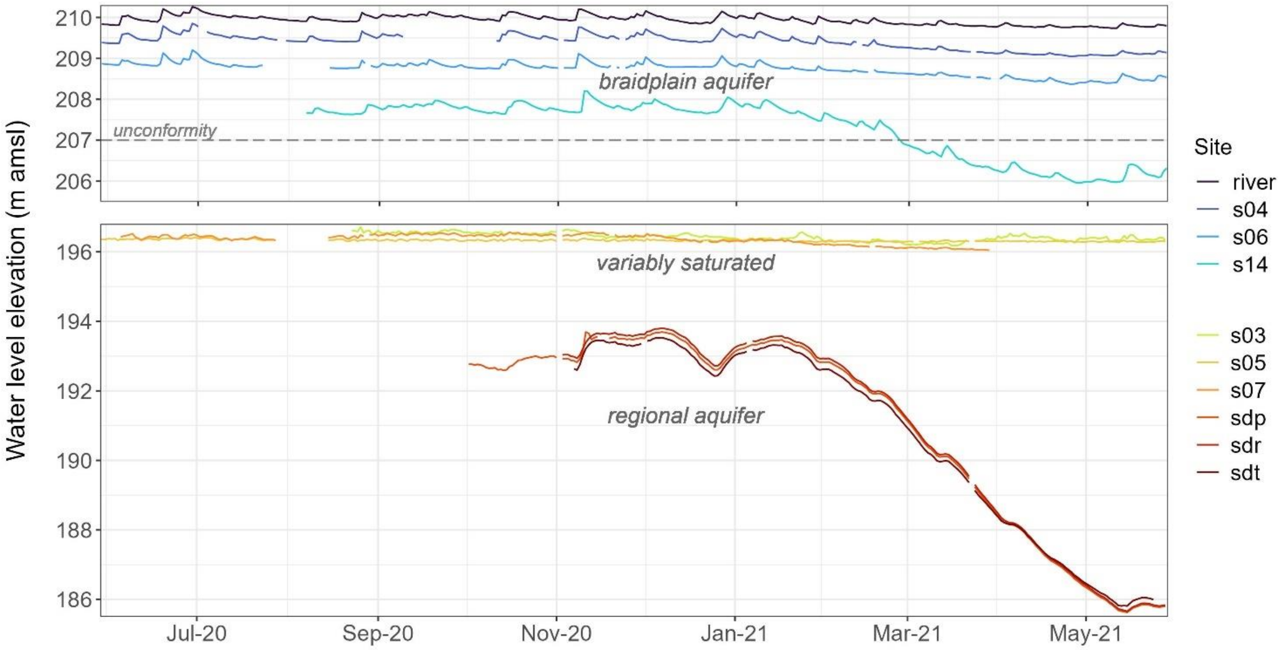

Figure 6. Water level time series data for the Waikirikiri River and braidplain and regional aquifers. Note the vertical offset in the two graphs is due to the thick variably saturated zone beneath the braidplain and regional aquifer. Site locations shown in Fig. 3.

Data from the Ngaruroro reach show characteristics of a regional aquifer that is both hydraulically connected to the BPA and either disconnected or transitional (Fig. 7). These data have been normalised by the median water level to highlight relative changes in response. The BPA site (ng07) responds similarly to the river stage but has a slower recession rate due to storage in the gravels. The two sites that are screened in the regional aquifer (ng02, ng04) are both located 150 m adjacent to and downgradient of the contemporary braidplain (see Fig. 3). The upstream site, ng04, has the most rapid recession rate and its peak response is slightly delayed compared to ng02 which responds similarly to the river channel stage. This suggests that this upstream section of the study reach may be hydraulically disconnected or transitional from the regional aquifer (assuming similar hydraulic properties throughout the regional aquifer). The water levels in ng04 are up to 2.4 m below the BPA base (mean 1.8 m) assuming a BPA thickness of 1.6 m below mean river bed level at this site. During flood flow events, the regional aquifer water level at ng04 does rise above the river bed elevation, indicating saturated conditions do temporarily occur during flooding.

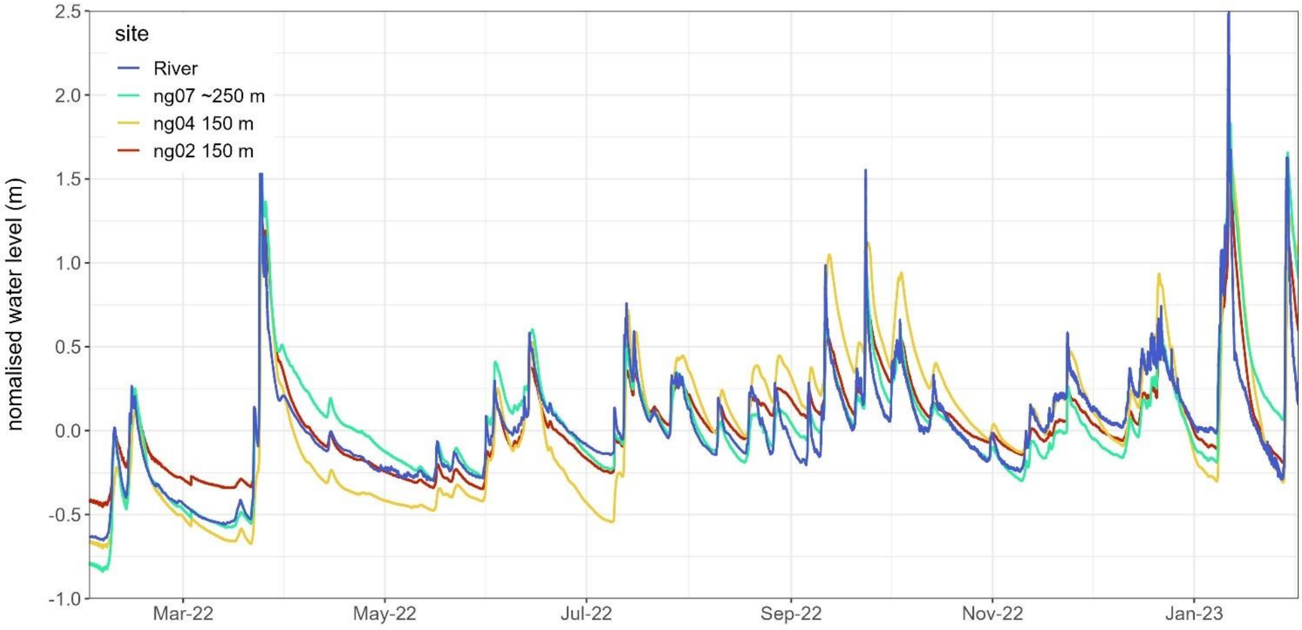

Figure 7. Normalised water level time series data for the Ngaruroro River, braidplain (ng07) and regional aquifers (ng02, ng04). Site locations are shown on Fig. 3. Distances in the legend indicate the down gradient distance from the nearest active river channel.

Figure 8 shows daily average temperatures from representative hydrological settings in each study reach, and the lateral distance downgradient of the nearest active river channel. For sites located within the BPA, temperature responses are similar to the river channel, and driven by individual flow events (ng07, w09, s06). However, event-driven responses can be attenuated, and the season response delayed, at large distances from a channel (s25). Note also that s06 becomes more responsive after a flood event on 30 May 2021 which has changed connectivity between the river and groundwater in this piezometer.

For sites within the regional aquifer (ng02, ng04, w12, w21, sdp), the event-driven response is difficult to detect, and the seasonal response depends on the hydraulic relationship between the braidplain and regional aquifers. Sites ng02 and ng04 are equidistant from the Ngaruroro BPA, however ng04 is in a position where the base of the braidplain gravels and regional water table are approximately 1.8m apart, potentially with an intervening variably saturated zone, whereas at ng02 the braidplain and regional aquifers are hydraulically connected. This difference in hydrologic condition may explain the delayed seasonal response in ng04. In the Waikirikiri system, the variably saturated zone is considerably thicker (about 12m), which almost completely attenuates the seasonal temperature response in the regional aquifer.

Figure 8: Representative temperature time series for the three study sites. Piezometer locations are shown in Fig. 3, sites ng07, w09, s06 and s25 are screened in the BPA.

In the Waikirikiri and Ngaruroro river systems, the temperature signals propagate efficiently from river channels to the BPA compared to the regional aquifer. This highlights the distinction between these two aquifers, with the BPA acting as an intermediary in groundwater – surface water exchanges.

5.3 Radon-222 sampling

A summary of the radon-222 results for various water sources in the Wairau and Waikirikiri reaches is shown in Table 3, with their estimated residence times. In the Wairau system, samples from a BPA source were collected from both piezometers and seepage faces within the river bed. The radon-222 activities for the two sources are very similar, with ranges 980-1800 BQ.m-

3 for BPA samples and 320-2270 BQ.m-3 for seepages. The radon-222 activities for the two sources are very similar, with ranges 980-1800 Bq m^{-3} for BPA samples and 320-2270 Bq m^{-3} for seepages. For this reason, we have treated both these sample sources as being representative of the BPA. To estimate residence times from radon-222 activities, we used an initial river channel condition of 180 Bq m^{-3} for Wairau and 200 Bq m^{-3} for Waikirikiri, reflecting the lowest measured river radon-222 activities. The secular equilibrium for the Waikirikiri BPA is estimated at 8000 Bq m^{-3} based on the highest activity observed in the BPA (7450 Bq m^{-3}), and the lowest activity observed in porewater samples from piezometer sumps in the variably saturated zone (9180 Bq m^{-3}). A secular equilibrium of 4800 Bq m^{-3} was estimated for Wairau Aquifer samples, with the assumption that this equilibrium would also apply to BPA samples.

The data show distinct populations for each sample source, with radon-222 activities increasing from river channel to BPA to regional aquifer. At both sites, radon activities in river run samples were significantly lower than those in BPA samples. In the Wairau reach, there is notable overlap in radon activities between the braidplain and regional aquifers, indicating a likely hydraulic connection between these two systems. Conversely, in the Waikirikiri reach, there is a downward increase in radon activities from the BPA to the variably saturated zone and further into the regional aquifer, with no overlapping values. This suggests a hydraulic disconnection between the BPA and the regional aquifer in the Waikirikiri reach.

Table 3. Measured radon-222 activities (Bq m^{-3}) and estimated residence times (RT) in days for the Wairau and Waikirikiri study reaches.

River	**Wairau**			**Waikirikiri**			
Sample Source	River run	Braidplain aquifer	Regional aquifer	River run	Braidplain aquifer	Variably saturated zone	Regional aquifer
Samples	16	12	19	10	38	7	6
Rn min	183	322	690	200	1490	9180	14515
Rn max	472	2267	4748	570	7450	12810	19970
Rn mean	312	960	2778	383	3955	10532	17307
min RT		0.2	0.6		1.0		
max RT	0.36	3.3	25	0.27	15.5		
mean RT	0.16	1.1	6.5	0.13	4.6		

Residence times were determined to be in the range of 0.2 to 3.3 days for the Wairau BPA in the study reach. In contrast, the Waikirikiri reach exhibited longer residence times, measuring up to 15.5 days. Residence times for the Waikirikiri variably saturated zone and regional aquifer were not estimated due to uncertainty regarding the secular equilibrium activity value.

5.4 Geophysics

ERT surveys of the contemporary braidplain in the Wairau and Waikirikiri reaches yielded varying degrees of success. The 455 surveys that returned the most consistent subsurface resistivity response were conducted in the river channel itself, due to the presence of water in the near surface improving the connection between electrodes and the underlying resistive substrate. Figure 9 shows dipole-dipole array resistivity profiles across a braid of the Wairau (~ 30 m wide), and two braids of the Waikirikikri (~40 m wide). The two profiles are shown at the same spatial and resistivity scale, and an interpretation has been made based on drilling information. Both profiles show a contrast between resistive (~1000 ohm-m) loose sandy gravels that 460 host the BPA, and the underlying lower resistivity (<800 ohm-m) associated with older, very poorly sorted sediments. The Wairau profile reveals the unconformity at the base of the active braidplain gravels as a less resistive layer at ~19.5 m elevation, and a saturated BPA thickness of ~3.5 m. On the Waikirikiri profile, the unconformity at the base of the braidplain gravels lies at ~207.5 m elevation, and the saturated thickness of the BPA is only 2-2.5 m. The underlying very poorly sorted glacial outwash gravels typically show relatively low resistivities (≤ 600 ohm-m) due to the relative abundance of clay-sized sediment, 465 even when not fully saturated.

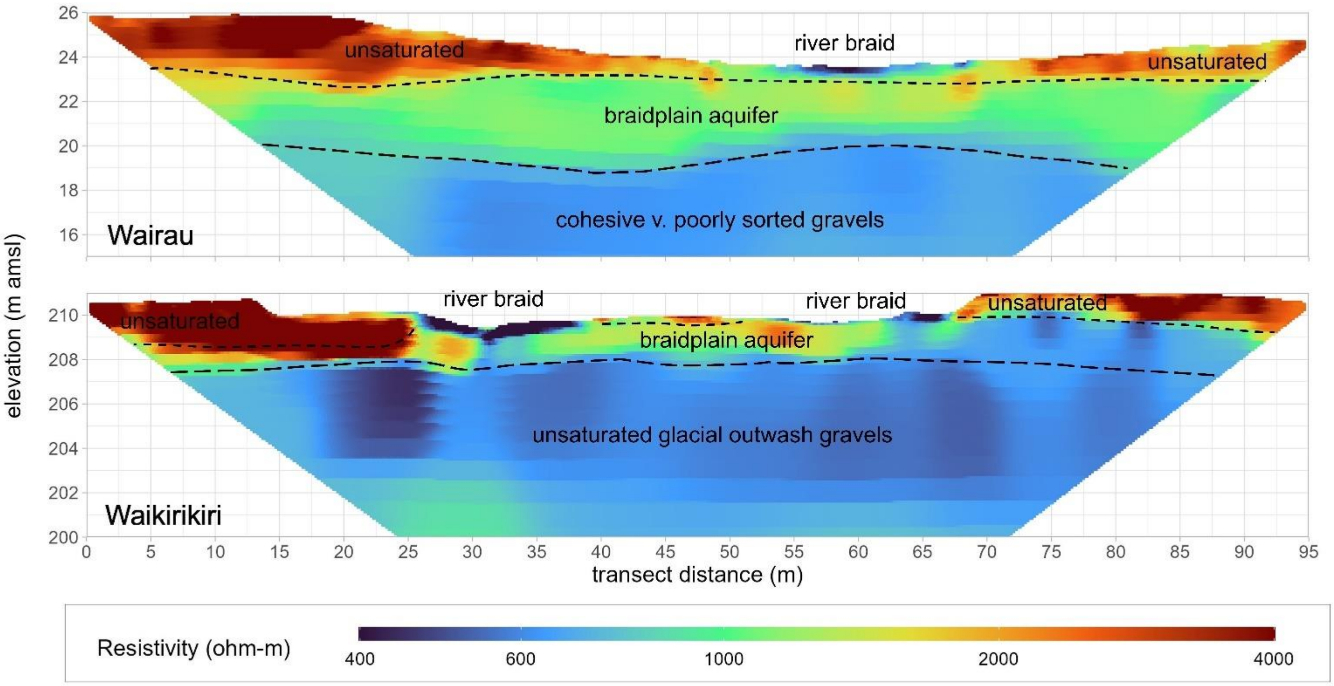

Figure 9. Subsurface resistivity collected by ERT across Wairau and Waikirikiri river braids.

5.5 Passive and active distributed temperature sensing

Hydrogeologic structure in the Wairau study reach has been assessed by monthly DTS and ADTS surveys (Fig. 10) carried out on a vertically installed fibre optic cable located 20 m from the active braidplain margin (w27 on Fig. 3). While w27 lies just outside of the existing engineered contemporary braidplain, this site does contain remnant braidplain sediments deposited prior to stabilisation of the river margins in the 1960's. The timing of the DTS surveys with respect to river temperature is shown in Fig. 10c. The survey temperature profiles show consistent inflections with depth due to the attenuation of the river recharge temperature response through saturated sediments of contrasting hydraulic conductivity (Fig. 10). These inflections correspond to the depths where a change in sediment characteristics can be seen in the bore log, manifest as progressively increased sediment cohesion, poorer sorting, and increasing silt and clay content with depth. In the DTS profile, the older silty clay-bound and indurated sediments have a large influence on subsurface flow, i.e., a reduction in flow through this material.

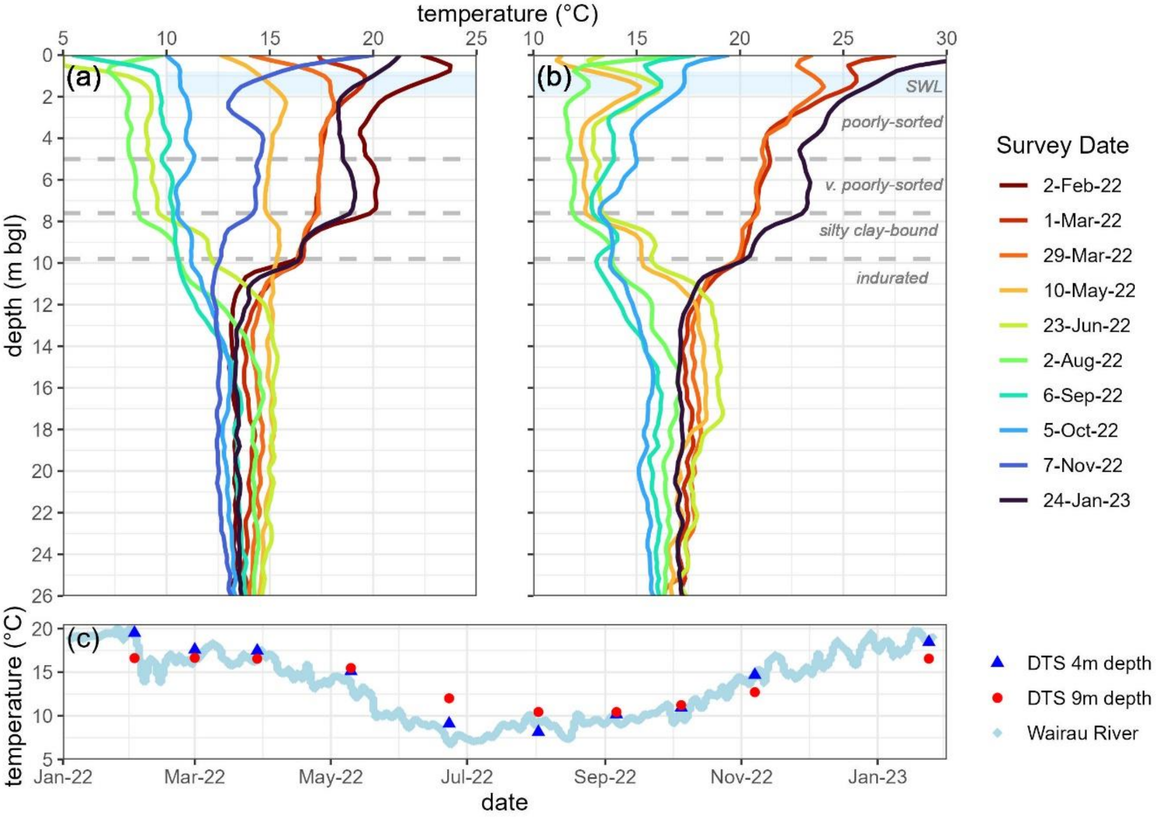

Figure 10. Vertical (a) DTS and (b) A-DTS surveys carried out on the south bank of the Wairau River on w27. The river temperature over the period of the surveys is shown in (c) along with temperatures measured by DTS at 4 and 9 m depth. SWL=static water level measurements over the period

6.0 Characteristics of the identified braidplain aquifers

A summary of the approximate dimensions and potential maximum groundwater storage volumes of the three braidplain aquifers investigated is shown in Table 4. In all three reaches, the BPA is laterally extensive, but very thin.

The Wairau River has the greatest BPA storage potential, largely due to its observed saturated thickness of up to 4.1 m. However, the Wairau is also a highly channelised river, and has a large bathymetric range, giving its BPA a large potential variability in saturated thickness in response to river channel stage fluctuations. Of significance for water management in the Wairau Plain is that the very poorly sorted gravels are thin beneath the Wairau contemporary braidplain and underlain by buried fans of silty clay-bound and indurated gravels which act as a vertical flow barrier (see Fig. 10). Gravel extraction from the river system has dropped the mean bed level by approximately 1 m within our study reach since the early 1990s (Gardner and Sharma, 2016). This has allowed the river to rework sediment to greater depths, which has thinned and reduced the effective transmissivity of the gravel sequence overlying the buried fan deposits in addition to reducing the hydraulic gradient between the river system and regional aquifer.

Table 4. Dimensions and maximum storage volumes of braidplain aquifers observed in the three study areas

River	Approximate width (m)	Contact depth (m) min-max (mean)	Porosity min-max (mean)	Storage volume ($m^3.m^{-1}$)
Ngaruroro	300	1.2 - 2.4 (1.6) n=4	0.12-0.35 (0.21) n=9	80-150
Wairau	450	2.4– 5.7 (4.1) n=6	0.09-0.46 (0.22) n=21	210-500
Waikirikiri	400	2.0 - 3.7 (2.8) n=16	0.09-0.22 (0.14) n=9	130-240

7.0 Discussion

The proposed conceptualisation enables a braided river system of high complexity to be represented by a few key hydrogeological elements. These are represented on Fig. 1 as a contemporary braidplain, the margins of which mark the lateral extent of the braidplain aquifer (1), an underlying unconformity with more consolidated and more poorly sorted sediments (2), and observations of the hydraulic relationship between the braidplain and regional aquifers (a or b). For braided rivers, this approach integrates existing concepts of an alluvial aquifer, and hydrological hyporheic and parafluvial zones into a single conceptualisation of the contemporary braidplain subsurface. By identifying the base and margins of the BPA, and the process which forms it (reworking of bed material), the vertical and lateral extents to which hyporheic and parafluvial exchange occur can be identified by a change in sediment characteristics.

Point-scale features of braided rivers are described well by the existing hydrological framework proposed by Fox and Durnford (2003) and modified by Brunner et al. (2009a and b). Under this framework, individual channels can be considered as hydrologically connected (gaining or losing), disconnected (losing), or transitional (losing). However, this framework starts to

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break down for braided rivers at local to sub-catchment scales, as all four of these hydrological states can occur along a single cross-section of the braidplain regardless of whether the river has a net gain or loss. However, at the reach or sub-catchment scale, a braided river can be considered a river system, which can be described by any one of those hydrological states in relation to the regional groundwater system. For example, a river braidplain reach can be hydrologically disconnected and losing water to groundwater overall, even though individual channels are hydrologically connected and locally gaining flow from BPA groundwater. The conceptualisation posed by Fox and Durnford (2003) can therefore be applied to different scales within a braided river system, but its application, and therefore interpretation of field measurements, requires knowledge of subsurface structure and saturation.

The difference in sediment characteristics above and below the unconformity at the base of the BPA indicates that the process of BPA formation is controlled by the mobilisation of bed material during flood flows, which loosen and sort the braidplain gravels, and winnow the finer fraction. This process of gravel mobility associated with flood events is supported by bathymetric observations of the depth of river channel scouring in deeper pools which agrees with the depths of the unconformity in core data. In the absence of drill core and particle size distribution data, we suggest that the elevation of pool depths measured soon after a flood event can be used to approximate the base of the BPA. This will only provide a minimum depth of the BPA base since the river is expected to deposit some sediment in scoured areas during the flow recession. The thickness of a river's BPA is likely to depend on the inter-relationship between several factors, including contemporary braidplain width, sediment characteristics and the balance of sediment supply, the frequency and magnitude of peak flow events, and the use of "hard engineering" to control a river's position. While some of these factors are natural, the factors related to width and depth are influenced by river engineering applied at each river. The Wairau River has the thickest BPA and has the highest hydrological energy of the reaches studied. This river is considered by some river engineers to be excessively narrowed, and a wider contemporary braidplain may result in a dispersion of energy during flood flows, and subsequent thinning of the BPA. Interestingly, the Ngaruroro River is also subject to high peak flows, although bed mobilising flows occur less frequently than the Wairau. It is likely that the Ngaruroro BPA is being thinned by the large volume of gravel extraction occurring within the study reach.

The LiDAR and bathymetric data gathered from our three study sites indicate that individual river channels locally merge with and diverge from the water table surface of the BPA. Water exchange across the bed is determined by bathymetry and hydraulic properties, where the river can be forced above the water table by gravel lobes or dropped into the water table in locations of scouring. Areas of relatively still water (pools) are therefore the surface expression of the BPA, with seeps representing locations where the bedform drops below the level of the BPA water table. This explains the occurrence of higher radon-222 activities in pools compared to flowing river channels, as well as differences in seasonal water temperature.

For the interpretation of field data, the proposed conceptualisation highlights the importance of identifying and knowing the nature of the relationship between these three potential water sources to interpret observations. For example, to understand the nature and magnitude of river-aquifer interaction by only sampling radon-222 in river channels can be misleading. This is

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because the radon activity measured in the river depends both on the river setting (run or pool), and the nature of the interaction between the BPA and regional aquifer.

From a modelling perspective, it is questionable if a streambed conductance term is an appropriate physical mechanism for representing braided river-aquifer exchange at the local or catchment scale. The role of bed conductance, if significant, is to regulate exchange between individual river channels and the BPA. Due to the relatively high transmissivity of the bed materials, hyporheic exchange is an integral process of braided river flow, and water can be seen to freely exchange between the surface and the bed. It follows that consideration of water storage in the bed sediments (BPA) with a conductance term to impede flow beneath those sediments would be a more appropriate approach for simulating braided rivers at larger scales than to simulate individual channels with bed conductance.

The BPA concept resolves vague definitions of “groundwater” in groundwater – surface water interactions in braided rivers by considering the river as a whole system with an associated subsurface storage component distinct from the regional groundwater system. This provides specificity to the concept of a “river corridor” (Harvey and Gooseff, 2015), where a river comprises not just the river channels, but the surrounding, fluvial deposits, riparian zones, and floodplains between which hydrologic exchange occurs. However, we acknowledge that the BPA concept may only apply to braided rivers that have stable or actively degrading beds, or have had some form of bank stabilisation, which is common where flooding is considered a risk to adjacent land. Stabilisation of river margins serves to increase the frequency of gravel remobilisation within the active braidplain and prevent reworking of adjacent bed material that may be part of the historical braidplain. Fine sediment can percolate through the gravels or be deposited on the surface, and if these gravels aren’t subsequently reworked, this can gradually consolidate and potentially clog the pore spaces, accentuating the difference between contemporary and adjacent historical braidplain sediments. Narrowing the area of braidplain that is reworked can thereby narrow the BPA. The conceptualisation may be less appropriate, or the BPA boundaries may be less distinct, where the contemporary braidplain margins are much wider than the active braidplain, and reworked over longer timeframes. This type of braided river behaviour is typically seen in mountainous areas with low land use pressure, for example in the Southern Alps of New Zealand, but would have occurred on lowland plains prior to widespread engineering of river margins in New Zealand during the 1960s. If river channels can adjust laterally over a wider area, it is expected that sediments within the contemporary braidplain will be more heterogeneous, with channels of permeable recently mobilised gravel intermingled with islands/areas of varying age and permeability. In these cases, the extent of the BPA beyond the active braidplain across the contemporary braidplain may depend on the frequency of contemporary braidplain reworking, or the connectivity with the active braidplain. Similarly, it would be difficult to detect the base of the BPA in situations where the river bed is rapidly aggrading.

8.0 Conclusions

By investigating the surface and subsurface sediment and saturation in three study reaches, we have developed a conceptualisation of how braided rivers exchange water at the local (reach) and sub-catchment (aquifer) scale. The interaction between the river system and groundwater can be considered to occur between (a) individual river channels and the BPA (hyporheic and parafluvial exchange), or (b) the braidplain and regional aquifers. Central to this conceptualisation is the presence of a braidplain aquifer (BPA), a thin (2-5 m) layer of loose, poorly sorted gravel which is formed via the process of bed mobilisation during flood-flows. The base of the BPA can be identified in drill core as an unconformity between poorly sorted unconsolidated gravels overlying more consolidated very poorly sorted gravels. Individual river channels can be hydraulically connected, transitional, or disconnected from the BPA, depending on the relationship between the braidplain water table and bathymetry. The nature of the hydraulic relationship between the braidplain and regional aquifers can also be hydraulically connected, transitional, or disconnected, depending on the relationship between the regional water table and base of the BPA gravels. Approaching the braided river as a (whole) system (river and BPA combined) enables field data to be interpreted within the context of its water source.

From a modelling perspective, the conceptualisation enables rivers to be appropriately represented at a local scale (river-BPA), or a regional scale (BPA/river system-regional aquifer), depending on the modelling objective. A parallel investigation not presented here is focussed on the implementation of the proposed conceptualisation into sub-catchment scale models to quantify how changes in river morphology and BPA storage influence recharge to the regional groundwater system. A key research gap is to understand the relationship between BPA dimensions, bathymetry, and river flow dynamics, and this is a subject for future research.

References

Anderson, E.I.: Modeling groundwater–surface water interactions using the Dupuit approximation. Adv. Water Resour., 28(4), 315-327, https://doi-org./10.1016/j.advwatres.2004.11.007, 2005.

Banks, E.W., Simmons, C.T., Love, A.J., and Shand, P.: Assessing spatial and temporal connectivity between surface water and groundwater in a regional catchment: Implications for regional scale water quantity and quality. J. Hydrol., 404(1-2): p. 30-49, https://doi:10.1016/j.jhydrol.2011.04.017, 2011.

Banks, E.W., Morgan, L.K., Sai Louie, A.J., Dempsey, D., Wilson, S.R.: Active distributed temperature sensing to assess surface water-groundwater interaction and river loss in braided river systems. J. Hydrol., 615, 128667, https://doi:10.1016/j.jhydrol.2022.128667, 2022.

Barthel, R., Banzhaf, S.: Groundwater and Surface Water Interaction at the Regional-scale - A Review with Focus on Regional Integrated Models. Water Resour. Manag., 30: 1–32, https://doi:10.1007/s11269-015-1163-z, 2016.

Bayat, H., Rastgo, M., Mansouri Zadeh, M., Vereecken, H.: Particle size distribution models, their characteristics and fitting capability. J. Hydrol., 529, 872-889, https://doi:10.1016/j.jhydrol.2015.08.067, 2015.

Begg, J.G and Johnston, M.R.: Geology of the Wellington area. Institute of Geological & Nuclear Sciences 1:250 000 geological map 10. 1 sheet + 64p. Lower Hutt, New Zealand. GNS Science, 2000.

Boano, F., Revelli, R., Ridolfi, L.: Reduction of the hyporheic zone volume due to the stream-aquifer interaction. Geophys. Res. Lett. 35: L09401, https://doi:10.1029/2008GL033554, 2008.

Boano, F., Harvey, J.W., Marion, A. Packman, A.I., Revelli, R., Ridolfi, L., Wörman, A.: Hyporheic flow and transport processes: Mechanisms, models, and biogeochemical implications. Rev. Geophys., 52: 603–679, https://doi:10.5194/hess-22-1917-201810.1002/2012RG000417, 2014.

Booker, D. J.: Spatial and temporal patterns in the frequency of events exceeding three times the median flow (FRE3) across New Zealand. J. Hydrol., 52 (1), 15-39, 2013.

Boulton, A.J., Findlay, S., Marmonier, P., Stanley, E.H., Valett, H.M.: The functional significance of the hyporheic zone in streams and rivers. Annu. Rev. Ecol. and S., vol 29, 59–81, https://doi: 10.1146/annurev.ecolsys.29.1.59, 1998.

Bourke, S.A., Cook, P.G., Shanafield, M., Dogramaci, S., Clark, J.F.: Characterisation of hyporheic exchange in a losing stream using radon-222. J. Hydrol., 519, 94–105, https://doi:10.1016/j.jhydrol.2014.06.057, 2014.

Bristow, C.S. and Best, J.L.: Braided rivers: perspectives and problems, in: Braided Rivers, edited by: Best, J.L. and Bristow, C.S., Geological Society, London, Special Publications. Volume 75 Pages 1-11, https:doi:10.1144/GSL.SP.1993.075.01, 1993.

Brower, A., Hoyle, J., Gray, D., Buelow, F., Calkin, A., Fuller, I., Gabrielsson, R., Grove, P., Brierley, G., Sai-Louie, A.J., Rogers, J., Shulmeister, J., Uetz, K., Worthington, S., Vosloo, R. (in press). New Zealand's braided rivers: The land the law forgot, Earth Surf. Proc. Land., 1–17, https://doi:10.1002/esp.5737

Brunner, P., Cook, P.G., Simmons, C.T.: Hydrogeologic controls on disconnection between surface water and groundwater, Water Resour. Res., 45(1), 1–13, W01422, https://doi:10.1029/2008WR006953, 2009a.

Brunner, P., Simmons, C.T., Cook, P.G.: Spatial and temporal aspects of the transition from connection to disconnection between rivers, lakes and groundwater, J. Hydrology 376 (1–2): 159–169, https://doi:10.1016/ j.jhydrol.2009.07.023, 2009b.

Brunner, P. and Simmons, C.T.: Hydrogeosphere: A Fully Integrated, Physically Based Hydrological Model, Groundwater, 50, 170-176, https://doi:10.1111/j.1745-6584.2011.00882, 2012.

Brunner, P., Therrien, R., Renard, P., Simmons, C.T., Hendricks Franssen, H.-J.: Advances in understanding river-groundwater interactions, Rev. Geophys., 55, 818-854, https://doi:10.1002/2017RG000556, 2017.

Cardenas, M.B. and Zlotnik, V.A.: Three-dimensional model of modern channel bend deposits, Water Resour. Res., 39: 1141, https://doi:10.1029/2002WR001383, 2003.

Cartwright, I. and Hoffmann, H.: Using radon to understand parafluvial flows and the changing locations of groundwater inflows in the Avon River, southeast Australia, Hydrol. Earth Syst. Sc., 20, 3581–3600, https://doi:10.5194/hess-20-3581-2016, 2016.

Coluccio, K. and Morgan, L. K.: A review of methods for measuring groundwater-surface water exchange in braided rivers, Hydrol. Earth Syst. Sc., 23, 4397–4417, https://doi:10.5194/hess-23-4397-2019, 2019.

Di Ciacca, A., Leterme, B., Laloy, E., Diederik, D., Vanderborght, J.: Scale-dependent parameterization of groundwater–surface water interactions in a regional hydrogeological model, J. Hydrol., 576, 494-507, https://doi:10.1016/j.jhydrol.2019.06.072, 2019.

Di Ciacca, A., Wilson, S., Kang, J., Wöhling, T.: Deriving transmission losses in ephemeral rivers using satellite imagery and machine learning. Hydrol. Earth Syst. Sc., 27, 703-722, https://doi:10.5194/hess-27-703-2023, 2023.

Dravid P.N. and Brown L.J.: Heretaunga Plain Groundwater Study - Vol 1: Findings, Hawke's Bay Regional Council, 1997.

Durridge: RAD7 electronic radon detector User Manual, 2020a.

Durridge: RAD H2O Radon in Water accessory for the RAD7 User Manual, 2020b.

Durridge: DRYSTIK Models ADS-3 andADS-3R Active Moisture Exchanger Accessory for the RAD7 User Manual, 2021.

Folk R.L. and Ward W.C., 1957. Brazos River bar: a study in the significance of grain size parameters, J. Sediment. Petrol., 27, 3–26, https://doi.org/10.1306/74d70646-2b21-11d7-8648000102c1865d, 1957.

Forsyth, P.J., Barrell, D.J.A., Jongens, R.: Geology of the Christchurch area. Institute of Geological & Nuclear Sciences 1:250 000 geological map 16. 1 sheet + 67p. Lower Hutt, New Zealand. GNS Science, 2008.

Fox, G.A. and Durnford, D.S.: Unsaturated hyporheic zone flow in stream conjunctive systems, Adv. Water Resour., 26 (9), 989–1000, https://doi.org/10.1016/S0309-1708(03)00087-3 2003, 2003.

Gardner, M. and Sharma, N.: Wairau River Mean Bed Level and Volumetric Analysis: 2010 to 2016, Report to Marlborough District Council, 2016.

González-Pinzón, R., Ward, A.S., Hatch, C.E., Wlostowski, A.N., Singha, K., Gooseff, M.N., Haggerty, R., Harvey, J.W., Cirpka, O.A., Brock, J.T.: A field comparison of multiple techniques to quantify groundwater-surface-water interactions, Freshw. Sci., 34, 139-160, https://doi:10.1086/679738, 2015.

Gray D.P, Hicks M., Greenwood M.: Advances in geomorphology and aquatic ecology of braided rivers, in: Advances in New Zealand freshwater science, edited by: Jellyman PG, Davie TJA, Pearson CP, Harding JS., New Zealand Freshwater Sciences Society, Christchurch, New Zealand, 357-378, 2016.

Harbaugh, A. W.: Modflow-2005, the U.S. geological survey modular ground-water model – the ground-water flow process. U.S. Geological Survey Techniques and Methods, 6-A16. Reston, Virginia, USGS, 2005.

Harvey, J. and Gooseff, M.: River corridor science: Hydrologic exchange and ecological consequences from bedforms to basins, Water Resour. Res., 51, 6893–6922, https://doi:10.1002/2015WR017617, 2015.

Harvey, J.W. and Wagner, B.J.: Quantifying Hydrologic Interactions between Streams and Their Subsurface Hyporheic Zones, in: Streams and ground waters, edited by Jones, J.B. and Mulholland, P.J., San Diego, CA: Academic Press, 3–44, doi: 10.1016/B978-012389845-6/50002-8, 2000.

Holmes, R. M., Fisher, S. G., & Grimm, N. B.: Parafluvial Nitrogen Dynamics in a Desert Stream Ecosystem, J. N. Am. Benthol. Soc., 13 (4), 468–478, https://doi:10.2307/1467844, 1994.

https://doi.org/10.5194/egusphere-2023-2767
Preprint. Discussion started: 13 December 2023

Huber, E., Huggenberger, P.: Subsurface flow mixing in coarse, braided river deposits, Hydrol. Earth Syst. Sc., 20, 2035–2046, https://doi:10.5194/hess-20-2035-2016, 2016.

Huggenberger P., Regli, C.: A sedimentological model to characterise Braided River deposits for hydrogeological applications, in: Braided rivers: process, deposits, ecology and management edited by Sambrook Smith GH, Blackwell, Malden, MA, 51–74, 2006.

Hupp, C.R. and Osterkamp, W.R.: Riparian vegetation and fluvial geomorphic processes. Geomorphology, 14, 277-295, https://doi.org/10.1016/0169-555X(95)00042-4, 1996.

Kalbus, E., Reinstorf, F., Schirmer, M.: Measuring methods for groundwater-surface water interactions: a review, Hydrol. Earth Syst. Sc., 10, 873-887, https://doi:10.5194/hess-10-873-2006, 2006.

Larned, S. T., Hicks, D. M., Schmidt, J., Davey, A. J. H., Dey, K., Scarsbrook, M., Arscott, D. B., Woods, R. A.: The Selwyn River of New Zealand: A benchmark system for alluvial plain rivers, River Res. Appl., 24, 1–21, https://doi:10.1002/rra.1054m, 2008

Laube, G., Schmidt, C., Fleckenstein, J.H.: The systematic effect of streambed conductivity heterogeneity on hyporheic flux and residence time, Adv. Water Resour., 122, 60-69, https://doi:10.1016/j.advwatres.2018.10.003, 2018.

Lee, J.M, Bland, K.J., Townsend, D.B., Kamp, P.J. J.: Geology of the Hawkes Bay area, Institute of Geological & Nuclear Sciences 1:250 000 geological map 8. 1 sheet + 93p. Lower Hutt, New Zealand. GNS Science, 2011.

Levy, J., Birck, M. D., Mutiti, S., Kilroy, K. C., Windeler, B., Idris, O., & Allen, L. N.: The impact of storm events on a riverbed system and its hydraulic conductivity at a site of induced infiltration, J. Environ. Manage., 92, 1960–1971, https://doi:10.1016/j.jenvman.2011.03.017, 2011.

Measures, R.: Modelling gravel transport, extraction and bed level change in the Ngaruroro River, NIWA Client Report CHC2012-121 for Hawkes Bay Regional Council, 2012.

Montgomery, J., Bind, J., Measures, R., Hoyle, J. (under review). Novel methods for measuring porosity in gravel bed rivers, Water Resour. Res.

Morel-Seytoux, H.J., Miller, C.D., Mehl, S. and Miracapillo, C.: Achilles' heel of integrated hydrologic models: The stream-aquifer flow exchange, and proposed alternative. J. Hydrol., 564, 900-908, https://doi.org/10.1016/j.jhydrol.2018.07.010, 2018.

Niswonger, R.G. and Prudic, D.E.: Documentation of the Streamflow-Routing (SFR2) Package to include unsaturated flow beneath streams - A modification to SFR1: U.S. Geological Survey Techniques and Methods 6-A13, 50 p, Reston, VA, USGS, 2005.

Pirot, G., Straubhaar, J., and Renard, P.: Simulation of braided river elevation model time series with multiple-point statistics, Geomorphology, 214, 148–156, https://doi:10.1016/j.geomorph.2014.01.022, 2014.

Pirot, G., Straubhaar, J., Renard, P.: A pseudo genetic model of coarse braided-river deposits, Water Resour. Res., 51, 9595-9611, https://doi:10.1002/2015WR017078, 2015.

Pirot, G., Huber, E., Irving, J., Linde, N.: Reduction of conceptual model uncertainty using ground-penetrating radar profiles: Field-demonstration for a braided-river aquifer, J. Hydrol., 571, 254-264, https://doi:10.1016/j.jhydrol.2019.01.047, 2019.

Poole, G.C. and Berman, C.H.: An ecological perspective on in-stream temperature: natural heat dynamics and mechanisms of human-caused thermal degradation, Environ. Manage., 27, 787-802, https://doi:10.1007/s002670010188, 2001.

Pryshlak, T.T., Sawyer, A.H., Stonedahl, S.H., Soltanian, M.R.: Multiscale hyporheic exchange through strongly heterogeneous sediments, Water Resour. Res., 51, 9127–9140, https://doi:10.1002/2015WR017293, 2015.

Rawlinson, Z.J, Westerhoff, R.S., Foged, N., Kellett, R.L.: Hawke's Bay 3D Aquifer Mapping Project, Heretaunga Plains SkyTEM data processing and resistivity models, GNS Science Consultancy Report 2021/93, 2021.

Reinfelds, I. and Nanson, G.: Formation of braided river floodplains, Waimakariri River, New Zealand, Sedimentology, 40, 1113-1127. https://doi.org/10.1111/j.1365-3091.1993.tb01382.x, 1993.

Rushton, K.: Representation in regional models of saturated river–aquifer interaction for gaining/losing rivers, J. Hydrol., 334(1), 262-281, https://doi.org/10.1016/j.jhydrol.2006.10.008, 2007.

Schälchli, U.: The clogging of coarse gravel river beds by fine sediment, Hydrobiologia, 235/236(1), 189–197, https://doi.org/10.1007/BF00026211 , 1992.

Shanafield, M. and Cook, P.G.: Transmission losses, infiltration and groundwater recharge through ephemeral and intermittent streambeds: A review of applied methods, J. Hydrol., 511, 518–529, https://doi:10.1016/j.jhydrol.2014.01.068, 2014.

Shanafield, M., Bourke, S.A., Zimmer, M.A., Costigan, K.H.: An overview of the hydrology of non-perennial rivers and streams, WIREs Water 8, e1504, https://doi:10.1002/wat2.1504Fsongol, 2021.

Songola, C.: Characterising Surface Water and Groundwater Interactions in Braided Rivers Using Hydraulics and Environmental Tracers: The Waikirikiri Selwyn River, MSc thesis, Lincoln University, 2022.

Sophocleous, M.: Interactions between groundwater and surface water: The state of the science, Hydrogeol. J., 10 (1), 52-67, https://doi:10.1007/s10040-001-0170-8, 2002.

Stanford, J.A. and Ward, J. V.: An Ecosystem Perspective of Alluvial Rivers: Connectivity and the Hyporheic Corridor, J. N. Am. Benthol. Soc., 12 (1), 48-60, https://doi.org/10.2307/1467685, 1993.

Steiger, J., Tabacchi, E., Dufour, S., Corenblit, D., Peiry, J.-L.: Hydrogeomorphic processes affecting riparian habitat within alluvial channel–floodplain river systems: a review for the temperate zone, River Res. Appl., 21, 719-737, https://doi:10.1002/rra.879, 2005.

Theel, M., Huggenberger, P., Zosseder, K.: Assessment of the heterogeneity of hydraulic properties in gravelly outwash plains: a regionally scaled sedimentological analysis in the Munich gravel plain, Germany, Hydrogeol. J., 28, 2657–2674, https://doi:10.1007/s10040-020-02205-y, 2020.

Therrien, R., McLaren, R. G., Sudicky, E. A., Panday, S. M.: HydroGeoSphere: A Three-dimensional Numerical Model Describing Fully-integrated Subsurface and Surface Flow and Solute Transport – User Manual, Groundwater Simulations Group, University of Waterloo, 2010.

Valett, H.M, Morrice, J.A., Dahm, C.N., Campana, M.E.: Parent lithology, surface–groundwater exchange, and nitrate retention in headwater streams, Limnol. Oceanogr., 41, https://doi: 10.4319/lo.1996.41.2.0333, 1996.

Warburton, J.: Active braidplain width, bed load transport and channel morphology in a model braided river, J. Hydrol., 35(2), 259–285, http://www.jstor.org/stable/43944775, 1996.

Ward, A.S.: The evolution and state of interdisciplinary hyporheic research, WIREs Water 3, 83-103, https://doi:10.1002/wat2.1120, 2015.

Ward, A.S. and Packman, A.I.: Advancing our predictive understanding of river corridor exchange, WIREs Water 6, https://doi:10.1002/wat2.1327, 2019.

White, D.S.: Perspectives on defining and delineating hyporheic zones, J.N. Am. Benthol. Soc., 12, 61– 69, https://doi.org/10.2307/1467686, 1993.

White, P.A., Kovacova, E., Zemansky, G., Jebbour, N., Moreau-Fournier, M.: Groundwater-surface water interaction in the Waimakariri River, New Zealand, and groundwater outflow from the river bed, J. Hydrol., 51, 1-23, https://www.jstor.org/stable/43944885, 2012.

Wöhling, T., Gosses, M.J., Wilson, S.R., Davidson, P.: Quantifying river–groundwater interactions of New Zealand's gravel-bed rivers: The Wairau Plain, Groundwater, 56, 647–666, https://doi:10.1111/gwat.12625, 2018.

Wöhling, T., Wilson, S.R., Wadsworth, V., Davidson, P.: Detecting the cause of change using uncertain data: Natural and anthropogenic factors contributing to declining groundwater levels and flows of the Wairau Plain aquifer, New Zealand, J. Hydrol., Regional Studies 31, 100715, https://doi:10.1016/j.ejrh.2020.100715, 2020.

Wu, F.-C & Huang, H.-T.: Hydraulic Resistance Induced by Deposition of Sediment in Porous Medium, J. Hydraul. Eng., 126 (7), 547-551, https://doi.org/10.1061/(ASCE)0733-9429(2000)126:7(547), 2000.

Wu, G.D., Shu, L.C., Lu, C.P., Chen, X.H., Zhang, X. Appiah-Adjei, E.K., Zhu, J.S.: Variations of streambed vertical hydraulic conductivity before and after a flood season, Hydrogeol. J., 23, 1603-1615, https://doi:10.1007/s10040-015-1275-9, 2015.

Zhou, Y., Ritzi, R.W., Soltanian, M.R., Dominic, D.F.: The influence of streambed heterogeneity on Hyporheic flow in gravelly Rivers, Groundwater, 52, 206–216, https://doi:10.1111/gwat.12048, 2014.