Enhancing the understanding of groundwater–surface water interaction in the northern Surat Basin

By

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And finally, my wife. For mustering our tribe during my early starts, and late finishes, while I pursued postgraduate studies around work and our life. Co-authoring this one wild and precious life with you, and our tribe, is a joy!

DECLARATION

I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

Signed:

Date: 24/05/2024

EXECUTIVE SUMMARY

The Dawson River – 'Wardingarri' – and Hutton Creek are regionally significant watercourses within the semi-arid southern Fitzroy River catchment, approximately 100 km north of Roma. This thesis is focused on integrating stream gauging data with environmental tracers to enhance the understanding of groundwater–surface water interaction along two perennial sections of these watercourses. These reaches are understood to be supported by groundwater discharge from the Precipice Sandstone, the basal aquifer of the Great Artesian Basin (GAB).

Beyond dissection and erosion of the overlying and confining Evergreen Formation, it is hypothesised that other landscape characteristics – such as faults and fractures, variability in stream substrate and stream slope – may influence the distribution of groundwater discharge to streams.

Understanding and quantifying the groundwater contribution to stream flow is typically more complicated than the surface water component (Hofmann, 2023). Tools and methods to quantify flux also vary considerably in terms of their suitability for upscaling. More broadly, understanding the sub-regional spatial and temporal connectivity regime – magnitude, timing and direction of flux between a groundwater system and surface water systems – is critical for effective groundwater resource management to ensure the maintenance of the underlying hydrogeological processes.

The study locations are within the Doonkuna (Hutton Creek) and Nathan (Dawson River) land systems, which are deeply dissected sandstone tablelands dominated by shallow and rocky soils. The stream channels comprise a mix of bedrock, cobble, gravel, sand and silt – with increasing silt and clay as the Dawson River overlies the downstream Evergreen Formation. Channel zones include small point bars, pools and riffles, with both reaches including highly sinuous zones with numerous angular and irregular bends (Brennan & Gardiner, 2004).

The underlying bedrock is the northern Surat Basin, one of the major Jurassic to Cretaceous hydrogeological sub-basins of the GAB. The main aquifers at the study locations are the Precipice and Hutton sandstones of the Surat Basin, which was deposited upon older eroded and folded geological basins, with two structural features proximal to the study locations – the Hutton-Wallumbilla fault system and the Arcadia Anticline.

Field observations, parameters and stream samples were collected at 30 locations on the Hutton Creek and Dawson River between 19 and 28 September 2023, during optimal baseflow conditions. Environmental tracer samples were collected concurrently with stream gauging data. The application of environmental tracers – ^{14}C, ^{222}Rn, ^{18}O, ^{2}H, ^{3}H, $^{87}Sr/^{86}Sr$ – in parallel with flux-based estimates, provided an opportunity to move beyond a physical flow volume, to the identification source aquifers, and to further subdivide the groundwater discharge components into local and regional flow contributions.

The thesis identifies that the net groundwater discharge from the study locations is approximately 6,500 ML/yr – 90% of which is associated with the Dawson River reaches. Differential stream data highlights the presence of significant inter-reach variability, both in terms of the direction and magnitude of flux with the surrounding groundwater system.

Analysis of ^{222}Rn concentrations were able to further refine the zones of higher groundwater flux with ^{14}C, ^{3}H and stable isotope results supporting the identification of reaches with local and regional groundwater flow contributions. The Hutton Creek has one zone dominated by older groundwater, with the Dawson River dominated by regional groundwater discharge, downstream of the confluence of Hutton Creek.

The Precipice Sandstone is the most homogenous and permeable aquifer in the Surat Basin. Consistent with previous assessments, this aquifer is interpreted to be the major groundwater source for both reaches, based on strontium isotope ratios and geological setting. This analysis indicates significant variability in groundwater discharge which appears to be controlled by factors beyond the underlying bedrock geology, stream substrate or slope. The stream gauging and environmental isotope data suggest that there is a high degree of local variability, with higher discharge zones likely to be the result of secondary porosity – fractures and structural features. This is consistent with recent studies in the northern Surat Basin, which characterise some parts of the Precipice Sandstone as exhibiting dual porosity.

This thesis highlights the benefits of integrating stream gauging and environmental tracer data to enhance the understanding of groundwater–surface water interaction. The environmental tracer data was able to elucidate deeper insights into the zones and sources of groundwater discharge, unable to be determined from stream gauging alone. This was even apparent where the study reaches were sampled during an optimal baseflow measurement period – extended dry period.

This updated conceptual understanding from this thesis is important in considering future climate regimes and potential impacts on regional groundwater flow from groundwater extraction and resource development, with implications for consequences of drawdown on dependent ecosystems.

INTRODUCTION

Overview

Surface water and groundwater systems are often conceptualised as hydraulically coupled reservoirs (Winter et al., 2000). In terms of groundwater flux, interactions are generally classified as either gaining, losing or disconnected, with the additional complexity of variations in the nature of interaction over very short distances (P. G. Cook, 2015; Winter et al., 2000).

Understanding the nature of groundwater-surface water connectivity – magnitude, timing and direction of flux – is critical for effective groundwater resource management and the maintenance of underlying hydrogeological processes, dependent ecosystems (Cartwright et al., 2011) and intrinsically linked cultural values.

The importance of groundwater discharge to streams and springs is most apparent within arid to semi-arid water-limited landscapes – such as the study area – where perennial waters often exhibit exceptional cultural and ecological significance, far beyond their limited spatial extents (Davis et al., 2021). The effective management of connected water resources necessitates building an understanding of the spatial and temporal connection between these resources (Hofmann, 2023; Winter et al., 2000). The degree of connection then informs the level of conjunctive water resource management that may be necessary (P. G. Cook, 2015).

Understanding and quantifying the groundwater component of a surface water flows to a stream is typically far more complicated than the surface water component (Hofmann, 2023). There are the broader flux directions, but there are often also parafluvial flow aspects, including bank storage, which must also be considered in some environments (P. G. Cook, 2015). In parallel, tools and methods to quantify flux vary in terms of their suitability for upscaling. For example, Darcian flux estimates derived from regional piezometric surfaces provide a significantly different scale of information to estimates derived from seepage meters (P. G. Cook, 2015).

This thesis is focused on enhancing the characterisation of groundwater–surface water interaction in the Dawson River catchment in the southern Fitzroy River Basin, which overlies the northern Surat hydrogeological sub-basin of the Great Artesian Basin (GAB). In this area, sections of Hutton Creek and the Dawson River flow perennially and are broadly interpreted to be regional discharge areas for the Precipice Sandstone, the basal aquifer of the GAB (Mollan et al., 1972; OGIA, 2015a; B. Smerdon & Ransley, 2012) (Figure 26).

In terms of groundwater stressors, there is significant groundwater extraction from the Precipice Sandstone, which has increased over the past 100 years – primarily for stock and domestic purposes, but also for town water supply and industrial use (OGIA, 2016). Additionally, coal seam gas (CSG) development has progressively expanded since 1994 in the Permian Bandanna Formation of the Bowen Basin, which underlies the Surat Basin. There are known features – geological contact zones – that are interpreted to locally increase the connectivity between the Precipice Sandstone and the Bandanna Formation, and impacts on groundwater pressure at the study locations are predicted in the longer term by the independent Office of Groundwater Impact Assessment (OGIA) (OGIA, 2021b).

This thesis focuses on the application of isotope hydrology to improve the hydrogeological conceptualisation of Hutton Creek and the Dawson River and the groundwater component of stream flow. This work integrates groundwater bore, spring and stream data within the study area, collected by the OGIA and collaborators since 2011.

Objectives

The study area is recognised as a regional discharge zone for the Precipice Sandstone. The primary mechanism for groundwater discharge is interpreted to be the dissection and erosion of the overlying and confining Evergreen Formation, which exposes the confined Precipice Sandstone within the stream bed, enabling groundwater discharge (OGIA, 2015a). Around 300 m of Mesozoic sediments were eroded during formation of the Dawson River in this area, resulting in the formation of a significantly dissected landscape (Exon, 1971; B. Smerdon & Ransley, 2012).

Beyond landscape dissection and erosion, it is hypothesised that other characteristics – such as faults and fractures, variability in stream slope and substrate – may influence the location and magnitude of groundwater discharge to stream, and that discharge may comprise both local and regional groundwater flow.

Integrating stream gauging and environmental tracer data, the objectives of this thesis are to identify:

- the spatial variability, direction and magnitude of flux;
- local and regional groundwater flow components of discharge; and
- the dominant groundwater source for each stream.

Stream data and environmental tracer data are analysed from a single survey period and therefore temporal variability is not assessed as part of this thesis. The results and findings seek to enhance the underlying conceptual model for the groundwater system and groundwater–surface water interaction in this area. This improved understanding will provide a basis for future impact assessments and to guide further research.

Location

The study sites are located along two stream sections in the upper Dawson River sub catchment, which forms part of the southern Fitzroy Basin catchment in central Queensland. The study sites – hereafter referred to as the Hutton Creek and Dawson River – are located approximately 100 km north of the township of Roma, between Injune and Taroom (**Error! Reference source not found.**).

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Figure 1: The study location (red) within the Surat Basin, a sub-basin of the GAB. The blue areas are the spring supergoups in the GAB (after Fensham, Ponder & Fairfax 2005). The Surat Cumulative Management Area (CMA) is also shown for context (black polygon) (modified after Flook et al., 2020)

The broader Fitzroy Basin catchment is recognised as the second largest in Australia (Yu et al., 2013) and encompasses the traditional lands of 16 First Nations groups. The study sites are within the traditional lands of the Iman First Nation, along the upper Dawson River ('Wardingarri').

The climate is sub-tropical and semi-arid, dominated by summer rainfall with mean monthly maximum temperatures ranging from 20 to 34 °C and an annual average rainfall of 630 millimetres (Injune Post Office).

The area is within the Brigalow Belt Bioregion, which is dominated by Brigalow forest, eucalypt forests, grasslands and riparian communities (Yu et al., 2013). The area was largely undisturbed until the 1960s prior to clearing for grazing, with more than 90% of the catchment now cleared for agricultural development (Yu et al., 2013).

In the immediate vicinity of the Hutton Creek study site, there has been significant land clearing for grazing operations. In contrast, around the Dawson River site, there are protected areas to the north – the Expedition Range National Park (limited depth) – and comparatively less land clearing for agricultural purposes (Figure 2).

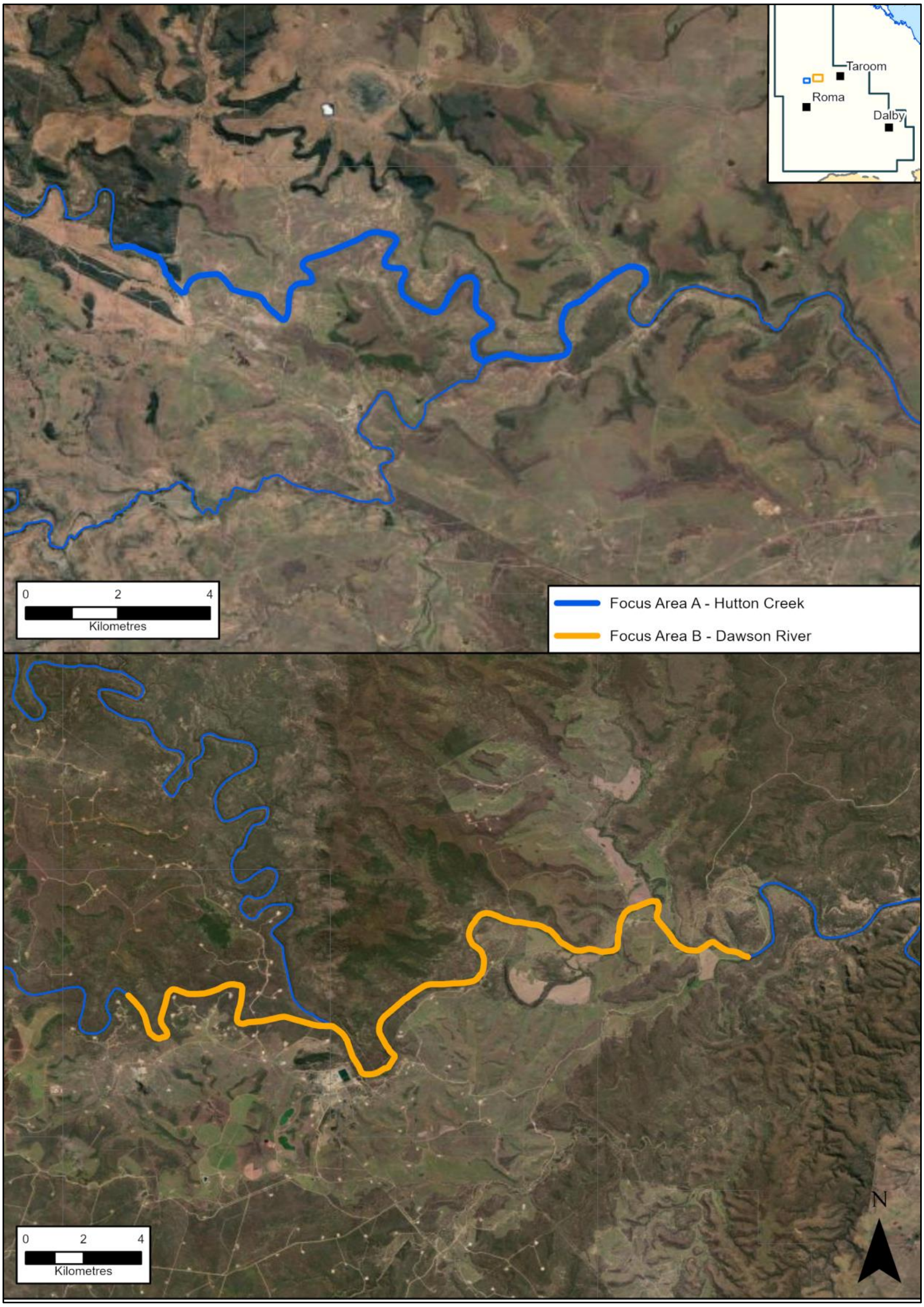

Figure 2: Aerial imagery showing the study locations and surrounding landscape. The land use around Focus Area A is largely cleared for gazing purposes. The land use around Focus Area B differs north and south of the Dawson River – to the north is the Expedition National Park and to the south is cleared grazing lands and coal seam gas development.

BACKGROUND

Landscape

The study sites are within the Doonkuna (Hutton Creek) and Nathan (Dawson River) land systems – a classification based on a pattern of topography, soils, and vegetation. Both land systems are characterised by deeply dissected sandstone tablelands dominated by shallow and rocky soils (Speck et al., 1968, p. 197) (Figure 3). The primary difference between these land systems is the pattern of dissection, which is more densely incised in the Nathan land system. The Doonkuna land system shows a proportionately higher area of summit slopes compared to the Nathan land system (Speck et al., 1968).

Around both Hutton Creek and the Dawson River, drainage lines are dissected down to the Precipice Sandstone – basal unit of the Surat Basin – in many areas and erosional processes are now expressed on the banks of drainage lines, rather than developing deeper channels (OGIA, 2015b). Plateaus are principally represented by the Boxvale Sandstone Member of the Evergreen Formation (Figure 4 and Figure 26). There is limited soil development on slopes and plateaus within these land systems, generally limited to skeletal, well-draining shallow rudosols, which are likely to be conducive to infiltration and local groundwater flow (OGIA, 2015b).

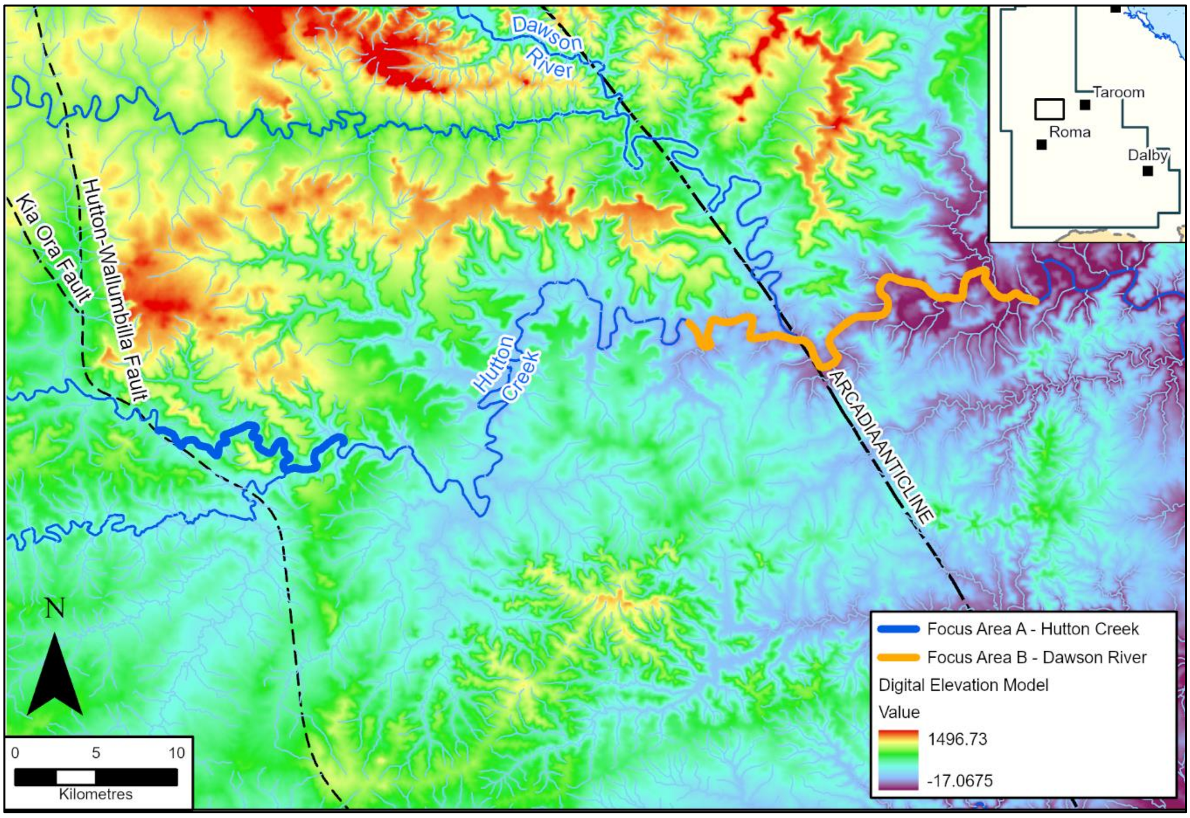

Figure 3: Terrain map of the study sites and sample locations. Around the Hutton Creek focus area, the Doonkuna land system is comparatively less deeply incised compared to the Nathan land system

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Figure 4: Schematic and description of the Nathan Land system highlighting that landform is dominated by crests (50%) and stony, scree and erosional slopes (40%) (modified after Speck et al. 1968)

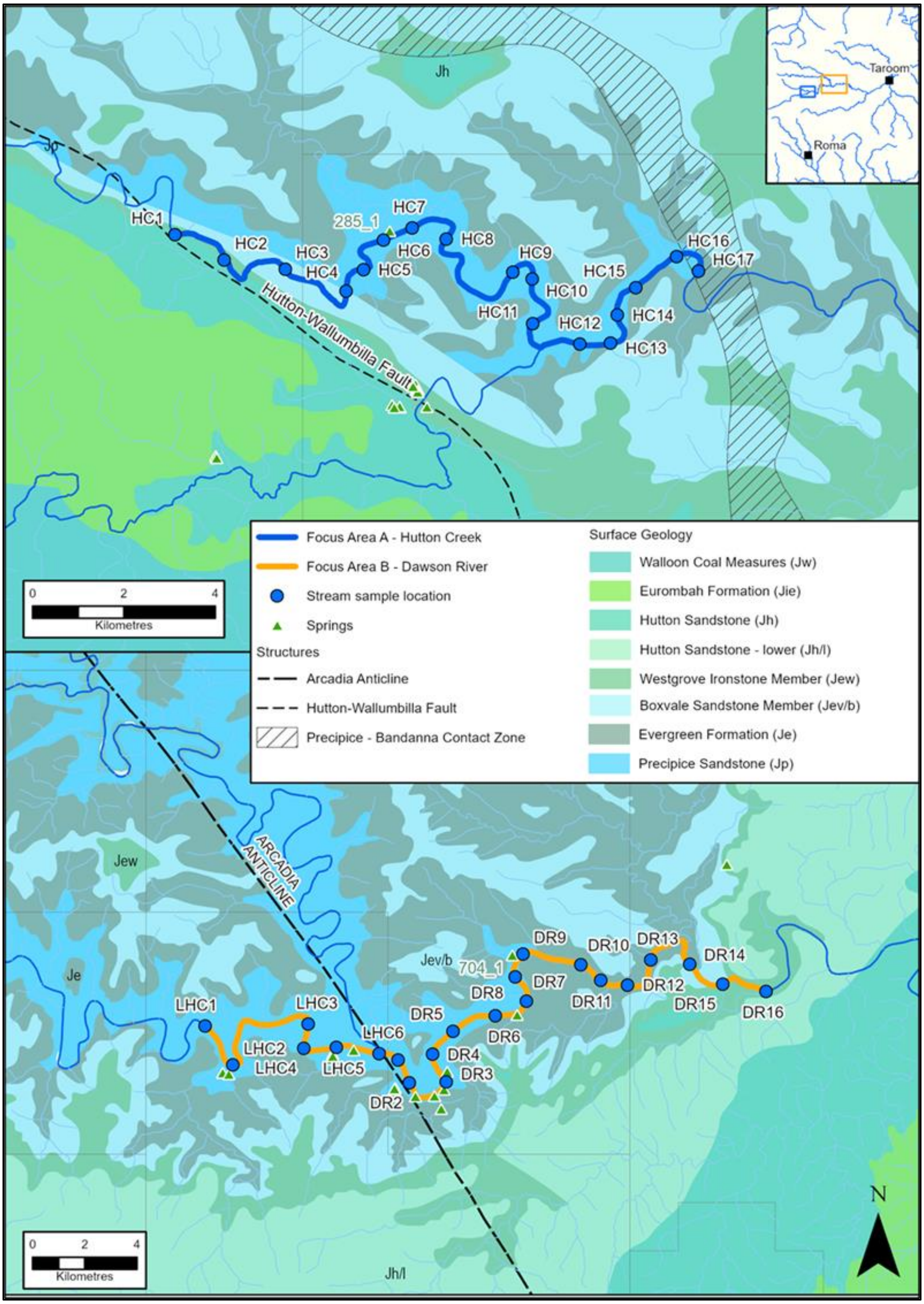

Figure 5: Hydrogeological map showing Focus Area A – Hutton Creek (top) and Focus Area B – Dawson River (Bottom). Stream sample locations, outcrop geology and structures are shown for reference. Two springs are labelled - Springrock Creek (285_1) and 704 (704_1).

Geomorphology

The upper Dawson River catchment has a dendritic channel pattern with confined valley settings along the Dawson River and partially confined valley settings along Hutton Creek (Figure 3). Within these valley settings, only minor floodplain pockets develop on the inside of some bends (Brennan & Gardiner, 2004).

The channel beds contain a mix of bedrock, cobble, gravel, sand and silt (Boobook, 2021) – with silt and clay increasing as the Dawson River progressively overlies the downstream Evergreen Formation – and channel zones that include small point bars, pools and riffles (Brennan & Gardiner, 2004). Generally, varying channel zones and composition are potential influences on steam bed hydraulic conductivity (P. G. Cook, 2015).

Both of the sampled reaches have highly sinuous channels with numerous angular and irregular bends – most prominent at Focus Area B along the Dawson River (Brennan & Gardiner, 2004). Images showing selected monitoring locations are provided in Figure 6. Rapid changes in stream morphology are interpreted by OGIA (2015a) to be unrelated to changes in the underlying geology and are likely related to geological structures in the area. Variations in stream geometry and geomorphology can influence the magnitude of flux with the convergence of equipotential flow lines on the outside of meander bends, resulting in comparatively higher rates of groundwater flux (P. G. Cook, 2015).

The combination of stream bed composition, morphology, orientation and underlying structures is likely to influence the magnitude and direction of groundwater flux and the groundwater–surface water interaction regime more broadly.

As discussed above and shown in Figure 3, there is significant topographic relief in the upper Dawson River catchment. Using the available digital elevation model (DEM), stream bed elevation is estimated and shown in Figure 7. Note, many sections along the Dawson River are within deeply incised valleys and this is therefore an estimate only.

The total stream slope along Hutton Creek is approximately 0.2%, with the Dawson River slightly less at around 0.1% slope. The data for the Dawson River indicate three distinct slope zones – the initial 12 km is around 0.20%, followed by a lower slope zone (0.05%) for approximately 10 km, then an increase to approximately 0.13% for the remaining reaches investigated in this thesis.

Figure 6: A selection of sample locations showing variations in stream morphology, width and substrate at Hutton Creek (top) and Dawson River (bottom)

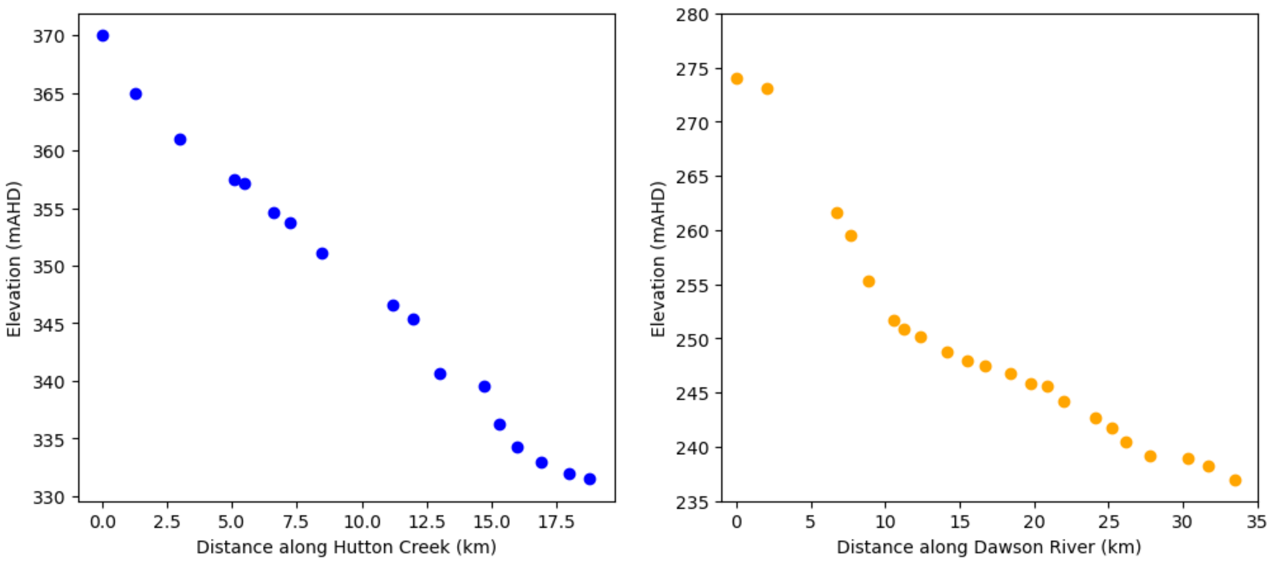

Figure 7: Approximate stream bed elevation along the study reaches. At the Hutton Creek location there is a relatively consistent stream slope. Distinct slope zones are interpreted along the Dawson River location.

Hydrogeology

Geology

The study locations are within the northern Surat Basin, one of the major Jurassic to Cretaceous hydrogeological sub-basins of the GAB (Figure 8 and Figure 27). The total area of the Surat Basin is 440,000 km^2, of which 40% is in Queensland, with the balance in northern New South Wales (OGIA, 2016a) (**Error! Reference source not found.**). The regional hydrostratigraphic framework for the Surat Basin is provided in the Appendix (Figure 26).

The GAB has historically been conceptualised as a groundwater system comprising alternating layers of relatively uniform, permeable sandstone aquifers and lower-permeability siltstone and mudstone aquitards (OGIA, 2016a). Over the last two decades, there has been a range of studies – such as the GAB Water Resource Assessment (Ransley & Smerdon 2012) – that have contributed to the evolution of the simple conceptual model, to a more complicated hydrostratigraphy, comprising within-formation heterogeneity and more variable groundwater flow directions (OGIA, 2016a). This evolution of system understanding has seen some formations, such as the Hutton and Precipice sandstones, further subdivided into sub-units (OGIA, 2016a).

The deposition of the Surat Basin upon older eroded and folded geological basins significantly influenced the overarching structure and architecture of the groundwater flow system (OGIA, 2016a) (Figure 8). As described by Exon (1976), around the northern margins of the Surat Basin, the lower Jurassic sequence – Hutton Sandstone, Evergreen Formation and Precipice Sandstone – is exposed and extensively eroded due to uplift during the Cenozoic.

From these northern areas of exposure, the sediments of the Surat Basin generally dip in a south-westerly direction, with some variability due to main depocenters, including the Mimosa Syncline (Figure 8 and Figure 27). The Mimosa Syncline is bound in the northern Surat Basin by fault systems on the east (Burunga-Leichardt) and west (Hutton-Wallumbilla) (OGIA, 2016a).

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Figure 8: Regional hydrogeological setting (modified after OGIA 2021a). The study sites are in the northern Surat Basin where the lower Jurassic sequence has been eroded (red box). A schematic cross section represents the Mimosa Syncline bound by regional basement structures.

Structures

As described in OGIA (2016), there are several tectonic events responsible for the current configuration and structural features of the Surat Basin (OGIA 2016, p31-32) including:

- A regional uplift and tilting during the middle Cretaceous terminated the deposition of the Surat Basin and resulted in large-scale erosion of Jurassic-Cretaceous sediments (Raza, Hill & Korsch 2009). This caused only minor deformation, with reactivation of Triassic thrust faults generally manifested as folding in the Surat Basin succession.
- A subsequent uplift and compression event in the late Cretaceous caused significant folding and small-scale faulting. The faulting displacement associated with this event is generally sub-seismic and less than 50 m.

The location of structures in the Surat Basin is, therefore, largely controlled by the location and reactivation of deeper faulting in the Bowen Basin (OGIA, 2016a). There are two regionally significant structural features proximal to the study locations – the Hutton-Wallumbilla fault system and Arcadia Anticline (Figure 8).

The Hutton-Wallumbilla fault system is a northwest-to-southeast strike regional structure interpreted to be a near-vertical thrust fault exceeding 100 km in length (Green, 1997). This feature is located on the western shoulder of the Mimosa Syncline, with a segment located adjacent to the Hutton Creek. This fault shows displacements of more than 300 m and is interpreted to primarily affect the Bowen Basin (OGIA, 2020).

The fault system developed during the back-arc extension phase of the Bowen-Gunnedah Basin (early Permian), which produced a series of graben and half-graben structures along the eastern margin of the Australian continent (Jones & Veevers, 1983). It is acknowledged, however, that basement features such as the Hutton-Wallumbilla fault system are observed to affect the overlying Surat Basin sequence where they have been reactivated post-deposition (OGIA, 2016a, 2020). This is likely to lead to heavy brecciation in the subsurface fault zone and zones of higher permeability (Coote, 1984; Jensen et al., 1964).

The Arcadia Anticline plunges from northwest to southeast along the Dawson River prior to the confluence with Hutton Creek. Along the axis of this anticline, the Bowen Basin sediments are exposed to the northeast in the Arcadia Valley. The lowermost highly permeable subunit of the Precipice Sandstone is likely most exposed at the axis of this feature, around the confluence of Hutton Creek and the Dawson River. KCB (2012) highlights, given the size of this feature, it is likely that many smaller faults and fractures are associated with this anticline, despite limited mapped structural features in this area.

McPherson, Rollet, Visy & Kilgour (2022) and McPherson, Rollet, Visy, Ransley, et al. (2022) examined airborne electromagnetic (AEM) data in the northern Surat Basin around the study location and on the eastern limb of the Mimosa Syncline (Figure 8 and Figure 27) around the Leichhardt-Burunga fault system. Around Hutton Creek, this work interprets that the Precipice Sandstone is conformable and undeformed on the eastern side of the Hutton-Wallumbilla fault system.

More broadly across the northern Surat Basin, McPherson et al. (2022) found that larger structural zones, folds and faults – such as the Hutton-Wallumbilla fault system and the Arcadia Anticline in this area – are interpreted to influence the pre-and-post-depositional architecture, which may result in aquifer compartmentalisation and inter-aquifer connectivity.

Aquifers

In the northern Surat Basin, the main aquifers with significant water storage, permeability and consumptive water use are the Precipice and Hutton sandstones (OGIA, 2016a). Where both formations are present, they are separated by the intervening and confining regional aquitard of the Evergreen Formation (OGIA, 2016a). At the study locations, the Evergreen Formation has been eroded and dissected by the Dawson River to expose the Precipice Sandstone within the channel (Figure 8).

The Precipice Sandstone is the lowermost unit of the Surat Basin and represents the start of the first major sedimentary cycle (Radke et al. 2012) (Figure 26). Deposited within a braided stream environment, the type section is along the Dawson River at the study location and was originally described as ‘thick-bedded, cross-stratified, fine to coarse-grained, pebbly quartzose sandstone with minor lithic sub-labile sandstone, siltstone and argillite’ (Mollan et al., 1972). The unit has progressively been further described as two subunits with a fine-grained uppermost unit and a lower coarse quartzose, thick bedded sandstone (Green, 1997). The thickness of the formation is interpreted to be up to 110 m within the Mimosa Syncline, a major depocenter of the Surat Basin (OGIA, 2016a).

The Precipice Sandstone – particularly the lowermost subunit – is considered the most homogenous and consistent aquifer of the Surat Basin, characterised by high aquifer transmissivity due to the dominance of coarse-grained clean sandstone with an effective porosity of 0.05-0.26 and hydraulic conductivity of 0.01-2.9 m/d (OGIA, 2016a). Recent investigations by Hayes et al. (2020) analysed formation pressure responses in the Precipice Sandstone due to ongoing injection by Origin Energy and interpreted extremely high permeability values – up to 200 m/day – which were interpreted to occur due to dual porosity in heavily fractured areas.

Groundwater discharge at springs is interpreted to occur from several aquifers in the Surat Basin, with the Precipice Sandstone the dominant source aquifer in the northern Surat Basin. The location of spring discharge is primarily driven by regional and local geology and topography (OGIA, 2016b).

In addition, several springs in the Precipice Sandstone – such as the Lucky Last and Boggomoss spring complexes – are associated with the regional fault systems of the Hutton-Wallumbilla and Leichhardt-Burunga fault systems, respectively (OGIA, 2016b).

Hydrodynamics

As described by Hodgkinson et al. (2010), OGIA (2021b, 2016) and others, the dominant groundwater flow direction in the Surat Basin is from recharge areas in the north and northeast towards the south and southwest. Importantly, these authors also identify a prominent and important groundwater divide, which aligns with the regional topographical feature – the Great Dividing Range – with potentiometric surfaces indicating flow perpendicular to this feature in the east (Figure 9).

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Figure 9: Regional groundwater flow directions in the Precipice Sandstone (after OGIA, 2021b). The two study areas are shown in blue and orange in the northwest.

Local groundwater flow conditions around the study locations are presented in OGIA (2015a), Jacobs (2018) and Flook et al. 2020 (Figure 10). Around the Hutton Creek location, flow directions for the Precipice Sandstone are interpreted to flow from the north and northwest to the southeast and are generally perpendicular to the Hutton-Wallumbilla fault system. This is interpreted to indicate either that the fault is a barrier or there is lateral connectivity across the fault zone (Flook et al. 2020). Based on the potentiometric surface mapping, groundwater elevation is interpreted to be higher than the streambed in this area, with the Precipice Sandstone (and potentially the Hutton Sandstone) interpreted to support baseflow.

Around the Dawson River study location, groundwater flow directions are predominantly from west to east and are interpreted to be a subdued reflection of topography (OGIA, 2015a). Groundwater conditions in the Precipice Sandstone are interpreted to be strongly artesian, supporting discharge to stream in the absence of the overlying and confining Evergreen Formation.

Local groundwater contours prepared by Jacobs (2018) indicate steep gradients on the southern side of Hutton Creek near the confluence with the Dawson River (Figure 10). Further downstream, the contours indicate a groundwater sink along this section of the Dawson River, indicating a potential reversal of groundwater flow directions in this area.

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Figure 10: Potentiometric surface map for the Precipice Sandstone in 2014. Blue circles are regularly sampled data points. Yellow circles are non-timestamped data. Red diamonds are rain gauges. Yellow area is the outcrop of the Precipice Sandstone (after Jacobs 2019).

Groundwater development

Groundwater supply

The Precipice Sandstone is a highly permeable and fresh groundwater source and is therefore a significant target for groundwater supplies, particularly where the formation is shallow in the northern Surat Basin and where there are minimal overlying aquifers. Across the Surat Basin, approximately 8,165 ML/yr is extracted from around 450 bores for stock and domestic, town water supply, industrial and stock-intensive purposes (OGIA, 2021b). Within 20 km of the study locations, there are 156 water supply bores, primarily for stock and domestic purposes, with an estimated total extraction of 156 ML/yr.

In addition to groundwater extraction, more than 30,000 ML of treated associated water has been reinjected into the Precipice Sandstone since early 2015 – averaging around 4,000 ML/yr. Pressure responses across the aquifer system have been observed at more than 80 km from the injection facility (OGIA, 2023).

Resource industry development

The major resource development activity in the vicinity of the study location is coal seam gas (CSG) development from the Bandanna Formation of the Bowen Basin at Santos's Fairview gas field (OGIA, 2021b). This field commenced production in 1994. Although the target coal seams are within the Bowen Basin sequence, there is an interpreted zone of potential connectivity with the Precipice Sandstone between the two study sites – the western contact zone (Figure 11) (OGIA, 2016a, 2021b, 2023).

The extraction of CSG requires large-scale depressurisation of the coal resource to desorb and mobilise the gas from the surface of the coal. The current maximum all-time prediction of impact from CSG to the Precipice Sandstone via the western contact zone is approximately 3 m drawdown in hydraulic head (OGIA, 2021b).

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Figure 11: Interpreted contact zones between the Bandanna Formation and overlying Precipice Sandstone (OGIA 2021a). The cross-section A – A' is proximal to the study locations.

Previous baseflow assessments

Early geological surveys and investigations (Mollan et al., 1972) note the occurrence of perennial streams supported by discharge from springs in the Precipice Sandstone, including Hutton Creek and the Dawson River. The magnitude and spatial variability of flux are generally not described.

Between 2007 and 2008, technical assessments were completed to evaluate the potential implications of the discharge of associated water from CSG to the Dawson River close to DR12 (Figure 5) – detailed in the Environmental Impact Statement for the Santos Gladstone Liquefied Natural Gas (GLNG) project.

URS (2009) reports on the findings from stream surveys in 2007 and 2008 – stream gauging and physical parameters – and landholder experiential knowledge about stream flow and dynamics of the Dawson River, in an area similar to the Dawson River study area in this thesis. Key observations and findings (Hydro Tasmania Consulting, 2008) include the following:

- a large number of springs (>30) were identified, ranging from very small seeps to flows of approximately 0.5 L/s, with several larger springs considered the major contributors of baseflow to the stream.
- a significant increase in flow – from 68 to 171 L/s – was observed downstream of the confluence with Hutton Creek, with the majority of additional flow occurring within 1.5 km of the confluence. Downstream losses were noted and interpreted to possibly relate to geological anomalies or nearby groundwater use.
- discharge was estimated to contribute 196 L/s (17 ML/day) to the Dawson River in this area.

During the development and analysis of the regional watertable map for the GAB, Smerdon and Ransley (2012) highlighted the effect of the deeply incised and dissected valley of the upper Dawson River on groundwater flow in this area. Local topography was interpreted to be sufficiently dissected to intersect the watertable, resulting in localised groundwater sinks along Hutton Creek and the Dawson River, the area more broadly being recognised as an area of groundwater discharge (loss) from the GAB. The study estimated the combined discharge to the Dawson River[1] from the Hutton and Precipice sandstones to be approximately 20,000 ML/yr (67 ML/day) – with more than 80% interpreted to be from the Precipice Sandstone (Ransley and Smerdon 2012).

Consistent with Smerdon and Ransley (2012), OGIA (2016) recognised the reduced confinement of the Precipice Sandstone due to landscape dissection by surface water flows, resulting in a regional discharge zone from the Precipice Sandstone in these areas. In parallel, OGIA (2016) highlights the

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[1] The total outcrop area assessed by Smerdon and Ransley (2012) includes the outcrop west of Taroom. This is a significantly larger area than the current study.

extensive and low-lying outcrop areas that are interpreted to have shallow watertables and likely support extensive communities of terrestrial groundwater-dependent ecosystems (GDEs).

Detailed ecohydrological conceptualisations of the spring complexes surrounding Hutton Creek were undertaken by OGIA in 2015 – Springrock Creek (OGIA, 2015b), Lucky Last (Flook et al. 2020) and 311 (OGIA, 2015a). At Springrock Creek – a tributary of Hutton Creek adjacent to HC6 (Figure 5) – OGIA (2015b) interpreted the combination of topographically driven local flow and regional groundwater flux from the Precipice Sandstone, with the volume of discharge interpreted to be equal to, or slightly greater than evapotranspiration.

Around the confluence of Hutton Creek and the Dawson River, OGIA (2015a) interpreted that regional groundwater flow from the Precipice Sandstone was the dominant source, with a high likelihood of local topographically driven groundwater flux along bedding planes in the banks of the Dawson River.

Since 2017, Santos has undertaken low-flow stream gauging of the study area in accordance with obligations established in the Underground Water Impact Report (UWIR) for the Surat CMA (OGIA, 2019a, 2021b). A multiple-lines-of-evidence analysis was applied in 2017 (Jacobs, 2019), incorporating the stream data to understand how aquifer pressure may be related to discharge and the implications for a change in the pressure regime.

The controls on groundwater discharge was a key area of investigation with relevant observations and conclusions from Jacobs (2019) were:

- The 2017 upper Hutton Creek survey indicated baseflow accretion where the channel transitions onto the Precipice Sandstone outcrop – maximum flow of approximately 16 L/s.
- The flow accretion trends were broadly consistent with the 2008 survey.
- Significant flow accretion is observed only where there is a significant gradient between the Precipice Sandstone groundwater levels and the decreasing channel elevation around the confluence of Hutton Creek and the Dawson River.
- The nature of the channel, banks and bed material between the lower Hutton Creek and the Dawson River (below the confluence) corresponds with the increase in baseflow accretion – lower angle banks, coarse sandy bed material and frequent shallow, faster-flowing sections.
- Injection to the Precipice Sandstone generates a clear pressure signal in the aquifer but there is little obvious increase in winter stream flows in the Dawson River.
- Based on the continuous downstream flow records at Utopia Downs, variability between years appears to be strongly linked to variations in rainfall excess and deficit – noting this is not observed in the hydrograph data.

These previous assessments have recognised the study areas as zones of regional discharge from the Precipice Sandstone and have, in many cases, collected valuable data to assess local stream flow conditions. This thesis seeks to build upon these assessments by characterising the spatial distribution of baseflow and understanding the local and regional flow contributions to stream flow.

DATA AND METHODS

Overview

Many watercourses transition between gaining and losing conditions on a range of spatial scales due to the variable relationship between groundwater and stream levels, driven by climate variability, surface and groundwater extraction, changes in channel morphology, heterogeneity of streambed sediments, land use and local groundwater extraction (P. G. Cook, 2015; Hofmann, 2023).

Environmental tracers offer some unique advantages over physical measurement methods – such as permanent gauging stations – with the potential to provide a deeper understanding of the spatial distribution of groundwater inflows than may be achieved with physical monitoring infrastructure, which is often sparsely located and expensive (P. Cook et al., 2003). It should be noted that the accuracy of estimated flux is significantly influenced by how well the end member concentrations are constrained; a multi-tracer approach to estimating flux is therefore often applied (P. Cook et al., 2003).

In addition to the application of environmental tracers to support flux-based estimates, these data provide an opportunity to move beyond the physical volume, to determine source aquifers and to further subdivide the groundwater discharge components into local and regional flow contributions. This will enhance the understanding of the internal dynamics of the discharge zone, leading to a more comprehensive understanding of groundwater–surface water interaction in this area (B. D. Smerdon et al., 2012). This conceptual understanding is important when considering future climate regimes and potential impacts on regional groundwater flow from groundwater extraction and resource development, with implications for the consequences of drawdown on dependent ecosystems.

In parallel with improving the conceptual understanding of groundwater–surface water interaction, numerous studies have applied a mass balance approach to estimating stream flow (P. Cook et al., 2003; Ellins et al., 1990). A range of analytes and isotopes will be applied in this thesis, with the following sections providing a summary of their application.

Data

Since the commencement of resource development in the Surat and southern Bowen basins, there have been numerous technical assessments to conceptualise the groundwater system, GDEs, and connectivity between the target CSG reservoirs and adjacent aquifers. For this assessment, a range of data sources have been compiled from the Queensland Government, tenure holder investigations and research organisations.

Historical data sources

Hydrochemistry and isotope data presented in this report include data collected by OGIA as part of research projects in the area since 2011, collaborations with CSIRO and data collected by tenure holders in accordance with the Surat UWIR and Australian Government project approval conditions. Stream flow data presented in this report was collected by Santos in accordance with the Surat UWIR 2021 (OGIA, 2021b) (Figure 12).

Field data collection for this thesis

Observations, field parameters and surface water samples were collected at 30 locations on Hutton Creek and the Dawson River between 19 and 28 September 2023. Optimal baseflow conditions were encountered with minimal rainfall – less than 1 mm at the Injune Post Office (Figure 8) – recorded in the eight weeks prior to sampling. Water samples were collected from the lowermost portion of the water column within the stream, to minimise exchange with the atmosphere and to maximise the potential for the collection of groundwater discharge.

To enable the comparison of samples with flow conditions, sampling was undertaken in parallel with stream flow gauging commissioned by Santos in accordance with its statutory obligations established in the Surat UWIR 2021 (OGIA, 2021b).

Analytical procedures

Field samples were analysed for Radon (^{222}Rn) using a Durridge RAD7 commercial radon-in-air monitor (Burnett et al., 2001). During the field campaign, samples were collected in 250-mL glass bottles, with analysis of samples undertaken within 12 hours of collection. A correction was applied to account for the decay that occurred between sampling and analysis. Also incorporated into the analysis are ^{222}Rn samples – historically collected at nearby springs and water bore locations – with a 1.3-L plastic sample bore and shaken with 20 mL mineral oil scintillant for four minutes to transfer the ^{222}Rn to the oil for subsequent analysis at CSIRO Adelaide (Leaney & Herczeg, 2006).

Stable isotopes of water (^{2}H and ^{18}O) and dissolved inorganic carbon (^{13}C DIC) were collected using a 125-mL plastic bottle and analysed at the Stable Isotope Geochemistry Laboratory, School of Earth and Environmental Sciences at the University of Queensland. Thermo Delta V with Gasbench was used for DIC and an Isoprime Dual Inlet Mass Spectrometer with Multiprep was used for ^{2}H and ^{18}O. Historical samples were analysed at the Stable Isotope Facility at the University of California (Davis) using continuous-flow Isotope-Ratio Mass Spectrometry (IRMS) and at the Environmental Tracer and Noble Gas Laboratory at CSIRO, Adelaide.

Samples for Radiocarbon (^{14}C) were collected using 1-L Nalgene plastic bottles and analysed at the Australian National University, College of Science, Radiocarbon Laboratory using a Single Stage Accelerator Mass Spectrometer (Fallon et al., 2010). Historical samples were analysed at the Australian Nuclear Science and Technology Organisation (ANSTO).

Samples for Tritium (^3H) were collected using 1-L Nalgene plastic bottles and analysed using Quantulus low-level liquid scintillation spectrometers by GNS Science, Tritium and Water Dating Laboratory, New Zealand.

Samples for strontium isotope analysis ($^{87}Sr/^{86}Sr$) were filtered through 0.45-micron filters into 60-mL plastic bottles containing nitric acid as a preservative, then analysed at the Radiogenic Isotope Facility, School of the Environment at the University of Queensland. Historical samples were analysed at the University of Melbourne (School of Geography, Earth and Atmospheric Sciences).

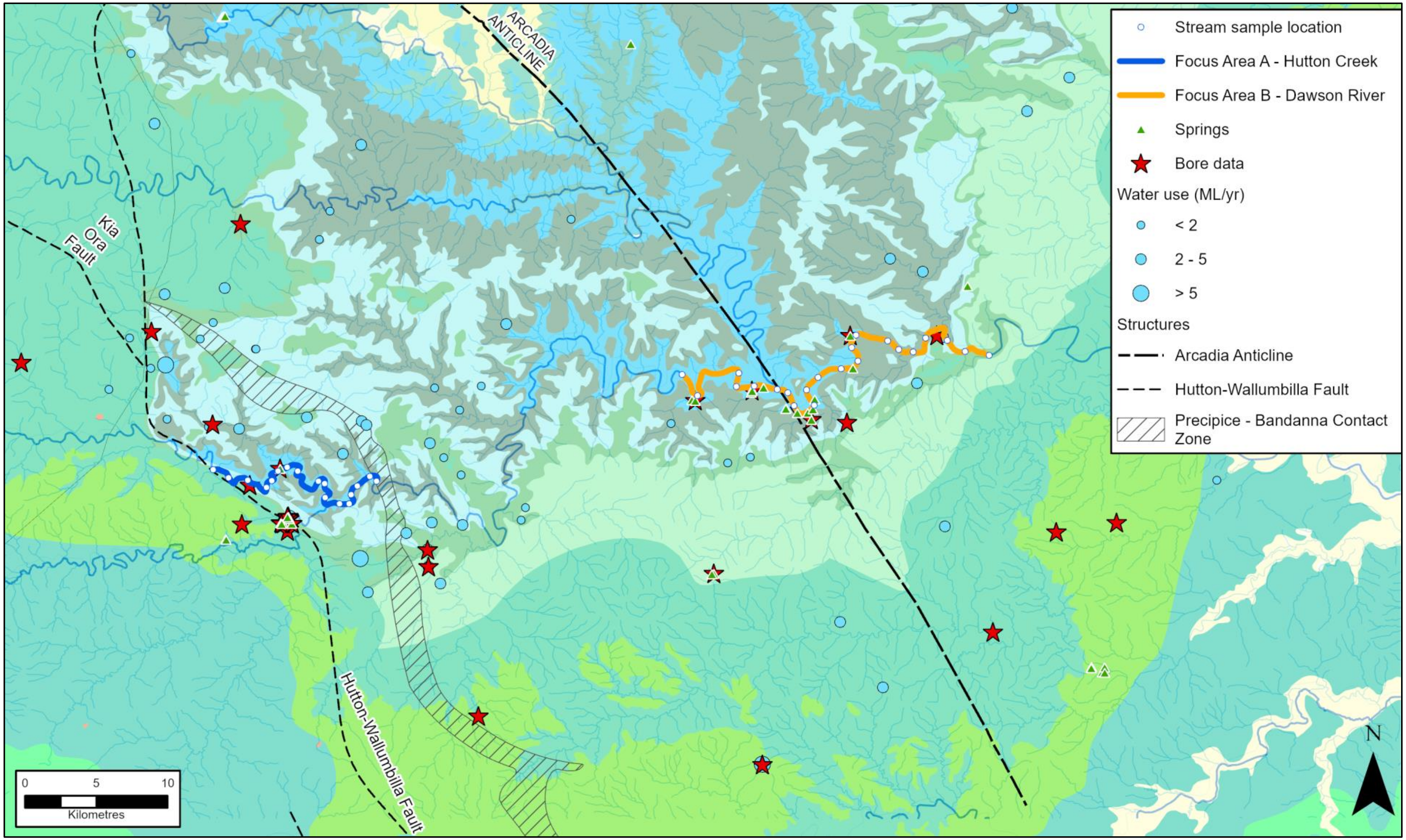

Figure 12: Data incorporated into the analysis in this thesis including samples from water supply bores, monitoring points, streams and springs

Methods

The primary objectives of this thesis relate to the spatial variability, direction and magnitude of groundwater flux and the separation of the local and regional groundwater discharge component of baseflow to Hutton Creek and the Dawson River.

There are no permanent gauging stations within the study area. This is interpreted to reflect: the minimal surface water extraction in this area, which has historically driven the placement of infrastructure; the dynamic nature of the stream bed during high-flow events, which makes permanent infrastructure placement problematic; and the resulting changes with maintenance of a rating curve. The dry season longitudinal flow survey provides a highly useful dataset to understand stream flow and accumulation along these reaches for groundwater.

In conjunction with stream flow data, environmental tracers are used in this thesis with their application summarised in Table 1. Broadly, the application of these methods focuses on separating the groundwater source, residence time and dominant flow path from the groundwater system.

Table 1: Project design – environmental tracers and application for this investigation

Tracer	Application for this thesis
Radon	Determine the presence of groundwater in the sample
Strontium	Distinguishing stream contributions from different groundwater sources
Stable isotopes	Recharge processes and potential contribution from different aquifers
Tritium	Distinguishing young from old contributions (local vs regional flow)
Carbon-14	Distinguishing young from old contributions (local vs regional flow)

The following sections provide a summary of the environmental tracers and their application to groundwater–surface water interaction studies where relevant to this thesis.

Stream flow analysis

Where continuous stream flow data are available, a range of quantitative indices assist with the separation of the groundwater contribution from surface water flows (Hofmann, 2023). In this location, there is minimal permanent gauging infrastructure. The dry season longitudinal sampling is a useful tool to determine the groundwater component of stream flow and to estimate accumulation along each reach. It is acknowledged, however, that there is uncertainty with stream gauging, particularly for low flows that occur at the Hutton Creek focus area.

Differential stream flow calculations between upstream and downstream gauging locations can be applied to estimate flux per unit of intervening reach, after accounting for other flux components or gains and losses (P. G. Cook, 2015). For this thesis, the flux (L/s/km) for each reach intervening section is calculated to assess the dominant direction and magnitude of flux (Equation 1), which may indicate zones of higher flux due to the hydraulic properties of the stream bed, underlying bedrock permeability or higher-pressure conditions. In parallel with this metric, flux components must be evaluated, such as inflow from tributaries with springs and local groundwater extraction.

$$\text{Reach discharge (normalised } \mathrm{Q_r}) = \frac{\text{Q downstream (l/s)} - \text{Q upstream(l/s)}}{\text{Reach length (km)}}$$

Equation 1

Environmental tracers

Stable isotopes

Oxygen (^{18}O) and Deuterium (^{2}H)

The water molecule includes two stable isotopes of hydrogen (^{1}H, ^{2}H) and three stable isotopes of oxygen (^{16}O, ^{17}O, ^{18}O) with their abundance primarily influenced by fractionation – in contrast to any radioactive decay process associated with radiocarbon isotopes (Fetter, 2001). These isotopes, and pairs of isotopes, are often applied in groundwater studies, as their abundance is influenced by climatic conditions during groundwater recharge; the fractionation process – separation into lighter and heavier fractions – is largely driven by temperature, moisture and rainfall intensity (Clark and Fritz, 2013; Hofmann et al., 2024). During the various phase changes in the hydrologic cycle, the abundance of the lighter and heavier isotopes changes relative to climatic conditions (Fetter, 2001).

Due to the small differences in absolute abundance, the convention is to evaluate the ratio of the most abundant isotopes (^{18}O/^{16}O and ^{2}H/^{1}H) as a derivation from the local or global standard (Clark & Fritz, 2013), with results expressed in parts per thousand (‰), relative to the least abundant isotope (Equation 2 and Equation 3) (Appelo & Postma, 2004; Fetter, 2001).

For ^{18}O and ^{2}H, the most frequently adopted reference is that of natural water V-SMOW – Vienna standard mean ocean water (Clark & Fritz, 2013). This line is derived in the general manner in which precipitation transitions from oceanic waters into the vapour phase, then transported to more elevated areas, where it moves into the water phase and falls as rainfall (Appelo & Postma, 2004).

$$\delta^{18}\mathrm{O}\ (‰) = \left[\left(\frac{\left(\frac{18O}{16O}\right) sample}{\left(\frac{18O}{16O}\right) SMOW}\right) - 1\right] *\ 10^3$$

Equation 2

$$\delta^{2}\mathrm{H}\ (‰) = \left[\left(\frac{\left(\frac{2H}{\mathrm{1H}}\right) sample}{\left(\frac{\mathrm{2H}}{\mathrm{1H}}\right) SMOW}\right) - 1\right] *\ 10^3$$

Equation 3

The proximity of water samples to the standard and local meteoric water lines provides qualitative insights into the prevailing climatic conditions at the time of recharge and assists in separation of groundwater sources. For example, in the southern Surat Basin, Baskaran et al. (2009) evaluated the composition of groundwater, surface water and rainfall to provide insights on groundwater-surface water interaction in the Border Rivers catchment.

Carbon 13 (^{13}C)

The stable isotopes of carbon are ^{12}C and ^{13}C. Consistent with the analysis for the stable isotopes of water, a relative fraction of the carbon isotopes is compared with a standard reference material – Pee Dee Belemnite (PDB) – relative to the least abundant isotope (Equation 4):

$$\delta^{13}C\ (‰) = \left(\frac{\left(\frac{^{13}C}{^{12}C}\right) sample}{\left(\frac{^{13}C}{^{12}C}\right) PDB} - 1 \right) * 1000$$

Equation 4

As described in Herczeg et al. (1991), the most important DIC sources for groundwater in the GAB are biological processes such as plant respiration in recharge areas (resulting in more negative ratios), the dissolution of carbonates in the aquifer matrix, such as calcite or dolomite, and the decomposition of organic matter within the aquifer (resulting in more positive ratios). Minimal contribution from the atmosphere is interpreted (Fetter, 2001).

Herczeg et al. (1991) describes the estimate of δ^{13}C-DIC resulting from plant respiration to be in the range of -20 to -24‰ and the dissolution of carbonates to be around -6‰. In a closed system, with only the contribution of dissolved carbonates to δ^{13}C-DIC, Herczeg et al. (1991) estimates concentrations would evolve to around -12 ±2‰. This can be used to qualitatively understand the evolution of groundwater from recharge to discharge locations and the potential separation of different sources of groundwater contribution to streamflow.

Radioactive isotopes

Radon (^{222}Rn)

Radon is a commonly applied tracer in surface-groundwater investigations as concentrations are typically several orders of magnitude higher in groundwater compared to surface waters (Cartwright et al., 2011; Fitts, 2013; Martinez et al., 2015). Concentrations in groundwater are the result of radioactive decay chains from rocks with high 238-uranium content becoming dissolved in groundwater (OGIA, 2017), with equilibrium achieved with the rock matrix over a few weeks (Cecil & Green, 2000). Radon has a half-life of 3.83 days and is ubiquitous within sedimentary rocks (Ellins et al., 1990). Rock types associated with higher concentrations include granites or high-grade metamorphic and basaltic rocks with a relatively high abundance of minerals such as apatite, zircon and allanite (Baskaran et al., 2009).

Following the discharge of groundwater to a stream, ^{222}Rn concentrations will rapidly decrease due to contact with the atmosphere, the resulting gas exchange and radioactive decay (P. Cook et al., 2003). Given the sensitivity of this tracer to groundwater inflows, spikes or peaks in concentrations within streams are interpreted as strong indicators of local points of groundwater inflow (Baskaran et al., 2009; Cartwright et al., 2011; P. Cook et al., 2003; Martinez et al., 2015).

Radiocarbon (^{14}C)

In addition to the stable isotopes of carbon (^{12}C, ^{13}C), the element also includes the radioactive isotope of ^{14}C with a half-life of 5,730 years. Radiocarbon dating is commonly applied to understand groundwater residence times between ~1,000 and 40,000 years (Fetter, 2001). Results are typically reported relative to the pre-industrial atmosphere, with the units of ‘percent modern carbon’ (pMC).

Atmospheric concentrations of ^{14}C are the result of cosmic radiation, with ^{14}C forming CO_2, resulting in atmospheric CO_2 having a constant radioactivity due to modern carbon (Fetter, 2001). At a given time, when precipitation forms and groundwater is recharged, the atmospheric concentration of CO_2 and ^{14}C activity is known. Upon entering the soil, other ‘dead’ carbon sources may dilute the modern carbon activity – including the dissolution of carbonates and soil CO_2 from plant respiration – which may provide erroneously longer residence times.

Although theoretically possible to correct a sample for the influence of dead carbon, as highlighted by Suckow (2014), there are significant uncertainties in using environmental tracers to determine residence time or ‘age’. The contribution of multiple flow paths to the sample, and how closely the tracer’s transport reflects that of the water molecule, are two examples which contribute to uncertainty in the estimation of residence time (Suckow, 2014). In this thesis, multiple tracers have been applied to distinguish between younger and older groundwaters.

Tritium (^{3}H)

Tritium (^{3}H) is a radioactive isotope of hydrogen and is commonly applied to understand short residence-time groundwater (<60 years), with a half-life of 12.3 years (Fetter, 2001). While ^{3}H naturally occurs in the upper atmosphere due to the influence of cosmic ray spallation of nitrogen atoms, it is also produced anthropogenically by thermonuclear testing (Tadros et al., 2014). Thermonuclear explosions occurred globally from 1953, with bomb-tritium concentrations being significantly higher than background for several decades, providing a semi-quantitative tool for a range of environmental studies, including the identification of groundwater recharge during this period (Clark & Fritz, 2013; Tadros et al., 2014). In the southern hemisphere, where there was more limited thermonuclear testing, remnant bomb pulse concentrations have now decayed well below that of modern rainfall (Cartwright & Morgenstern, 2012).

Although there are subtle temperature-driven seasonal fluctuations due to stratosphere-to-troposphere exchange, annual trends provide benchmarks for comparison with groundwater data (Tadros et al., 2014). Monthly analysis of the Tritium concentrations in rainfall has been undertaken since 1960 and shows a maximum concentration of 160 TU in 1963 (Tadros et al., 2014), with a rapid decline to present day, interpreted to be around 1 TU. Tadros et al. (2014) suggest that the rate of decline far exceeds natural decay rates and likely 'wash-out' of ^{3}H to the oceans and groundwater.

Groundwater recharge events that occurred since thermonuclear testing will show elevated concentrations commensurate with the atmosphere at the time. In combination with other tracers, ^{3}H presents a useful tool to understand the contribution or component of more recent water to sampled waters, in addition to providing increased confidence in other residence-time tracers.

Strontium isotope ratio (^{87}Sr/^{86}Sr)

Strontium has four naturally occurring isotope species – three stable (^{84}Sr, ^{86}Sr, ^{88}Sr) and one radiogenic (^{87}Sr) produced from the decay of Rubidium (^{87}Rb), with a half-life of around 48.8 billion years. Strontium concentrations in groundwater are largely controlled by water-rock interactions (McNutt, 2000) with observed variations due to the provenance of formation materials (OGIA, 2023).

The strontium isotope ratio (^{87}Sr/^{86}Sr) has been applied to groundwater studies for several key reasons (McNutt, 2000): strontium is found in measurable quantities in most formations; it is soluble; it is largely unaffected by fractionation processes; and there are considerable present-day variations.

In the Surat Basin, strontium isotope ratios have most recently been applied as a line of evidence to evaluate the potential for connectivity between CSG reservoirs and adjacent aquifers (Baublys et al., 2019; Hofmann et al., 2024; OGIA, 2023). In recognition of the effectiveness of this tool, its collection is now included in routine monitoring obligations on resource tenure holders in the Surat UWIR (OGIA, 2021b, 2023).

RESULTS

Stream gauging

Stream flow data collected for the Hutton Creek location are shown in Figure 13. Two peaks in flow are observed at this location – 6.3 L/s at 1.3 km (HC2) and 10.7 L/s at 11.2 km (HC9). There is a decline in stream flow to around 0.0 L/s from HC2 to HC3, with portions of the creek between HC3 and HC4B observed to be dry during the survey. Downstream from this location, there is a progressive increase in stream flow over the next 8 km, reaching a peak of 10.7 L/s at 11.2 km (HC9). A decline in stream flow is then observed for the remaining sections. The overall trend in flow is consistent with previous stream gauging surveys undertaken by tenure holders.

During the field survey, several discrete point discharge zones were identified within the stream banks and are annotated in Figure 13. In addition, a minor tributary – Springrock Creek – joins Hutton Creek between HC6 and HC7, with only minor flow (~0.1 L/s) observed from this tributary during the survey period (Figure 13). Injune Creek joins Hutton Creek between HC11 and HC12. No flow was observed during the survey – both the Injune and Springrock creeks were observed to have permanent disconnected waterholes.

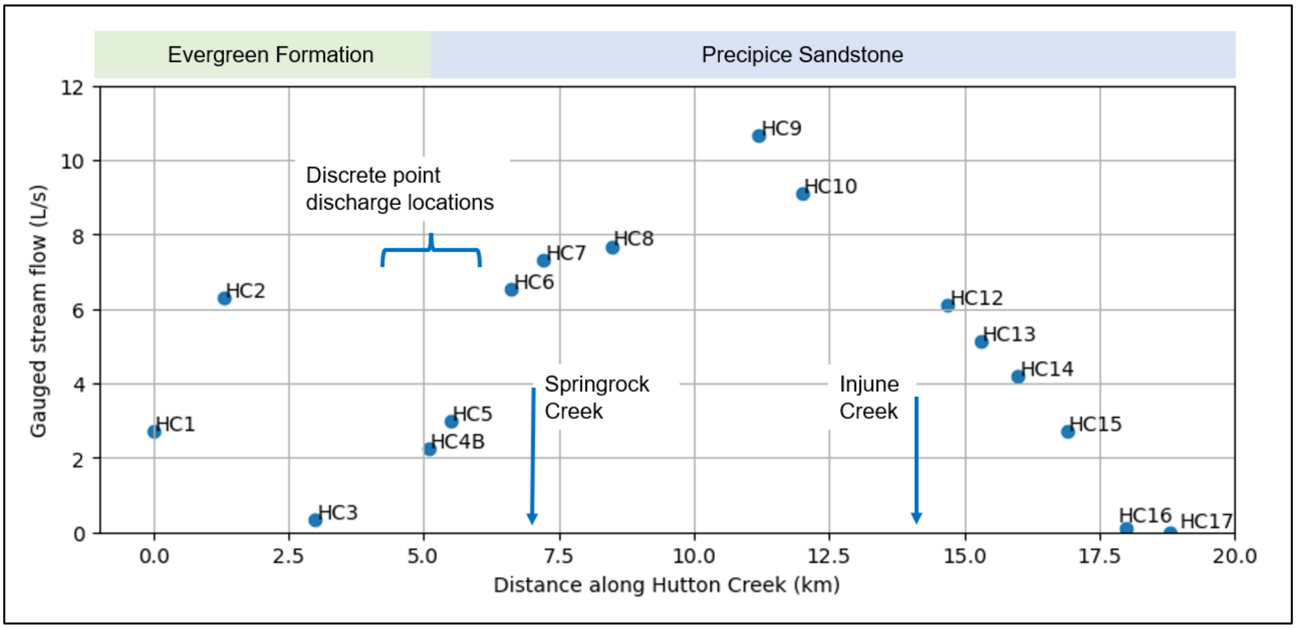

Figure 13: Stream flow gauging data for the Hutton Creek. The location of where tributaries join the Hutton Creek and zone of discrete discharge observed during the field survey are also shown. The mapped bedrock geology along the reach is also shown at the top of the figure.

The variability in the magnitude of gain and loss in each gauged section of Hutton Creek is provided in Figure 14. Gaining conditions range from approximately 4.2 L/s/km between HC1 and HC2, to 0.30 L/s/km between HC7 and HC8. Losing conditions range in magnitude from approximately 3.5 L/s/km between HC2 and HC3 to 1.9 L/s/km between HC9 and HC10. The data indicates a distinct gaining zone between HC3 and HC7.

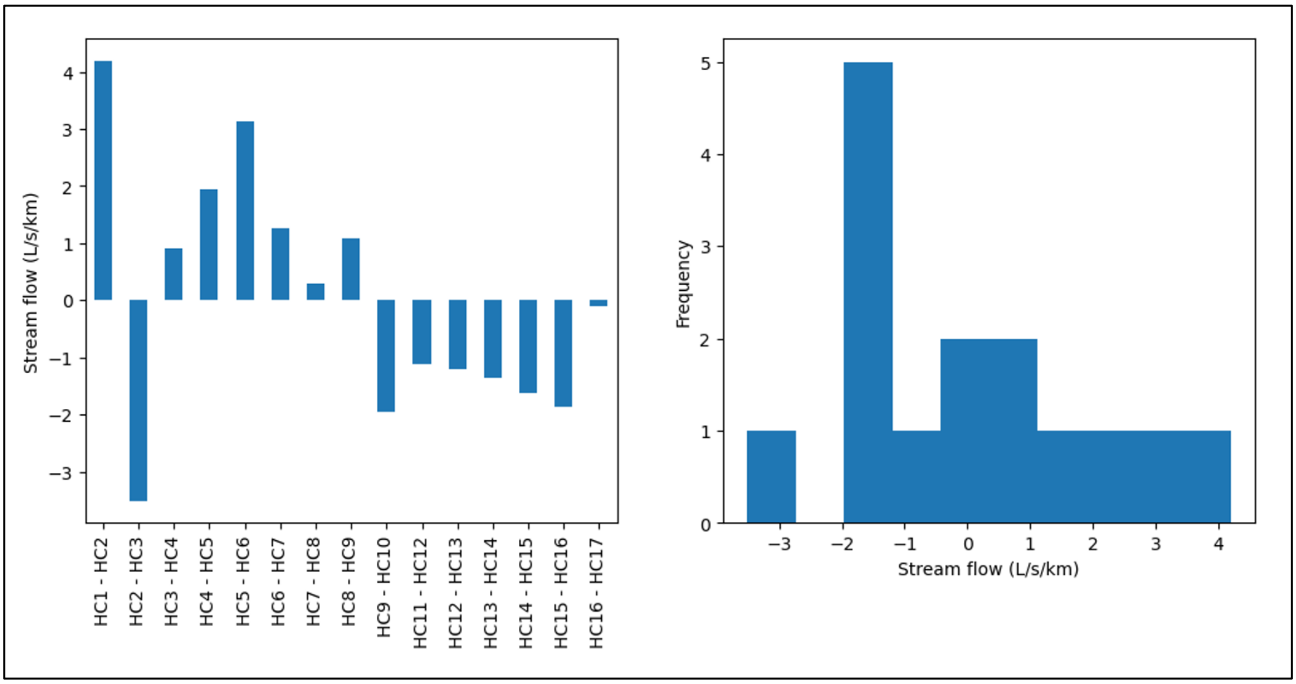

Figure 14: Stream flux for each reach of the Hutton Creek. Calculated reach flux is shown based on Equation 1 (left). A histogram of reach flux is also shown (right).

Stream flows measured at the Dawson River sites (Figure 15) are two orders of magnitude higher than those measured at some of the Hutton Creek sites. Broadly, there is a progressive increase in stream flow, from 4.6 L/s at LHC1 to 232 L/s at DR12 (26.2 km). As there is discharge of treated associated water adjacent to the Dawson River downstream of DR11, these lower reaches were not sampled for environmental isotope data.

The confluence of the Dawson River and Hutton Creek occurs between LHC6 and DR1. There was no surface water flow from the upstream section of the Dawson River at the time of the survey. Similar to Hutton Creek, during the survey, several discrete point discharge locations were identified within the stream bed and stream banks and are annotated in Figure 15.

The variability in the magnitude of gain and loss in each gauged section of the Dawson River is shown in Figure 16. The magnitude of gain for individual reaches varies from <0.1 L/s/km between DR5 and DR6 to 39.5 L/s/m between DR6 and DR7. The magnitude of loss at individual reaches varies from 23.4 L/s/km (DR14–DR15) to 0.4 L/s/km (DR15–DR16).

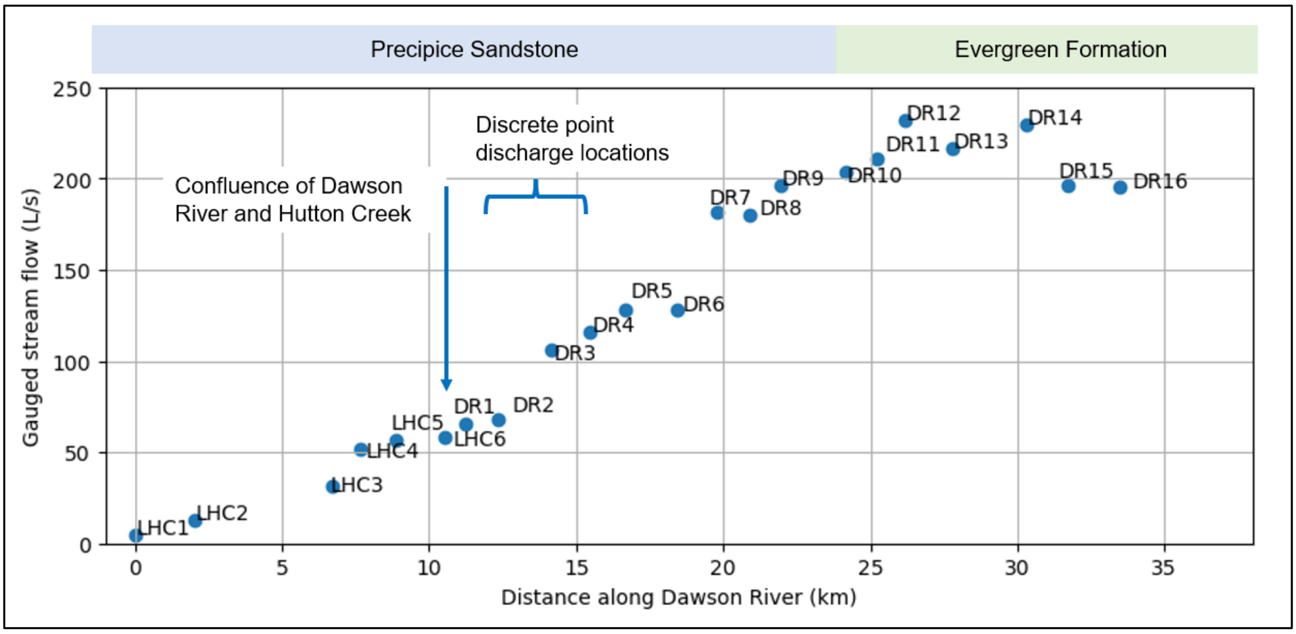

Figure 15: Stream flow gauging data for the Dawson River. The location of where tributaries join the Dawson River and zone of discrete discharge observed during the field survey are also shown.

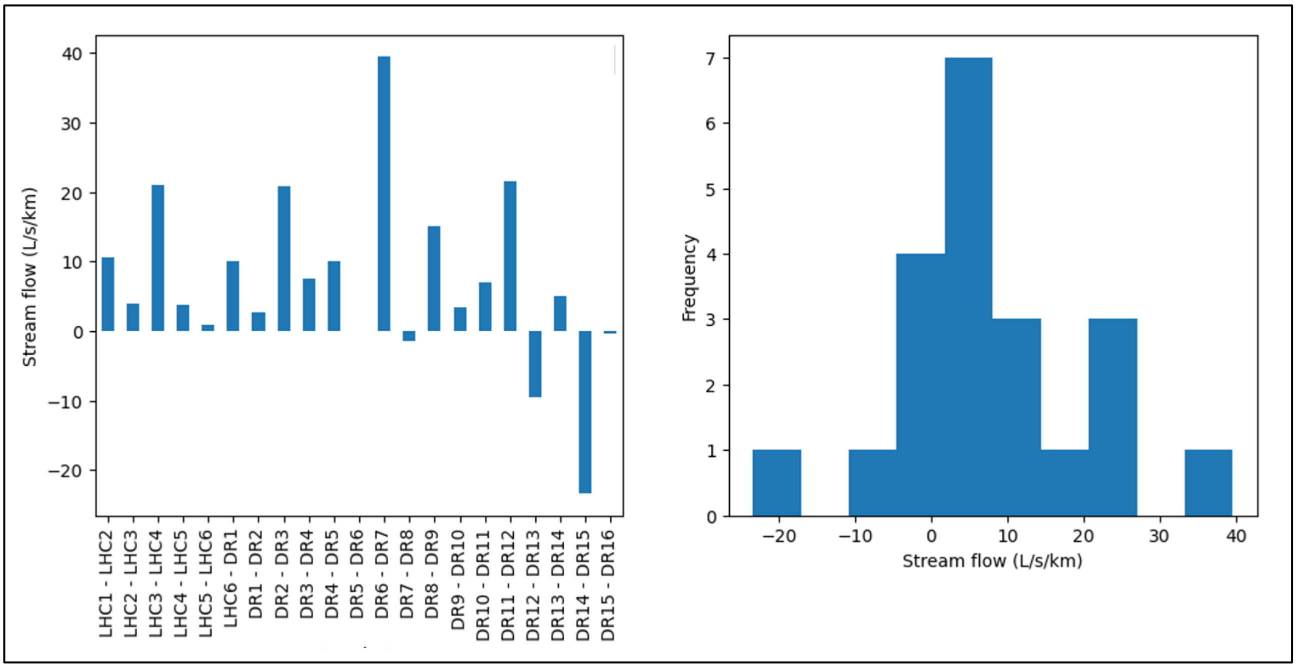

Figure 16: Stream flux for each reach of the Dawson River. Calculated reach flux is shown based on Equation 1 (left). A histogram of reach flux is also shown (right)

Environmental tracers

Radon (^{222}Rn)

^{222}Rn concentrations and stream flow data for samples at Hutton Creek and the Dawson River are shown in Figure 17. The Hutton Creek samples generally show concentrations of <1 Bq/L – at seven sites – with a zone of elevated concentrations observed between HC4 and HC8, ranging from 1.55 to 7.65 Bq/L. Comparatively, the Dawson River samples indicate higher variability but with lower concentrations compared to the Hutton Creek. Concentrations along the Dawson River vary from <1 Bq/L – at five of the sample sites – to 2.97 Bq/L at DR3.

Surface waters with no groundwater input generally have concentrations of <0.1 Bq/L. All samples show higher than expected background concentrations for surface water – several orders of magnitude, at some locations.

The plots combining the reach discharge rate and the ^{222}Rn concentrations (Figure 17 - RHS) indicate a minimal correlation between these variables, particularly along the Dawson River. This may relate to degassing of groundwater discharge within the stream due to turbulent flow and the proximity of the major discharge zones along the reach, compared to the sampling location.

In terms of background groundwater concentrations, analysis from a Precipice Sandstone water supply bore near Hutton Creek (RN167934) indicates aquifer concentrations of around 5.35 Bq/L. Several high-flow springs fed by the Precipice Sandstone along tributaries of the Dawson River show very high concentrations – spring 704 (9.67 Bq/L) at the headwaters of a minor tributary near DR9 and spring DR2 (22.09 Bq/L) a discrete discharge point near DR2 (Figure 5). Note, these spring samples are not shown in Figure 17 to enable the higher resolution of the stream sample results.

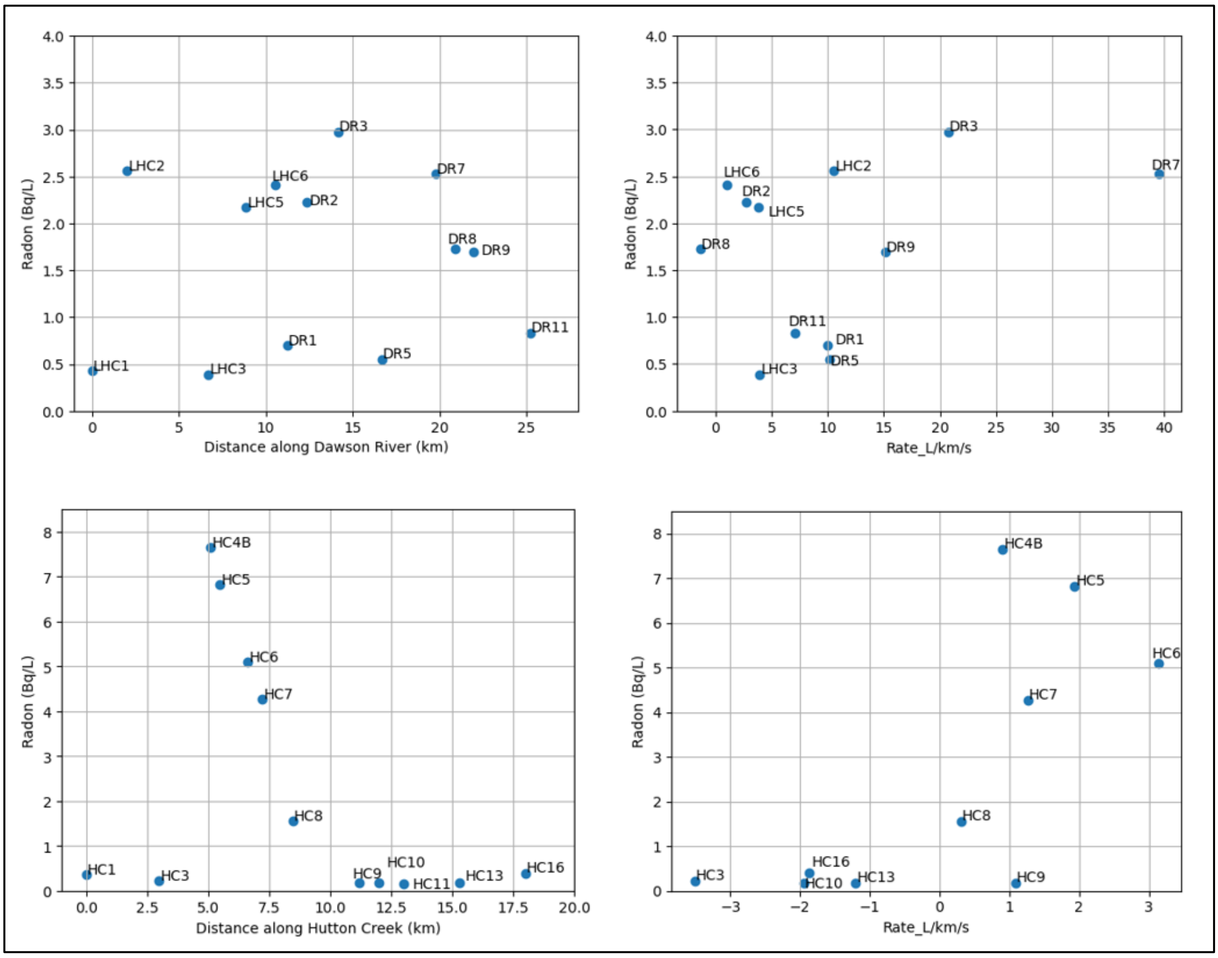

Figure 17: ^{222}Rn concentrations along the Dawson River (top) and Hutton Creek (bottom) and correlation with discharge rate (RHS) – attached to downstream sample location.

Oxygen (^{18}O) and Deuterium (^{2}H)

Stable isotope results for Hutton Creek and the Dawson River are shown in Figure 18, Figure 19 and Figure 20. Included in Figure 18 for comparison are the Toowoomba, Charleville and Alice Springs local meteoric water lines (LMWL) (Crosbie et al., 2012), along with samples from groundwater bores (green triangles) and springs sourced from the Precipice Sandstone – Spring 704 and DR2 Spring.

Samples from the groundwater bores cluster around the LMWL for modern rainfall at Alice Springs and Charleville, with values of $\delta^{18}O$ ranging from -5.2 to -6.21‰ and $\delta^{2}H$ from -35.4 to -43.8‰. Results from the stream samples indicate greater variability than the bore population. One group of slightly depleted stream samples clusters around the modern LMWL for Alice Springs, primarily along the Dawson River – LHC1, DR1, DR3, DR5, DR7, DR8, Spring 704 and DR11. A second group of samples, showing depleted values, occurs parallel to the LMWL, dominated by Hutton Creek sites. There are also several samples that plot along an evaporative line, including HC3, HC9, HC10, HC11, HC13, HC16, LHC1, LHC2, LHC3 and Springrock Creek.

The sizes of the symbols for stream samples in Figure 18 are based on measured stream flow (L/s). The group of samples clustered around the LMWL correlates with higher stream flow; those plotting along the evaporative line have much lower stream flow, highlighting the likely evaporative influences on data from these locations. At Hutton Creek (Figure 19), only four locations show ^{18}O ratios within the range of local groundwater samples – HC1, HC4B, HC5 and HC6. In contrast, at the Dawson River (Figure 20), three samples indicate stable isotope ratios beyond the range of local groundwater samples – LHC1, LHC2 and LHC3.

During various phase changes in the hydrologic cycle, the abundance of the lighter and heavier isotopes changes relative to climatic conditions (Fetter, 2001). Hofmann et al. (2024) recently concluded that depleted stable isotope compositions of groundwaters in the Hutton and Precipice sandstones (Surat Basin) were most likely the result of monsoon rainfall events, rather than recharge under cooler climatic conditions – which may be expected for depleted compositions. This conclusion was on the basis that low-pressure systems from the Northern Territory traverse across into the northern Surat Basin recharge beds and are significantly influenced by the sequential depletion and rainout of atmospheric moisture mass as it traverses the continental land mass (Hofmann et al., 2024). This is consistent with the overall trend of slightly depleted samples, with the exception of those that appear to be affected by evaporation.

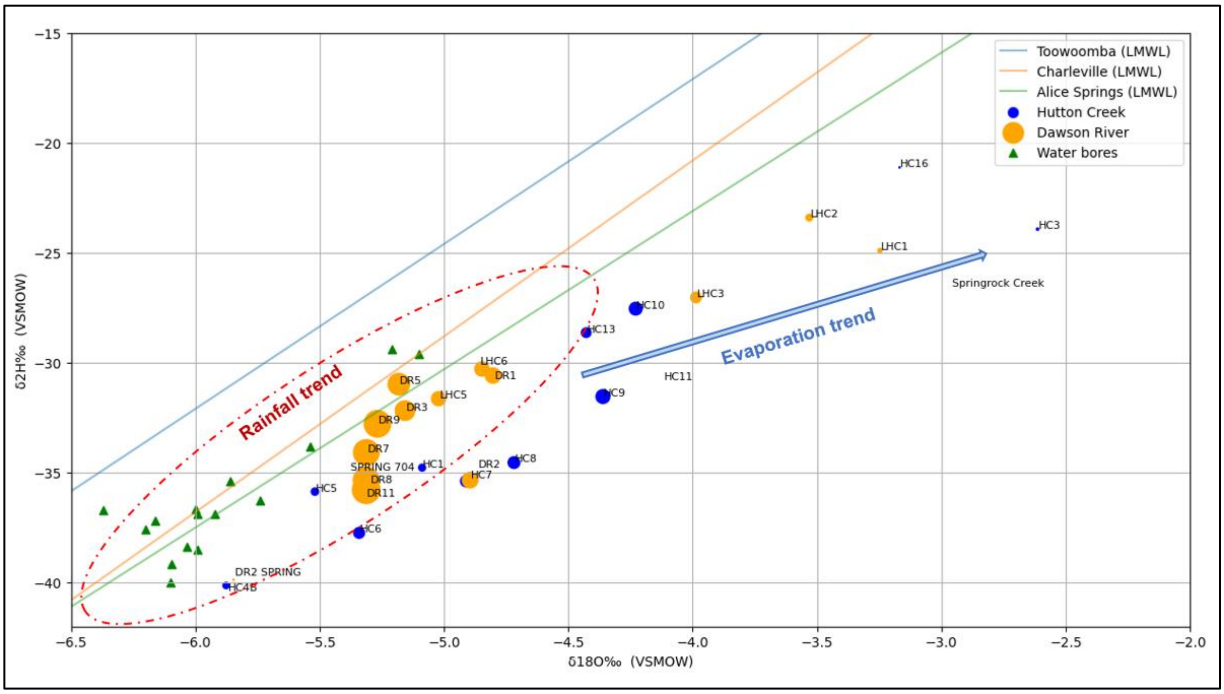

Figure 18: Stable isotope results for the Hutton Creek, Dawson River and Precipice Sandstone water supply bores within 20km of the study location. Stream symbol size is proportional to stream flow rate.

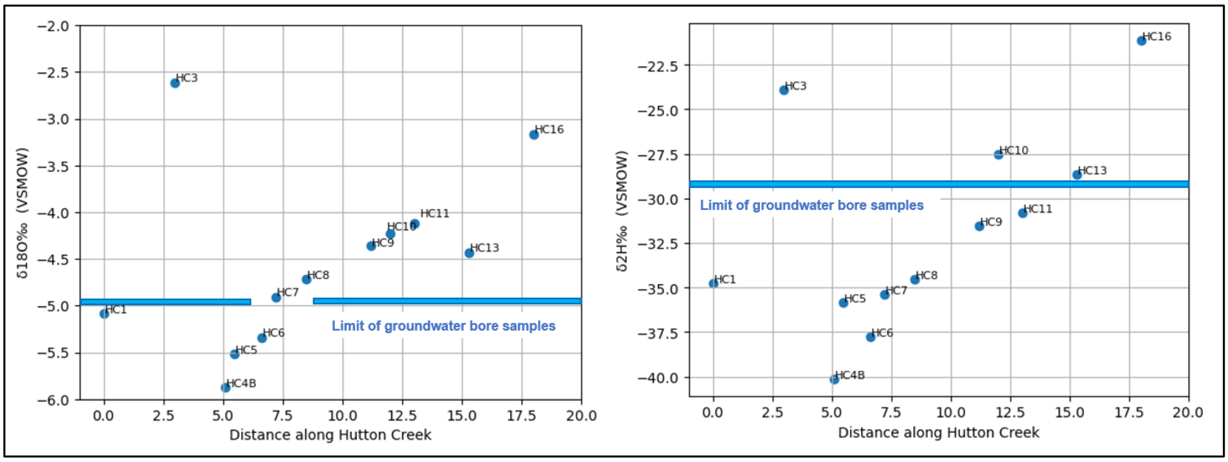

Figure 19: Stable isotope results for the Hutton Creek – ^{18}O (left) and ^{2}H (right)

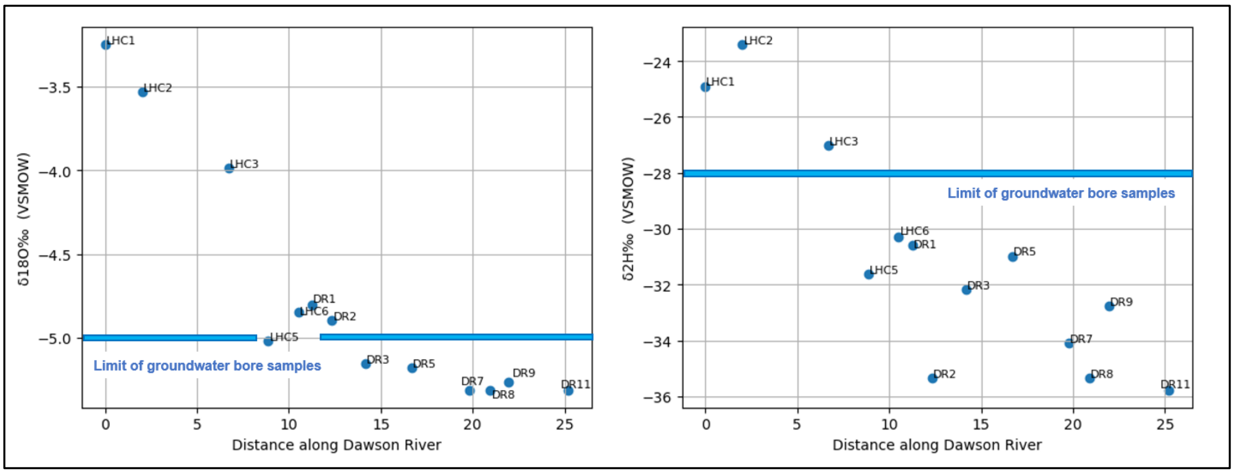

Figure 20: Stable isotope results for the Dawson River – ^{18}O (left) and ^{2}H (right)

Carbon 14 (^{14}C) and Carbon 13 (^{13}C)

Results for ^{14}C and ^{13}C for the streams and nearby water bores are shown in Figure 21. The ^{14}C data is uncorrected for the dissolution of carbonates from within the aquifer matrix. Results for both Hutton Creek and the Dawson River indicate a correlation between residence time and $\delta^{13}C$.

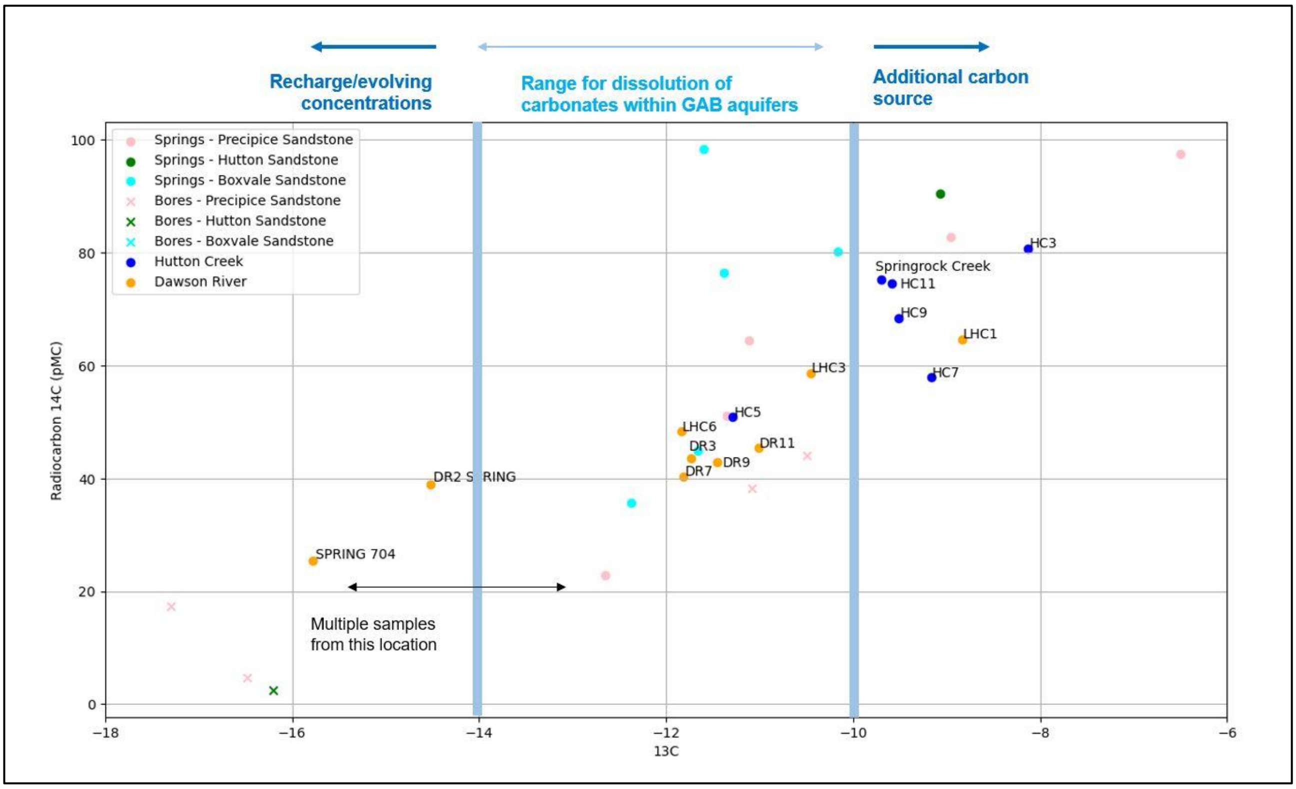

Figure 21: Scatter plot of uncorrected ^{14}C and ^{13}C results for Hutton Creek and the Dawson River

As described in the pervious section, Herczeg et al. (1991) estimates $\delta^{13}C$-DIC in the recharge area to be in the range of -20 to -24‰, primarily the result of plant respiration. In a closed system, with only the contribution of dissolved carbonates contributing to $\delta^{13}C$-DIC, Herczeg et al. (1991) estimates that groundwater concentrations would evolve into the deeper parts of the groundwater system to around -12 ± 2‰. The relationship between residence time and $\delta^{13}C$-DIC is the inverse of the typical expected relationship – reduction in $\delta^{13}C$ with increasing aquifer residence time – and requires further analysis with a more regional dataset.

Carbon 14 (^{14}C) and Tritium (^{3}H)

Results for ^{14}C and ^{3}H for the stream samples are shown in Figure 22. The two study locations show distinct but similar relationships, with Hutton Creek overall indicating shorter residence time. There are a significant number of sites with the combination of low modern carbon (< 60 pMC) and tritium values (<0.04 TU), indicating very long residence time, with minimal modern contribution – DR3, DR7, DR9, DR11, DR2, Spring 704, HC5 and HC7.

Radon concentrations are integrated into the plot to potentially highlight those locations where more groundwater is interpreted to be present in the sample. At locations where longer residence time is interpreted based on ^{14}C and ^{3}H also show higher ^{222}Rn concentrations.

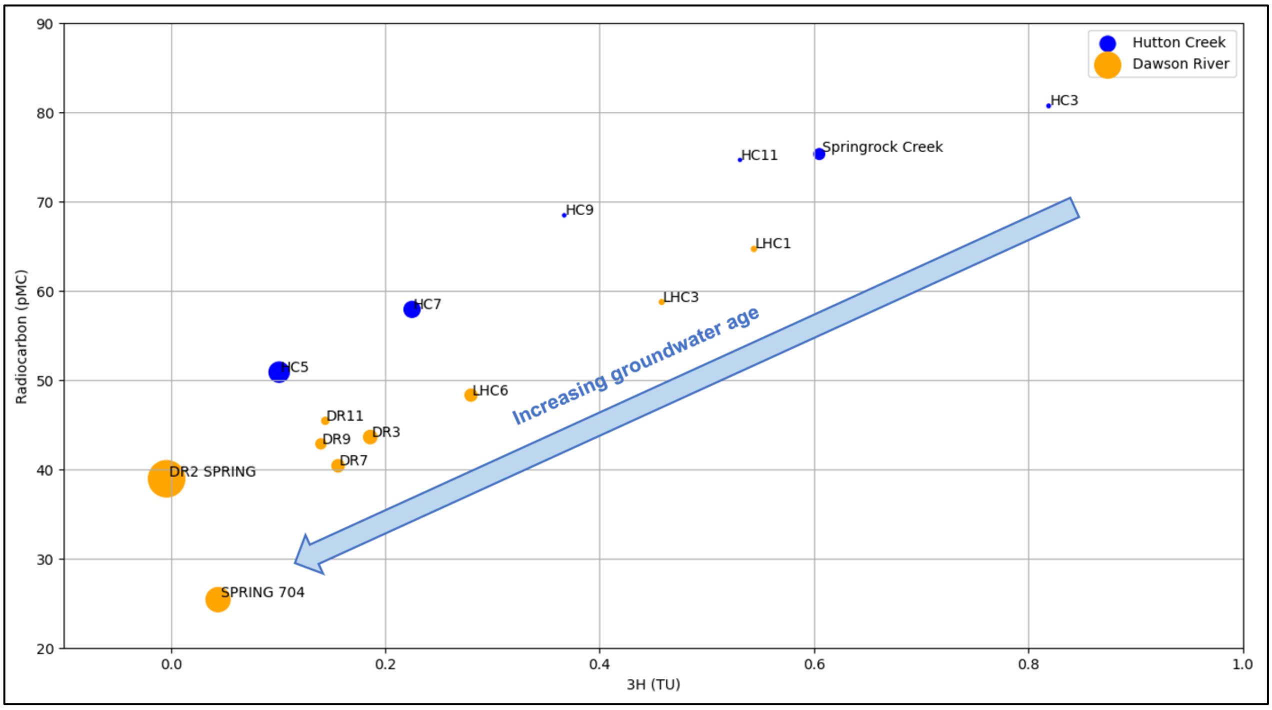

Figure 22: 14C vs Tritium results for Hutton Creek and the Dawson River. Symbol size is based on Radon concentration.

Strontium isotope ratio (87Sr/86Sr)

The strontium isotope results for the stream samples are shown in Figure 23. Data for groundwater bores and springs within 20 km of the study sites are also shown for comparison.

With the exception of Springrock Creek, strontium isotope values for the Hutton Creek samples are tightly clustered between 0.70620 and 0.70625. The samples from the Dawson River show a wider range of values, from 0.7063 to 0.707. Similar to the Hutton Creek, Spring 704 shows a higher ratio compared to samples from the channel of the Dawson River.

Samples from groundwater bores within 20 km of the streams show a wide range in strontium isotope ratios for both the Precipice and Hutton sandstones, which collectively encompass the stream sample values. The available data for the Precipice Sandstone range from 0.70623 to 0.70753, and the Hutton Sandstone ranges from 0.70556 to 0.70689. Values for both formations are within the broader ranges in the Surat Basin as described by Hofmann et al. (2024). A single local sample from a bore completed in the Boxvale Sandstone Member of the Evergreen Formation indicates a strontium isotope value of 0.70688.

The data show an apparent increase in the strontium isotope value with each downstream sample location at the Dawson River study location.

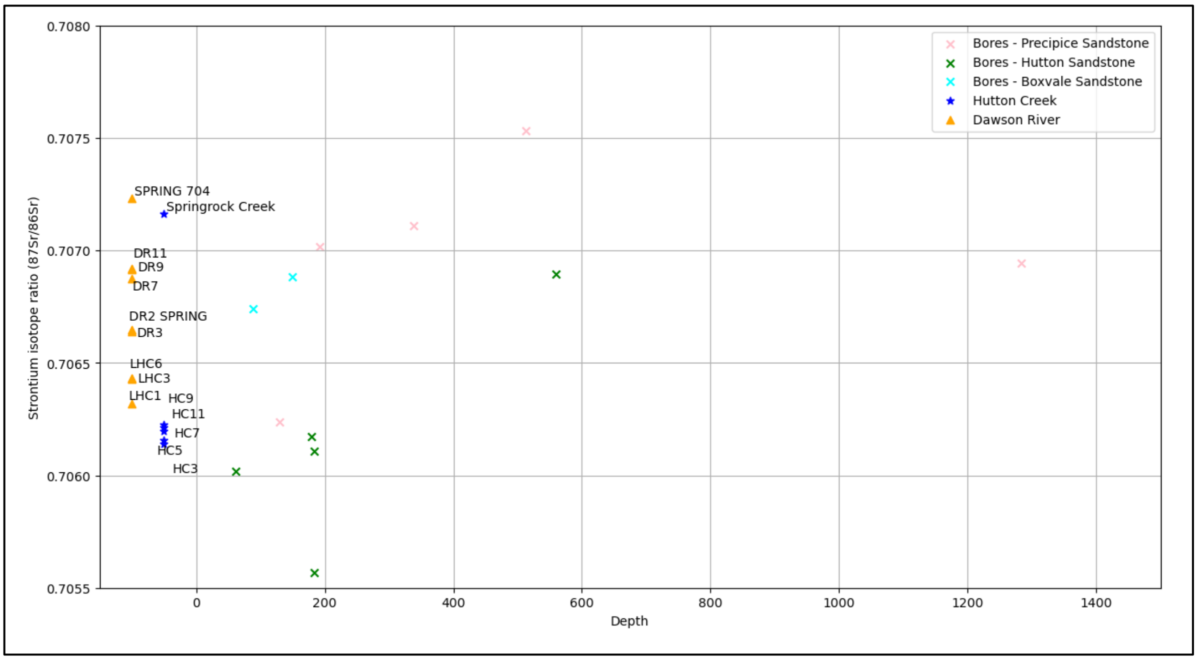

Figure 23: $^{87}Sr/^{86}Sr$ isotope ratios for sample locations on Hutton Creek and the Dawson River.

DISCUSSION

Spatial variability in groundwater–surface water interaction

The dry-season longitudinal stream survey data and field observations provide significant insights on the magnitude and direction of groundwater–surface water interaction at both study locations. The available information and data on landscape, geomorphology, stream flow and environmental tracers are synthesised for each site in Figure 24 and Figure 25.

The overall slope of the streambed at the Hutton Creek site is relatively consistent at around 0.2% (Figure 7). The stream substrate transitions from silts and clays between HC1 and HC3, to a short boulders and silt section (HC4 to HC6) and is then predominantly sandy clay for the remaining reaches. The surface geological mapping indicates the early part of this reach (HC1 to HC4) overlies the lower Evergreen Formation – interpreted to be a tight aquitard (Figure 26) – with the lower reaches (HC4 to HC17) overlying the outcrop of the Precipice Sandstone aquifer.

The differential stream flow data indicate that Hutton Creek is under predominantly gaining conditions until HC9, with the largest inflow interpreted between sites HC1 and HC2 (Figure 14 and Figure 14). In contrast, the lower reaches indicate losing conditions. The exception to these overarching trends is the second gauged reach – HC2 to HC3 – which indicates a significant flux from the stream to the groundwater system. At this location, a stock and domestic water supply bore is located adjacent to Hutton Creek (<100 m) and is interpreted to be the primary reason for the direction of flux from stream to groundwater at this location.

Environmental tracer data are consistent with the differential stream gauging information. Radon concentrations peak significantly at HC4, with elevated concentrations also observed at HC5, HC6 and HC7, indicating significant groundwater contribution around these locations. The combination of the high stream flow and low ^{222}Rn concentrations at HC1 suggests there may be a significant groundwater inflow upstream, with the water in the stream degassed prior to the sample location. Upstream of HC1 – between 500 and 3,000 m – the Hutton Creek meanders over sections of the Precipice Sandstone outcrop. Based on this data these reaches may also be areas of groundwater discharge to stream (Figure 5).

Analysis of ^{222}Rn results at discrete point discharge locations – springs DR2 and 705 – versus more diffuse discharge through the stream bed, supports the suggestion of relatively rapid degassing once groundwater is in the watercourse environment. This also supports the conclusion that areas of very high ^{222}Rn concentrations are proximal to high groundwater discharge zones.

Consistent with the conclusions of previous authors, the surface geology appears to provide limited control on the location, direction and magnitude of flux at Hutton Creek. Areas of higher discharge are observed overlying the Evergreen Formation and higher elevation sections of the Precipice Sandstone, with the more incised and lower elevation reaches – HC9 to HC17 – in the Precipice Sandstone indicating losing conditions. There was minimal discharge observed over the lower elevation sections of the outcropping Precipice Sandstone aquifer and discharge in reaches overlying the Evergreen Formation aquitard. This observation suggests that there is either inaccuracies in the geological outcrop mapping in this area, or there is a higher degree of structural complexity resulting in zones of groundwater discharge within the broader area. This contrasts with the area being characterised a regional discharge zone resulting from the dissection of the Evergreen Formation to expose the Precipice Sandstone.

The major groundwater inflows occur on an abrupt change in the stream direction, from south-east to northeast (HC4 to HC7), perpendicular to the regional Hutton-Wallumbilla fault system (Figure 24). At this location, there is also a minor but observable change in streambed substrate and increased confinement of the stream and bedrock exposure in the stream banks.

McPherson et al. (2022) also identified uplift and compartmentalisation in the Airborne Electromagnetic (AEM) data overlying the fault system along this section of Hutton Creek. An uplifted block of the Bowen Basin is interpreted to have influenced the change in stream direction and is perpendicular to the local flow directions (Flook et al. 2020). This combination of aquifer geometry and piezometry is likely to create a zone of groundwater discharge between HC4 and HC7.

In parallel, where porosity is potentially increased due to fractures, ^{222}Rn is interpreted to increase due to higher porosity and concentrations of gas, which can then interact with groundwater (Rahimi et al., 2022). In combination with the field observations of multiple discrete discharge locations, it is interpreted that secondary porosity – fractures and structures – is a key control on groundwater discharge from the Precipice Sandstone in this area, particularly at HC4 and to a lesser extent at HC5, HC6 and HC7.

This interpretation is consistent with Hayes et al. (2020), which established, via inverse modelling, that faults and in situ stresses exert significant control on permeability in the Precipice Sandstone. Additionally, there are fault-controlled palustrine springs along the Hutton-Wallumbilla fault system – within 3 km of the identified gaining reaches (Figure 24) – highlighting the occurrence of discrete discharge locations around this regional feature (Flook et al., 2020).

Based on the 2023 stream survey data, the interpreted total groundwater flux from the Precipice Sandstone to Hutton Creek is estimated to be less than 50 ML/yr with the interpreted gaining and losing sections shown in Figure 24.

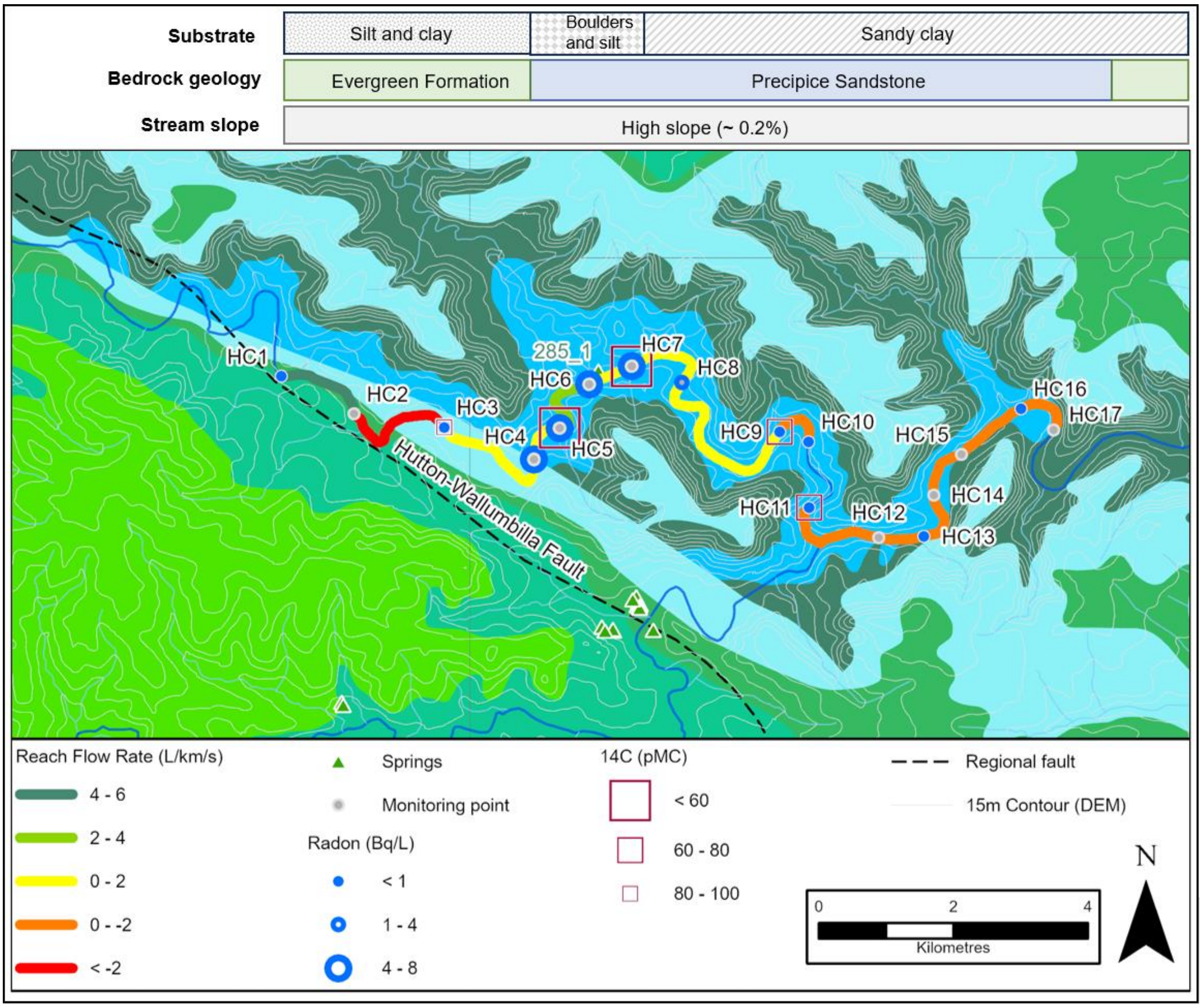

Figure 24: Summary schematic – Hutton Creek

In contrast to Hutton Creek, data and observations from the Dawson River site indicate distinct sections of streambed slope and substrate. Prior to the confluence of the two watercourses at DR1, the slope of the stream is approximately 0.2%, which then reduces to around 0.05% between DR1 and DR9. The initial high slope section of the stream is significantly confined, and the substrate is dominated by boulders. This transitions to a lower slope, less confined and lower-energy section – from DR1 to DR9 – at which the river transitions between pools and riffles, with the substrate primarily coarse sand. Minor channel subdivisions are also observed along this section. There are some substantial meander sections overlying the Arcadia Anticline, suggesting potential structural or bedrock controls on stream morphology (Brennan & Gardiner, 2004; OGIA, 2015a).

The differential stream gauging analysis indicates the Dawson River is under gaining conditions from LHC1 to DR12. Intermittent gaining-losing conditions are then observed between DR12 and DR16. As shown in Figure 25, the reach is interpreted to overly the Precipice Sandstone from LHC1 until DR9 (22 km), from which it then transitions onto the Evergreen Formation.

Although gaining conditions occur for the initial 26 km of this site, there is significant inter-reach variability, often over very short distances (Figure 16). For example, the highest gaining reach identified is DR6–DR7 (~40 L/s/km), located between two reaches with flux rates of around zero. The accompanying radon concentrations suggest loss, or at the very least degassing, of groundwater discharge occurring at upstream reaches.

There are five reaches where groundwater discharge exceeds 15 L/s/km (Figure 16 and Figure 25) – LHC3–LHC4, DR2–DR3, DR6–DR7, DR8–DR9 and DR11–DR12. These reaches occur along almost the full length of the study reach and encompass high to low slopes, substrates dominated from boulders to clay, and various stream geometries from meander bends to straight sections with diverse aspects.

The observed ^{222}Rn concentrations also show significant variability along the study reach (Figure 17). In contrast to the results at the Hutton Creek site, comparatively higher concentrations are observed at consecutive sampling locations. The width of the Dawson River and stream flow is much greater than the Hutton Creek, resulting in more turbulent flow. This may explain the comparatively lower ^{222}Rn concentrations at the Dawson River due to the stream character, accelerating the rate at which degassing may occur once groundwater is discharged to stream.

While the Precipice Sandstone is the most homogenous aquifer in the Surat Basin (OGIA, 2016a), the combination of variability in discharge, radon concentrations, substrate and bedrock conditions suggest secondary porosity – fractures and structures – may be a significant control on the location of high-volume discharge to stream in this area.

The Precipice Sandstone is folded over the Arcadia Anticline in this area, with the axis of the anticline plunging northwest-to-southeast along the Dawson River from the Arcadia Valley towards the Mimosa Syncline. Located approximately located between LHC6 and DR3, the axis is likely to result in weakness and potential fracture zones with minor post-depositional reactivation. The potential influence of underlying structures on topography and drainage is highlighted by McPherson et al (2022). The anticline is likely to be the underlying influence on the direction and orientation of the Dawson River, upstream of the confluence with Hutton Creek.

On the basis of the available data, the Dawson River focus area is predominantly a gaining reach, with significant inter-reach variability. Consistent with OGIA (2015a) and Hayes et al. (2020), the differential gauging and radon data highlight that secondary porosity – fractures and structures – is likely to influence groundwater discharge in this area, with the reactivation of the underlying Arcadia Anticline.

Based on the 2023 stream survey data, the interpreted net groundwater flux from the Precipice Sandstone to the Dawson River in this area is estimated to be approximately 6,400 ML/yr with interpreted gaining and losing sections shown in Figure 25.

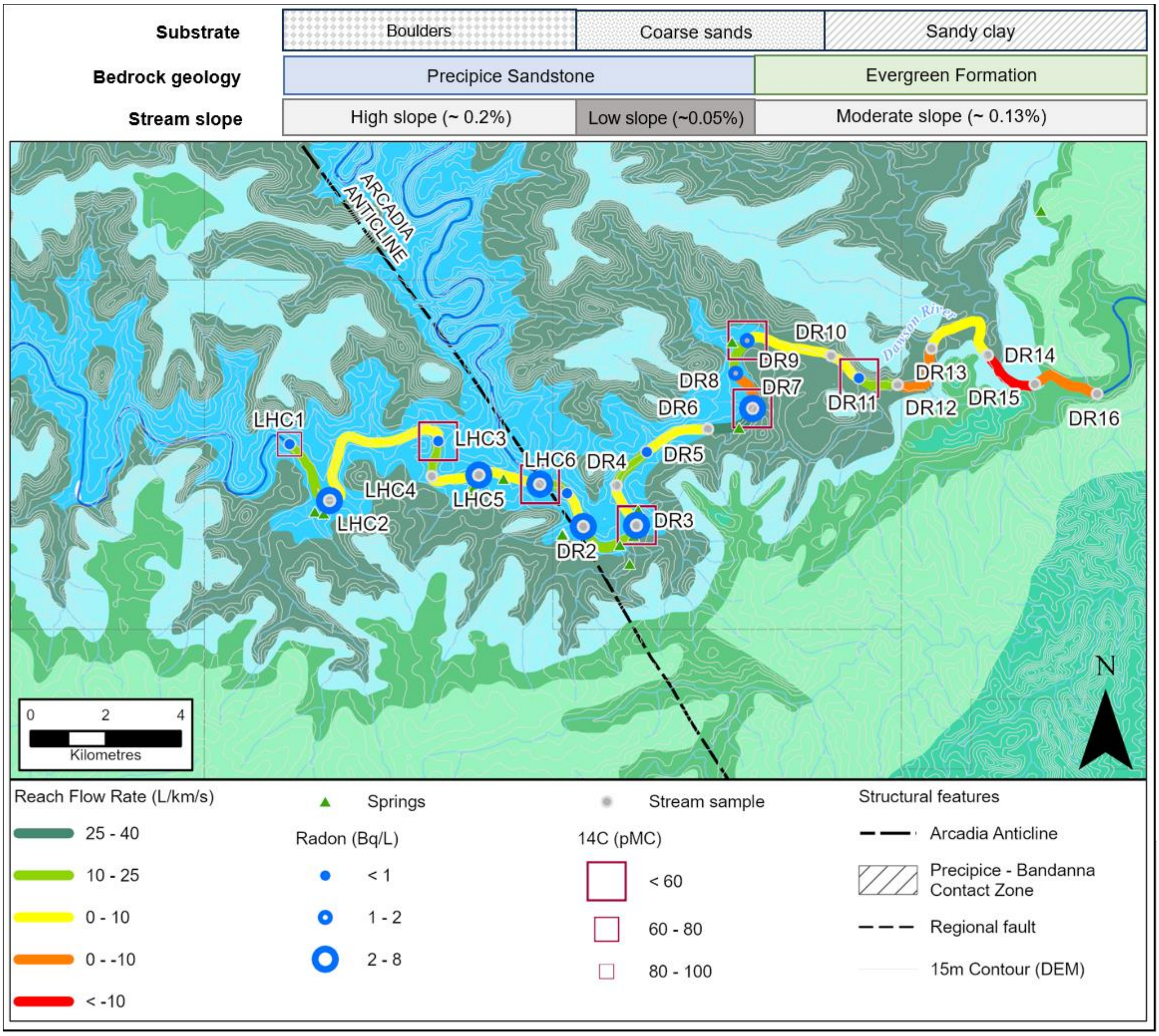

Figure 25: Summary schematic – Dawson River

Local and regional groundwater flow systems

Understanding the contribution of local and regional groundwater flux to stream flow is important to assess future changes to those components – such as climate, groundwater extraction and resource development. In combination with other data, the stable and radiogenic isotopes provide insights into residence time and groundwater flow paths contributing to stream flow.

The radiocarbon and tritium data for Hutton Creek indicate that older groundwaters – longer residence time – dominate stream flows at HC5 and HC7. The data indicate modern groundwaters are observed both upstream and downstream of these locations and at the Springrock Creek spring complex (Figure 22).

Stable isotopes of water also show HC5 and HC7 have a more regional groundwater flow signature (Figure 18) – particularly HC5 – with the remaining sites showing an evaporative signature, most likely reflecting the low discharge volumes, evaporation and resulting enrichment in the remaining waters. The radon data also show a significant peak in concentrations around HC4. This is supported by electrical conductivity (EC) data, which shows the lowest EC was observed at HC4 and HC5 – 238 to 248 µs/cm – with the highest at the Springrock Creek spring complex – 845 µs/cm – supporting the interpretation of an evaporative groundwater signature at this location.

The combination of these results suggests discharge is dominated by regional groundwater flow between HC4 and HC5, with local groundwater flow the major contributor at other locations along Hutton Creek. As highlighted by OGIA (2015b), given the significant topographic relief and skeletal rudosols in this area, there are likely to be local groundwater flow contributions to the stream.

Data for the Dawson River site also indicate a combination of local and regional groundwater flow to stream, although more broadly dominated by a regional discharge when compared to Hutton Creek. The radiogenic isotopes indicate older groundwaters dominate around and downstream of the confluence of Hutton Creek and the Dawson River – LHC6, DR3, DR7, DR9, DR11, DR2 spring and spring vent 704 (Figure 22).

Upstream locations show more evaporative signatures, and a significant contribution of local groundwater flow based on the stable isotope, ^{3}H and ^{14}C data. This is supported by the stable isotopes, which also indicate more evaporative concentrations at LHC1, LHC2 and LHC3. Similar to Hutton Creek, EC for these locations ranges from 346 to 430 µs/cm – higher than downstream locations.

The combination of these results suggests discharge to the Dawson River monitoring sites is dominated by regional groundwater flow downstream from the confluence of the two watercourses.

Aquifers contributing to groundwater discharge

In the northern Surat Basin, there are three potential aquifers in the vicinity of the study locations – the Precipice Sandstone, the Boxvale Sandstone Member of the Evergreen Formation and the Hutton Sandstone (Figure 5). The Precipice Sandstone is present at all sample locations, with the other potential contributing aquifers present to varying degrees due to landscape dissection and erosion.

At the upstream sampling locations along Hutton Creek, all three aquifers are present. The creek traverses the Hutton-Wallumbilla fault system, with the Hutton, Boxvale and Precipice sandstones present on the southern side of the fault system (Flook et al. 2020). On the northern side, the Precipice Sandstone is present, with the Boxvale Sandstone occurring in isolated plateaus with limited lateral continuity (Figure 4 and Figure 5).

At the Dawson River sampling locations, the Hutton Sandstone is absent, and the Boxvale Sandstone occurs in a similar way to the Hutton Creek location – isolated plateaus. In addition to these aquifers, Jacobs (2018) – based on OGIA's geological model (OGIA, 2019b) – highlights the potential for a limited subcrop of the Clematis Sandstone beneath the Precipice Sandstone approximately between DR3 and DR5.

As discussed previously, strontium isotope ratios are largely controlled by water-rock interactions (McNutt, 2000) and have been applied as a line of evidence, to evaluate connectivity between formations and support the identification of contributing aquifers to bores and springs (OGIA, 2023). More broadly, the samples from the two study locations show some separation and longitudinal trends.

At the Hutton Creek location, the strontium isotope ratios in stream samples cluster around a narrow range of 0.70615 to 0.70625 (Figure 23). This is within the range of nearby water bore sample data from all three potentially contributing aquifers – the Hutton, Precipice and Boxvale sandstones. In combination with the results for total dissolved solids, however, the stream samples are most closely aligned to the Precipice Sandstone, which has considerably lower values than the Hutton Sandstone.

The Springrock Creek spring sample – a tributary of Hutton Creek (Figure 5) – is also shown and has a considerably higher strontium isotope ratio. As discussed above, ^{14}C and tritium data for this sample indicate a modern component to discharge or the influence of rainwater at this location. This may suggest local flow systems contribute to groundwater discharge and this strontium isotope ratio may reflect the strontium composition of the shallow rudosols or weathered Evergreen Formation in this area.

The stream samples from the Dawson River show a much larger range in strontium isotope ratio results compared to the Hutton Creek section – 0.706319 to 0.707233 – and a progressive increase in the observed ratio with each downstream sample location (Figure 23). The sampled locations along this reach are entirely overlying the Precipice Sandstone. The Hutton Sandstone is absent, with the Boxvale Sandstone only present in isolated sections on surrounding plateaus.

The limited available samples from the Clematis Sandstone indicate a strontium isotope ratio higher than those of the Precipice Sandstone and may represent a plausible end member for progressive increases downstream of the interpreted subcrop. Strontium isotope ratios increase from the start of this reach however, indicating a progressive increase rather than a potential influx from the Clematis Sandstone at this discrete location.

The locally available data from the Precipice Sandstone broadly indicate an increase in the strontium isotope ratio with depth. This reach is progressively more incised into the Precipice Sandstone and may suggest that the lower portion of this formation has a higher $^{87}Sr/^{86}Sr$ ratio. Local groundwater inflow is a potential explanation, however, the available ^{14}C and tritium data indicate that this reach is dominated by regional discharge, so it would be more difficult for local groundwater contributions to explain these increases.

CONCLUSION

The Dawson River (‘Wardingarri’) and upstream Hutton Creek are culturally and ecologically significant watercourses. Sections of these streams are widely recognised as regional discharge areas for the Precipice Sandstone – the basal aquifer of the GAB – following the dissection and erosion of the overlying Evergreen Formation, exposing the aquifer in the streambed.

In this thesis, it was hypothesised that beyond dissection and erosion, other local characteristics – such as faults and fractures, variability in stream substrate and stream slope – may influence the spatial distribution of groundwater discharge to stream. Integrating longitudinal stream gauging and environmental tracer data, this study sought to identify the spatial variability, direction and magnitude of flux and the local and regional groundwater flow components of discharge.

Key conclusions from the analysis are as follows:

- Net groundwater discharge from Hutton Creek is estimated to be less than 50 ML/yr, with the Dawson River around two orders of magnitude higher at approximately 6,400 ML/yr. This difference reflects a combination of the stream length and the magnitude of groundwater discharge at each location.
- There is significant inter-reach variability in terms of the direction and magnitude of flux between the groundwater system and stream. At Hutton Creek, there is a single significant gaining zone (~3 km) with a uniform distribution around the peak discharge reach (HC5–HC6). At the Dawson River site, there is a large gaining zone (~25 km) that shows significant inter-reach variability, with no prominent peak in discharge rate.
- Building upon the insights from the stream gauging data, the radon data further refines the zones of higher groundwater flux. This is most apparent at Hutton Creek, with a significant peak in concentrations at HC5. At the Dawson River, these data complement the gauging data, highlighting the variability in zones of groundwater flux.
- The radiocarbon, tritium and stable isotope results support the identification of reaches with longer and shorter aquifer residence times. Hutton Creek has one zone dominated by older groundwater, with the Dawson River also dominated by older groundwater, downstream of the confluence of Hutton Creek.
- The Precipice Sandstone is the most homogenous and permeable aquifer in the Surat Basin and is interpreted to be the major groundwater source for both reaches, based on strontium isotopes and geological setting. There is, however, significant variability in groundwater discharge, which appears to be controlled by factors beyond the underlying bedrock geology, stream slope or substrate.

- The regional structural features of the Hutton-Wallumbilla fault system and the Arcadia Anticline are proximal to the study locations. Consistent with Hayes et al. (2020), the stream gauging and environmental isotope data suggest that secondary porosity within the Precipice Sandstone itself may result in higher zones of permeability and discharge to the stream.

The analysis is based on a single stream gauging and environmental isotope sampling event in September 2023. Additional sampling events – particularly stable isotopes – and stream bed characterisation may assist in increasing confidence in the understanding of local flow system contributions to groundwater discharge at some sites, such as Springrock Creek.

The analysis in this thesis highlights the benefits of integrating stream gauging and environmental tracer data to enhance the understanding of groundwater–surface water interaction. Analysis of the environmental tracer data provided the basis to elucidate deeper insights into the zones and sources of groundwater discharge, which are unable to be determined from stream gauging alone. This was even the case where the study reaches were sampled during the dry season baseflow dominated period.

Consistent with Exon (1971), Mollan et al. (1972), Smerdon & Ransley (2012) and OGIA (2016a), sections of Hutton Creek and the Dawson River are confirmed to be regional discharge zones for the Precipice Sandstone. This study has highlighted that there is a high degree of local variability in discharge rates, with higher discharge zones likely to be due to secondary porosity resulting from interaction between the Surat Basin and underlying regional structures in the Bowen Basin.

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APPENDICES

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Figure 26: Hydrostratigraphy of the Surat and southern Bowen basins (after OGIA 2021a)

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Figure 27: Structural elements of the Surat and Clarence-Moreton basins (after OGIA 2016a)