Evolution of Knowledge on Springs in the Surat and Southern Bowen Basins: Survey, Conceptualisation and Wetland Dynamics

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Abstract

Permanent wetlands supported by discharge from the Great Artesian Basin (GAB) are of global significance due to their unique ecological assemblages and cultural values. Since 2005, rapid growth in coal seam gas (CSG) development has occurred in the Surat Basin, a sub-basin of the GAB. In parallel with this expansion, there has been substantial investment by government and industry to identify spring wetlands and their source aquifers, understand natural variability in groundwater discharge and to manage predicted impacts resulting from groundwater drawdown. The assessment of consequences to the springs from groundwater drawdown relies upon sound hydrogeological conceptualisation including: the mechanisms through which springs occur; understanding of the wetland water balance; knowledge of historical spatio-temporal changes in wetland extent; and an ability to distinguish between the effects of groundwater drawdown from natural variability in the wetland water balance and other non-hydrogeological influences. In parallel with changes to groundwater pressure, key factors that influence wetland dynamics include the soils surrounding the wetlands, landscape setting, the type of groundwater flow system (local and/or regional), adjacent land use and climate. Integrating multiple lines of evidence and knowledge is pivotal to understanding the influences of a change in groundwater pressure on the abundance and resilience of biota that are dependent on the groundwater discharge. This paper provides a synthesis of the research and monitoring undertaken in the Surat and southern Bowen basins since 2011. Detailed surveys and hydrogeological conceptualisation have led to new insights on the occurrence and distribution of springs and the key influences on the spring wetland water balance. This knowledge has provided the scientific basis for the management and monitoring of predicted impacts. The approach of evolving the underpinning science to inform a specific management and monitoring requirement is more broadly applicable to groundwater-dependent ecosystems.

Keywords: groundwater-dependent ecosystems, Great Artesian Basin, Surat Basin, spring dynamics, wetland water balance, coal seam gas

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Introduction

Wetlands associated with springs sourced from the Great Artesian Basin (GAB) are of international conservation significance. The GAB is a hydrogeological grouping of geological formations, comprising a number of component sub-basins (Habermehl, 2020). Collectively, this resource covers an area of 1.7 million km², nearly one-fifth of the Australian continent, across four states (Ransley & Smerdon, 2012). The Queensland portion of the GAB covers 65% of the state, and ranges in thickness from less than 100 m to more than 3000 m in the Eromanga Basin in Central Queensland (UWIR, 2019).
The Surat Basin, a sub-basin of the GAB (Figure 1), is a predominantly Jurassic and Early Cretaceous sedimentary sequence (deposited 60 to 200 million years ago) attaining a maximum thickness of around 2500 m (Habermehl, 1980; Hoffmann et al., 2009). The basin is a highly heterogeneous mix of alternating layers of sandstones, siltstones, mudstones and coal (OGIA, 2019). The primary CSG reservoir in the Surat Basin is the Walloon Coal Measures. Portions of the Surat Basin are underlain by the Bowen Basin.

Groundwater naturally discharges in the form of springs and baseflow to streams, predominately around the margins of the GAB. However, due to structural features such as faults or basement highs that occur between sub-basins, springs can also form away from the margins. Although many springs share similar hydrogeological mechanisms, there is significant diversity in their expression at the surface, driven largely by variability in the hydrochemistry, soils and local climatic conditions. Examples of springs across the GAB, which highlight the variability in their surface expression, are shown in Figure 2.

Figure 1. The GAB with sub-basins, major regional clusters of springs (spring supergroups, shown in blue) (Fensham & Fairfax, 2003), local (hatch) and regional recharge areas (dark grey around the GAB periphery), regional flow directions (orange arrows) (Ransley et al., 2015) and the Surat Cumulative Management Area (OGIA, 2019).
A wetland associated with a spring can be subdivided into two distinct zones: the ‘aquatic wetland extent’ and the ‘wetland extent’. The aquatic wetland extent represents the zone of permanent saturation and is dominated by aquatic species, as defined by Fensham & Fairfax (2009). The broader ‘wetland extent’ is a larger area of historical or periodic wetland extent. In this area, there may be
no aquatic species or free water, but key wetland indicators – wetland soil development – suggest historically significant periods of inundation.

There is a range of hydrogeological and non-hydrogeological stressors which have the potential to impact both the condition and wetland habitat. Change in groundwater pressure in aquifers that support springs is recognised as the most significant threat to spring wetlands (Fensham et al., 2010). Changes in groundwater pressure may occur in response to climatic variability and resultant recharge, consumptive water use and petroleum, and gas and mineral resource development.

In contrast to consumptive water use, groundwater extraction for CSG development is a more concentrated stressor on the groundwater system. In the Surat Cumulative Management Area (CMA) (160,000 km²), CSG extraction commenced around 2005, within the Surat and southern Bowen basins. The rapid expansion of this industry was a key driver for the need to advance the understanding of springs in this area. In parallel, new knowledge on springs has been incorporated into the management and monitoring arrangements for all water users under the Water Plan (Great Artesian Basin and Other Regional Aquifers) 2017 (GABORA Water Plan).

In the Surat CMA, the primary CSG reservoirs are the Walloon Coal Measures (Surat Basin) and the Bandanna Formation (Bowen Basin). During the initial CSG development phase, the target reservoir must be depressurised, as the gas is adsorbed to the coal seams, held in place under hydrostatic pressure. This differs significantly from conventional petroleum and gas development, where oil and gas reserves are held within structural or stratigraphic geological traps, rather than under hydrostatic pressure. As a result, CSG wells initially produce significant amounts of water (termed ‘associated water’) and minimal gas. Over time, as the well develops and hydrostatic pressure in the reservoir reduces, discharge from the well is progressively dominated by gas (OGIA, 2019). Currently, the annual volume of associated water produced from the Surat Basin is about 50,000 ML (OGIA, 2019) from around 7000 production wells.

This extraction is in addition to a current consumptive and industrial water use across the CMA that exceeds 160,000 ML/year (OGIA, 2019) across shallow alluvial, basalt and GAB aquifers. The allocation and protection of consumptive water use is managed under the GABORA Water Plan, for purposes including stock and domestic, town water supply, agriculture and intensive livestock purposes.

In response to the rapidly expanding CSG industry, there has been significant investment by the Queensland Government and industry since 2011 to identify and monitor springs in areas potentially affected by these activities. Within the Surat CMA, there are 88 spring complexes, of which 19 have high conservation values protected under Commonwealth (Environment Protection and Biodiversity Conservation Act 1999 (the EPBC Act)) and state legislation.

Springs in this area are predominantly fed from the major aquifers including the Clematis Sandstone, the Precipice Sandstone, the Boxvale Sandstone Member of the Evergreen Formation, the Hutton Sandstone, the Gubberamunda Sandstone and the Bungil Formation (Figure 3). In addition to these aquifers, there are springs associated with the Tertiary volcanics and Cenozoic sediments.

Recent groundwater modelling (UWIR, 2019) predicts that several spring complexes are likely to be affected by groundwater drawdown as a result of CSG development. The accurate assessment of impacts and the development of appropriate mitigation and management strategies must be informed by knowledge of the ecological and cultural values of these sites, knowledge of factors that influence wetland extent and groundwater pressure in supporting aquifers, and knowledge of the historical variability in these systems.

For some spring wetlands, rainfall variability can be a significant influence on the wetland vegetation extent and condition. This results in a dynamic pattern of expansion and contraction in wetland extent in response to periods of higher rainfall and recharge to the source aquifer that feeds the wetland. In combination with changes in groundwater extraction, land use, disturbance by feral animals (such as pigs), exotic weeds, and grazing pressure during higher and lower rainfall periods, the temporal dynamics of the wetland extent – and habitat – can vary significantly.
To assess change in wetland extent, a field-based methodology for the measurement of aquatic wetland extent has been established (Fensham & Fairfax, 2009). The method involves defining the edge of the wetland area by delineating the wetland boundary – where aquatic vegetation is less than 50% vegetation coverage.

In parallel with in-field mapping of the wetland
extent, remote sensing has been applied at the broad or regional scale (Ndayisaba et al., 2017; Nhamo et al., 2017; Petus et al., 2013; White & Lewis, 2011; Xie et al., 2016). Improvements in spatial resolution have enabled increased precision in wetland delineation (Davidson et al., 2018). However, remotely sensed imagery is only available for recent decades.

Given the high spatio-temporal variability in rainfall in Australia, analysis of a longer period of historical data is desirable. Prior to the inception of satellite-based imagery, opportunistically collected aerial photography – such as that collected for early mineral exploration – represents a unique source of historical data for comparative studies of wetland location and extent. In areas of high potential groundwater extraction, accurate location and elevation information, as well as knowledge of source aquifers and environmental values of springs, are necessary for a comprehensive assessment of potential impacts.

This paper provides an overview of some of the findings from field surveys, monitoring and research at groundwater-fed wetlands in the Surat CMA. The paper presents the evolution of knowledge in relation to springs, from field surveys through to remote sensing, to inform the conceptualisation of wetland dynamics. The components of the wetland water balance and both groundwater and non-groundwater influences on observed change in wetland extent over time are discussed. Understanding the drivers of spring dynamics is critical for determining appropriate monitoring methods and for understanding how changes in groundwater pressure could affect wetland ecosystems. Importantly, the approach is more widely applicable, as many of the methods and research questions are relevant to other parts of the GAB.

Management of Groundwater Impacts on Springs

In Queensland, the Water Act 2000 (Water Act), the GABORA Water Plan and management protocol create the framework for the management of water use impacts on springs. The protection of flow to the identified groundwater-dependent ecosystems (GDEs) – including springs – is achieved through the water licence assessment process. Through this mechanism, cumulative predicted drawdown limits are recorded for each individual spring. These are assessed and managed during water licence transactions.

CSG development in Queensland is regulated by state and Commonwealth governments, which assess the potential for impacts on groundwater resources, associated ecosystems and other water users. In Queensland, the Petroleum and Gas (Production and Safety) Act 2004 and the Petroleum Act 1923 authorise petroleum tenure holders to undertake activities related to petroleum exploration and production. Prior to a tenure being issued, under the Environmental Protection Act 1994 an environmental authority must be obtained, which primarily deals with the management of surface water and contamination as it relates to surface water and groundwater.

Petroleum tenure holders have a statutory right to take or interfere with groundwater. However, since 2010, under the Water Act, tenure holders are subject to a number of responsibilities to manage impacts on groundwater pressure arising from the exercise of underground water rights, including groundwater monitoring, the make-good of affected water supply bores and the mitigation of impacts on springs.

In areas of concentrated CSG development, the impacts on groundwater pressure resulting from individual tenure holders may overlap. In areas where this occurs, the Water Act allows for a CMA to be prescribed by the state, which allows for a cumulative approach to the assessment and management of these groundwater impacts (OGIA, 2019). The Surat CMA (Figures 1 and 3) was established in 2011 in response to expanding CSG development in the Surat and southern Bowen basins.

In the Surat CMA, the Office of Groundwater Impact Assessment (OGIA) is responsible for assessing cumulative groundwater impacts from resource activities and for developing appropriate water monitoring and spring management strategies. The assessment includes primary research and field investigations, system conceptualisation, regional groundwater flow modelling and development of integrated management arrangements. OGIA assigns responsibility to individual tenure holders for implementing specific management actions. The collective assessments and management arrangements are established in an Underground Water
Impact Report (UWIR), which is required every three years.

In parallel with the state approvals process, the Commonwealth Government also regulates new CSG activities through the EPBC Act, under which, nationally and internationally important flora, fauna, ecological communities and heritage places are recognised as “matters of national environmental significance” (MNES). As MNES relate to groundwater in the GAB, the community of native species dependent on natural discharge of groundwater from the GAB is listed as “Endangered” (Pointon & Rossini, 2020). Specifically, this is the ecological community associated with discharge springs, where groundwater emanates from a confined aquifer, not present at the surface.

In addition to individual species and communities, water resources are also recognised as MNES (“Water Trigger” EPBC Act amendment, 2013). The Commonwealth Government is therefore responsible for approving CSG projects, but that intervention is limited to consideration of impacts on water resources and other matters of national significance.

**Monitoring and Research**

Since the establishment of the Surat CMA in 2011, there has been significant investment in research to improve knowledge about the location, values and seasonal dynamics of springs. Prior to 2011, earlier spring surveys by the Queensland Government were primarily focused on recording springs’ location and botanical information. Building upon that dataset, an extensive hydrogeological and botanical survey was led by OGIA (then the Queensland Water Commission) in 2011. The updated dataset provided the basis for the initial source aquifer assessments and was also used to characterise ecological values as part of the first Underground Water Impact Report for the Surat CMA (UWIR, 2012) (Queensland Water Commission, 2012).

Five spring complexes were predicted to be impacted by more than 0.2 metres in the long term. As a result, detailed desktop and field investigations were undertaken at these locations, in parallel with seasonal monitoring completed by industry in accordance with the UWIR 2012 and tenure holders’ EPBC approval conditions across 17 spring complexes.

Under the EPBC Act, the Commonwealth Government set monitoring and other requirements on tenure holders as conditions of approval of CSG developments. The primary objective of monitoring at springs was to establish both an understanding of the natural variability and a baseline so that the potential impacts on the spring wetlands resulting from CSG water extraction may be identified.

**Hydrogeological Conceptualisation**

The overall approach to building knowledge about springs broadly applied the principles of the groundwater-dependent ecosystem toolbox (Richardson et al., 2011) – identify, characterise and assess the likely response to a change in the groundwater regime.

The hydrogeological, landscape and flora data collected between 2013 and 2015 were integrated to produce detailed ecohydrogeological conceptualisations (Flook et al., 2020) at a landscape and local scale level for 17 spring complexes.

Importantly, at each site, non-hydrogeological indicators of changes in the water balance – referred to as ‘ecological endpoints’ – were also identified. Ecological endpoints (Gross, 2003) represent key physical, biological and chemical elements of the spring wetland that are primarily influenced by groundwater discharge, and include indicators such as the extent of wetland vegetation that is dependent on groundwater discharge.

A detailed conceptualisation aids in the synthesis of an improved understanding of a spring’s source aquifer and the mechanisms by which springs occur. These two hydrogeological elements underpin predictions of the likelihood of impact from a change in the groundwater regime, resulting in a change in groundwater discharge from the spring at the surface. The identification of ecological endpoints provides a useful tool for the assessment and monitoring of change in the wetland linked to groundwater. These components collectively form the basis of the impact assessment and monitoring of change.

**Discharge Mechanisms**

The occurrence and distribution of springs in the Surat CMA are primarily driven by regional and local geology and topography. They are also influenced by geological and hydrogeological features such as
faults, changes in aquifer geometry and groundwater divides. Understanding the primary mechanism of connectivity to underlying aquifers is important for determining which aquifer is feeding the spring and critically informs the assessment of likelihood of a groundwater impact to a spring.

Building upon the work of Whitehouse (1954), Habermehl (1980) and Fensham & Fairfax (2003), three generalised hydrogeological mechanisms for spring formation are identified, noting that individual springs can occur due to more than one of these mechanisms (Figure 4):

(a) A spring can form where there is a change in the hydraulic properties of the geology within the landscape. Such a spring is often referred to as a contact spring. Where a higher-permeability layer overlies a lower-permeability layer, flow across the boundary is restricted. As a result, water tends to flow laterally and may reach the surface as a spring. This can occur where there is a change in permeability within a single aquifer or where there is a change in geology. Approximately 40 km north of Roma, two spring complexes have formed in this way – Six Mile and Spring Ridge.

(b) A geologic structure, such as a fault, can provide a path to the surface for water flow. If an underlying aquifer is confined by impermeable material and the water pressure in the aquifer is high enough, water can flow to the surface as a spring. Regional faulting features, such as the Hutton-Wallumbilla Fault and the Leichhardt-Burungga Fault, are associated with springs in the central area of the Surat CMA (OGIA, 2016).

Figure 4. Schematics showing the generalised mechanisms by which springs occur in the Surat Basin (after OGIA, 2019): (A) Change in permeability. (B) Presence of a geological structure. (C) Erosion of the surface geology.
Erosion and dissection of the landscape by surface water flows can provide opportunities for groundwater to reach the surface. This can occur where an outcropping aquifer has been eroded to create a depression of sufficient depth to reach the watertable. This situation is generally associated with creeks and streams. In other areas, a confining unit may be dissected, resulting in a reduction in the thickness of the confining unit and providing an opportunity for groundwater to flow to the surface. Springs in the Surat CMA formed by erosion of the surface geology include springs in watercourses, such as the Dawson River.

These are generalised mechanisms by which springs occur. However, at many spring locations, a combination of mechanisms may exist and influence one another. For example, where structural features exist in the near surface (Figure 4B), these areas are more erodible and therefore erosion and dissection of the landscape may occur (Figure 4C) in parallel.

The discharge mechanisms can be further informed by analysis of hydrochemical data that have shown many wetlands receive groundwater inflows from both regional and local groundwater systems. Some springs (for example, at the Abyss complex) are fed by seasonal groundwater inflows in addition to regional groundwater discharge (Flook et al., 2020). The incorporation of multiple lines of evidence and the evolution of monitoring techniques aid in the refinement of a detailed subsurface hydrogeological conceptualisation, but also further refine the wetland water balance.

**Wetland Water Balance**

The detailed wetland conceptualisation highlights the importance of understanding the components of a spring’s water balance. Under natural conditions, a spring’s ecological composition and function intrinsically rely upon maintenance of the spring water balance. The water balance (Figure 5) includes all major inflows and losses from a spring.

Characterising the natural hydrological dynamics of the wetland system is critical to determining ecological water requirements of the dependent ecosystems and hypothesising potential consequences of a change to a component of the water balance.

**Figure 5.** Conceptual schematic of a spring wetland water balance (after OGIA, 2016).
Variation in groundwater discharge and aquatic wetland extent has been observed through physical monitoring and mapping by industry and OGIA (OGIA, 2015b). Long-term variation is observed through the analysis of historical imagery and the presence of landscape features that indicate wetting or drying phases of the wetland area, such as dead trees, salt-scalded soil, collapsed spring vents, and spring vents that have stopped flowing.

Figures 6 and 7 show wetland area data for two spring vents at the Lucky Last spring complex, illustrating seasonal and long-term variability in the wetland supported by these springs. The extent of wetland vegetation and variability was assessed for the period 1948–2013 from opportunistically captured aerial photographs (OGIA, 2014).

At this location, there is significant variability in the aquatic vegetation extent through time. However, individual wetlands show a generally consistent trend of expansion and contraction across the historical period of record.

Similar to the analysis of a water level hydrograph, the measurement of aquatic wetland extent through time provides a monitoring signal and trend for subsequent analysis. The data represent the culmination of both the wetland water balance and non-hydrogeological influences on the wetland. Determining the influence of a change in groundwater pressure on the wetland requires detailed hydrogeological conceptualisation of the site and characterisation of the current and historical influences on the wetland.

Figure 6. Field-based mapping of the aquatic vegetation extent at the Lucky Last spring complex.

Figure 7. Wetland area mapped from aerial photography at the Lucky Last spring complex.
Influences on Wetland Dynamics
The water balance and, therefore, the observed dynamics in the wetland extent and discharge regime are influenced by stressors both hydrological – rainfall variability, groundwater recharge and abstraction – and non-hydrological, such as land use changes. Understanding the drivers of hydrogeological changes provides the basis for more meaningful analysis of temporal ecological datasets collected at spring wetlands. The detailed analysis of monitoring data and site conceptualisations highlight that the following elements are important for understanding temporal and spatial variability in wetland dynamics.

Topographic and Landscape Setting
Topographic setting refers to the position of the wetlands within the local relief. It provides an insight into the potential influence of local flow systems (via groundwater and/or surface runoff) on the hydrological regime at the wetland. For example, wetlands located in topographic lows or depressions are likely to receive surface runoff and discharge from local groundwater flow systems.

Spring wetlands in the Surat CMA are predominantly riverine (in a watercourse) or palustrine (vegetated, non-watercourse). Riverine wetlands, by definition, occur on the valley floor. Palustrine wetlands may occur in topographic lows, on slopes, or at the break of a slope. Some wetlands are considered palustrine even if they receive intermittent inflows from flooding, but their dominant water source and the reason for their occurrence is groundwater discharge. The primary distinction between wetlands, therefore, is whether they occur within riverine settings and are influenced by surface water inflows in addition to groundwater discharge.

In terms of seasonal dynamics and wetland geometry, wetlands located on slopes in the Surat CMA are likely to form discharge tails. At these wetlands, seasonal dynamics are more apparent than those positioned on more even ground. This is interpreted to primarily be a response to seasonal changes in evapotranspiration, with components of the wetland water budget transitioning from evapotranspiration to physical groundwater discharge from the wetland. In most cases, groundwater pressure in the vicinity of the wetland remains relatively stable. This is shown in Figure 8 with two wetlands, in different landscape settings, at the Boggomoss spring complex near Taroom.

Figure 8. Variations in extent at Wetland 1 (a circular flat wetland located on the flat) and Wetland 52 (on a slight slope with large increase in wetted area during autumn months) (Lyons et al., 2015; OGIA, 2015a).
Geomorphology
The geomorphology and substrate of wetlands can significantly influence the wetland dynamics. Geomorphology refers to the current landscape evolution processes of the wetland setting, and whether they are predominantly erosional or depositional in nature. Substrate refers to the base material in which the wetland has formed, within the broad categories of soil, rock or colluvial/alluvial material.

These attributes collectively describe the stability of the landforms in which wetlands are located and the likelihood of change in the wetland form over shorter geomorphological time scales (months to years) due to landform evolution processes. Alluvial and colluvial substrates are considered the least geomorphologically stable. Rock is considered to be the most stable, although grazing and vegetation management can affect the stability at sites regardless of landform.

In the Surat CMA, the majority of wetlands are located in erosional landscapes, exacerbated by land use change and grazing. The wetlands in the depositional environment of the Dawson River are the exception. In terms of substrate, most wetlands are located in soil, with the exception of some spring complexes located along the mid to upper tributaries of the Dawson River.

In a depositional environment, sedimentation and deposition may influence the wetland extent, in the absence of a change in the underlying groundwater flow regime. Similarly, within an erosional environment, changes to the geometry of a wetland can occur over short timeframes. Figure 9 provides an example of wetlands within different geomorphological settings.

Regolith and Soils
In the context of spring wetlands, regolith is the material in which a wetland occurs that has been altered by the physical, biological and chemical processes associated with groundwater discharge and the associated ecology. It includes the weathered substrate – the soil found within the wetland – and comprises inorganic and organic material to varying degrees. It forms an important aspect of wetland functioning, in that it influences the water-holding capacity of the wetland and the type of vegetation supported. It is noted that there is a feedback loop between regolith and ecology, with each influencing the other.

Regolith depth varies between wetlands, with deeper profiles of at least 5 m noted at many complexes including Boggomoss, Scott’s Creek and Elgin 2. At these complexes, the wetlands can hold a greater quantity of water in proportion to their cross-sectional area and therefore are more likely to support a greater biomass of vegetation and may have greater resilience to short-term hydrologic changes. Elsewhere, the regolith depth is shallow. This has important implications for understanding wetland dynamics and the drying and wetting cycles at these wetlands.

Figure 9. (A) Spring wetlands north-east of Injune (Abyss) within an erosional environment. (B) wetlands within a depositional environment (Scott’s Creek).
Mounded regolith features are a distinguishing characteristic of a number of wetlands. These mounds are interpreted to have formed primarily in response to biological processes in which organic matter builds up over time due to the decomposition of wetland vegetation, as opposed to the precipitation of solutes emanating from groundwater discharge. The growth of mounded features may also be accentuated by the erosion of the surrounding landscape.

Figure 10 provides an example of the importance of understanding the interplay between topography, surrounding soils and their properties. These elements significantly influence local groundwater recharge and discharge characteristics and, in many cases, the wetland geometry, due to slope and the hydraulic properties of the surrounding soils. In this example, the soils of the upper water catchment are relatively well drained, with the infiltration rate of the floodplain soils decreasing upon saturation, resulting in confining properties. The expansion and reduced hydraulic conductivity of the soils immediately surrounding the wetlands results in discrete discharge features.

In other parts of the GAB, the immediate regolith and surrounding soils significantly influence dynamics of the wetland area. In the South Australian portion of the GAB, travertine mounds occur at many springs. At these locations, as groundwater rapidly discharges to the surface, the drop in pressure between the surface and subsurface environments causes calcium carbonate in solution to precipitate. Precipitation is facilitated by calci-fixating cyanobacteria to form travertine. The formation of these features significantly influences the variability in extent and dynamics of these wetlands (Keppel et al., 2018).

**Climate**

Climatic variability has the capacity to influence spring wetlands in several ways: directly, through regional and local groundwater recharge to a spring’s source aquifer, direct rainfall infiltration to the wetland and seasonal cycles of evapotranspiration from the wetland; and indirectly, through increased groundwater abstraction and grazing pressure on the wetland.

**Figure 10.** Land system and dominant soil types at Dawson River 8 spring complex (adapted from Speck et al., 1968 and SKM, 2014).
Wetlands in the study area predominantly receive groundwater flow from regional groundwater flow systems. In these aquifers, groundwater has travelled a significant distance from the aquifer recharge zone. Variations in longer-term rainfall patterns and associated recharge are often observed in groundwater monitoring bores located in areas of recharge. However, there is often limited groundwater monitoring infrastructure in the vicinity of spring wetlands, particularly across the historical time period, to utilise groundwater monitoring data in understanding aquifer behaviour at the spring. Until the more recent period, the selection of groundwater monitoring locations has primarily been driven by water resource development requirements.

**Groundwater Abstraction**

There are approximately 22,300 water supply bores in the Surat CMA. Of this number, approximately 8000 are accessing formations of the Surat Basin, 600 in the Bowen Basin, while the remainder – approximately 13,700 – are screened in the overlying shallow alluvium and basalt (UWIR, 2019). Most water supply bores – approximately 90% – are constructed to depths of less than 200 metres. At these depths, sufficient supplies are generally available for stock and domestic purposes.

In the Surat CMA, spring wetlands are also predominantly located on the margins of the sub-basins and are fed by aquifers at depths of less than 100 m (Figure 3). Historically, water supply bores were often located near springs, as they were known to be high-potential water supply locations.

A significant challenge is understanding the historical groundwater extraction and resulting changes in groundwater pressure in the vicinity of the springs. In terms of wetland dynamics, it is important to conceptualise pre-development conditions and how the wetland may have changed through time in response to a potential reduction in groundwater pressure and implications for the wetland area.

In the absence of historical groundwater pressure monitoring, Figure 11 – showing the growth in water supply bores and water use (OGIA, 2019) within 10 km of springs sourced from the confined Hutton Sandstone – is used as a proxy for water use changes over time.

As shown, there was expansive groundwater development from the 1940s through to the 1980s, since which time bore development has stabilised. It is likely that groundwater levels have declined in response to this development in the vicinity of these springs. This is broadly consistent with the period of development across much of the Surat Basin. This provides an indication of growth and may be useful for correlation with changes in wetland extent in the absence of groundwater pressure data.

**Figure 11.** Time series of water bore development in the Hutton Sandstone, within 10 km of two spring complexes fed by this aquifer – Scott’s Creek and Dawson River 8.
Land Use

Land use can influence the observed wetland extent, the overall condition of the wetlands and their seasonal and long-term dynamics. In the Surat CMA, observed effects of grazing activities include compaction, disturbance and changes in the wetland water chemistry. Pugging around the edges of mounded spring wetlands can create small drains, which alter the area of saturated soil. Within the wetland, conceptually, this could increase areas of ponding, increasing evaporation, which may result in elevated conductivity within the wetland. Grazing of wetland vegetation alters the balance between evaporation and transpiration within the wetland in addition to nutrient loads. The indirect effects of changes in land use can have long-term impacts on wetland area and condition.

Integrating Science with Management

The growth in the CSG industry and other water extraction in the Surat CMA required the rapid advancement in knowledge and understanding about springs, to inform the assessment of impacts and the development of monitoring approaches to further understand baseline conditions and to hypothesise their response to change.

Ecohydrogeological data collected through targeted field surveys provided the basis for the initial assessment of likelihood and consequence of impact. Hydrogeological conceptualisation and the detailed assessments of wetland attributes informed the development of a spring typology (OGIA, 2016) to support risk assessment and guide monitoring and management arrangements (Figure 12) – including four spring types. Attributes are selected as the key differentials in describing how the wetlands occur within the landscape and how they are likely to respond to a change in the groundwater regime connected to the wetland.

Importantly, this approach provides a direct linkage between detailed hydrogeological conceptualisation and a tool to guide a specific management requirement. In other parts of the GAB, such as in South Australia, springs have also been classified to support the assessment of risk and decision making (Green et al., 2013). Since then, building upon this work and in response to potential CSG development, local-scale assessments have been completed to inform specific management questions in South Australia (Gotch et al., 2015). More recently, whole-of-basin approaches are being developed, including the GAB springs adaptive management plan (Brake, 2020), which seeks to bring together the current science to improve the on-ground management of GAB springs.

In all cases, to support a specific management requirement, the currently available science has been integrated and presented in a manner to support decision making. In parallel, knowledge continues to evolve. In the case of the Surat CMA, the periodic assessment (every three years) provides the opportunity to continue to advance knowledge and provide a direct linkage to management arrangements.

Ongoing advances in spring monitoring design, based on current knowledge, are necessary to continue to build and refine understanding about natural variability in spring discharge, and to confirm or amend the hydrogeological conceptualisation and water balance.

Figure 12. Wetland typology developed to inform management arrangements in the Surat CMA.
Future research directions include targeted seasonal monitoring to better understand temporal dynamics of water flows; evaluation of techniques to improve the ability to monitor wetlands; integration of Indigenous knowledge of dynamics; and further investigation of historical aerial imagery and finer-scale remote sensing to elucidate spatial dynamics.

Conclusions
In response to rapidly advancing CSG development in the Surat and southern Bowen basins, detailed field surveys and hydrogeological conceptualisation have been completed since 2011 to provide foundational science for the management of potential impacts – spring location, source aquifer, values and natural variability in groundwater discharge. The approach of evolving the underpinning science to inform a specific management requirement is more broadly applicable to all groundwater-dependent ecosystems.

The ecology and processes that occur within wetlands intrinsically rely on the maintenance of the spring wetland water balance. Beyond the hydrogeological occurrence of the springs, quantifying the spatial and temporal dynamics of the wetland water balance requires site-specific data for each component. This is important, as ecological monitoring data and observed change can only be meaningfully analysed with an understanding of the wetland water balance and change in individual components. On the basis of the work completed in the Surat CMA, important factors to understand change are landscape setting, regolith and surrounding soils, climate and adjacent land use.

A significant challenge is the identification of the historical extent of wetlands and natural variability prior to groundwater development and landscape change. In this paper, opportunistically collected aerial imagery and characterisation of local groundwater development provide context for further understanding historical conditions. In more arid parts of the GAB, remote sensing has proved effective and a more distinct boundary between spring vegetation and the surrounding landscape can be achieved (White et al., 2016).

Importantly, in the Surat CMA, targeted research has been undertaken to inform a specific management requirement. Findings from research have been synthesised in technical reports, but also into management tools – such as the spring typology – which support the assessment of risks to springs and provide a basis for initial monitoring design. Critically, the underpinning legislative framework provides for an iterative cycle of research, monitoring and growth in knowledge, which directly inform revisions to management arrangements.

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