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Northern Perth Basin subsurface resources interaction

Final report

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CSIRO Energy

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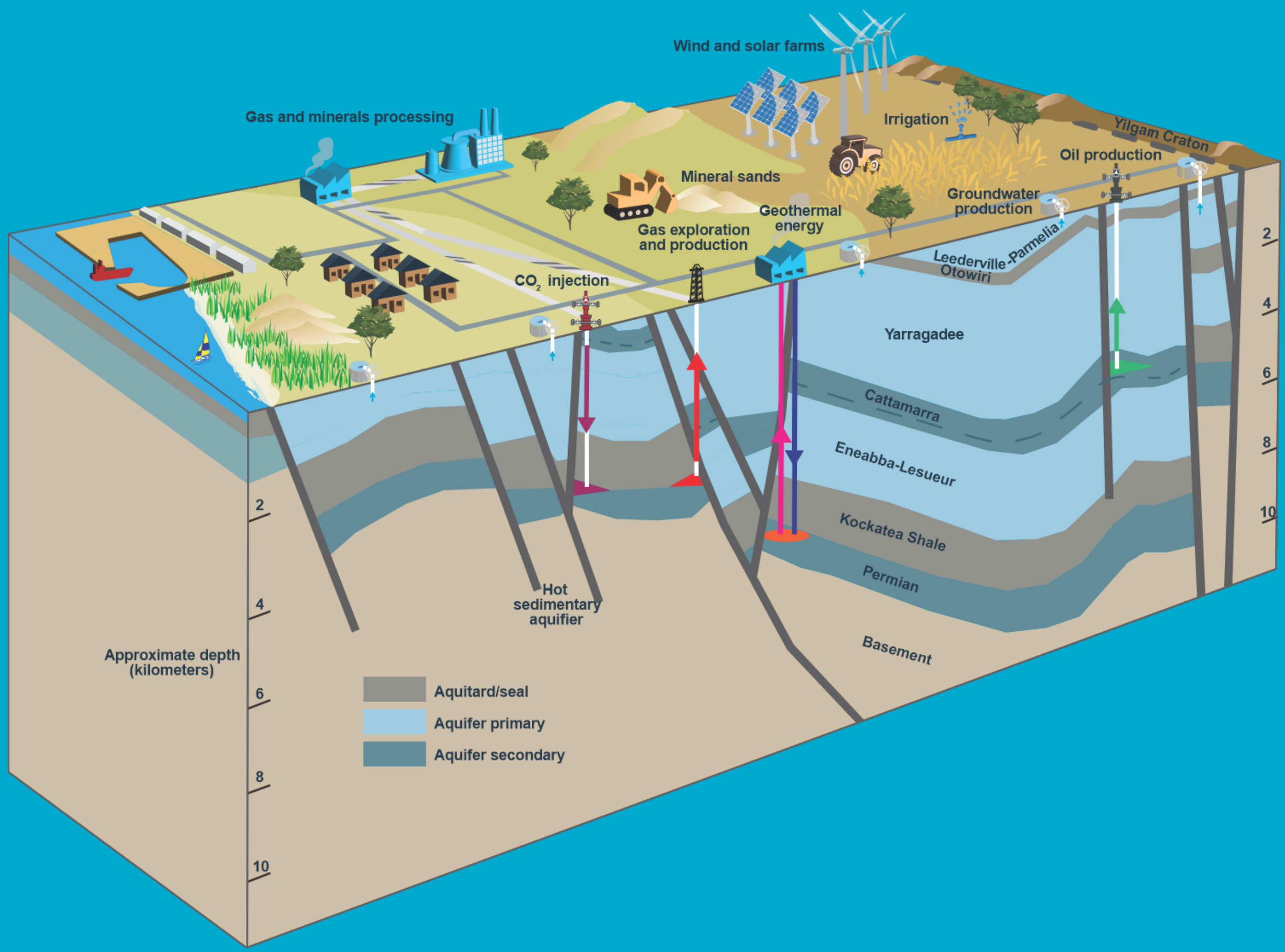

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Acknowledgement of Country

CSIRO acknowledges the Traditional Owners of the lands, seas and waters of the area that we live and work on across Australia and pays its respects to Elders past and present. CSIRO recognises that Aboriginal and Torres Strait Islander peoples have made, and will continue to make, extraordinary contributions to Australian life including in cultural, economic, and scientific domains.

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Executive Summary

The northern Perth Basin is experiencing a rise in subsurface and above-ground resource development activities, including natural gas, geothermal energy, carbon geological storage (CGS), underground gas storage (UGS), and groundwater extraction. The expanding industrial footprint presents opportunities and challenges, with resource developments either complementing one another or creating potential conflicts due to competing land and subsurface use.

This study aims to provide a data-driven framework for evaluating subsurface resource interactions and identifying potential risks and opportunities for regulators, industries and communities. The project uses a Geographic Information System (GIS)-based multi-criteria and hierarchy evaluation process to assess the suitability of different resources and quantify their spatial interactions.

At a regional scale, subsurface resource interactions in the northern Perth Basin follow 3 primary stratigraphically controlled categories:

1. **Petroleum, CGS, UGS, and geothermal resources within the Permian intervals below the Kockatea Shale:** this interval has the highest potential for resource interaction, with prospective CGS and petroleum areas strongly overlapping due to their reliance on shared reservoirs and seals. While geothermal and UGS show potential, their viability remains uncertain due to a limited number of current geothermal and UGS projects.
2. **Groundwater, petroleum, and CGS within the Triassic-Lower Jurassic Cattamarra Coal Measures/Eneabba/Lesueur interval:** the potential for resource interaction in this interval is moderate to low. This is because the interval is poorly suited for CGS and petroleum as primary interacting resources. Usable groundwater is present, but it is located either in sub-crop areas along the coast, where no other resources are present, or at uneconomic depths. Also, groundwater remains stratigraphically isolated from deeper resources, minimising direct competition.
3. **Groundwater resources within the Upper Jurassic-Cenozoic interval:** these aquifers are the region’s primary groundwater source, supporting municipal, agricultural, mining, and industrial uses. They are largely separated from deeper resource units, although localised migration pathways may exist and warrant further investigation.

The study found that direct interaction between deep subsurface resources and groundwater is limited, as thick regional seals typically prevent hydraulic connectivity. However, localised migration pathways could exist in areas of high fault displacement or legacy well networks, potentially allowing for fluid movement between deep and shallow subsurface systems.

Key findings and implications:

- **Resource competition and synergy:** zones with the highest resource interaction occur in a northern hotspot inland of Geraldton, particularly in the Beharra Springs, Dongara, and Donkey Creek terraces. This area requires integrated subsurface planning to balance petroleum extraction, carbon geological storage, and potential geothermal or gas storage projects.

- **Groundwater use considerations:** while direct conflicts between groundwater and deeper resources are minimal, industrial groundwater should be accounted for to ensure sustainable water allocation, particularly as new developments increase demand. Groundwater resources are particularly strained in the southern part of the study area, near Perth, where a seawater desalination plant is planned at Alkimos to accommodate increasing demand. Some excess resources remain in the Jurien and Arrowsmith management areas further north, where groundwater allocation plans are currently being updated.
- **Structural influence on interactions:** faults and legacy petroleum wells present potential fluid migration risks in some areas, emphasising the need for ongoing monitoring and risk assessments for resource extraction and groundwater protection.
- **Regulatory and planning needs:** future subsurface development strategies may require regulatory coordination and staged resource use, ensuring that industries can coexist while minimising environmental and water resource impacts.

This study provides foundations for future resource management decisions at the basin scale, offering a spatial framework for assessing subsurface resource interactions in the northern Perth Basin. Further technical assessments will be necessary at the local scale to refine long-term resource planning strategies, focusing on the role of faults in lateral and vertical hydraulic communication, groundwater allocations, demand for CGS and geothermal energy viability. Sustainable resource management that integrates economic, environmental and societal considerations will be essential in ensuring energy projects, groundwater use and industrial development in the region can co-exist. The government, in consultation with industry and community stakeholders, may need to prioritise resources and ensure that adequate compensation provisions are in place in case of potential detrimental impacts.

1. Introduction

The northern Perth Basin, located in Western Australia's Mid West region, is seeing a significant increase in energy-related industrial activities. This includes subsurface resource development (natural gas, geothermal energy, geological storage of carbon dioxide, natural hydrogen, underground hydrogen storage, sediment-hosted mineral deposits) and above-ground renewable energy developments (wind and solar farms) (Figure 1). Various land-use and subsurface demands are becoming increasingly challenging for regulators and residents in the community. Many potential industrial activities could complement one another (for example, the use of renewable energy to power transport of gas, mining and communities). However, other activities could conflict, such as the use of subsurface structures for storage of natural gas, hydrogen or carbon dioxide, or pressure effects beyond the storage complex. Industrial activities may also have varying surface footprints, energy needs and water use. This project aims to evaluate the activities and map out interdependencies and risks that could occur if they compete. Staging and timing of activities, sharing costs and identifying opportunities for improvement within the community (such as more renewable energy or cleaner water) may be beneficial. Conducting an evaluation of resource interactions in the region can help understand the challenges and risks mitigated, resulting in better outcomes for the resources industry and for people who live and work in the region.

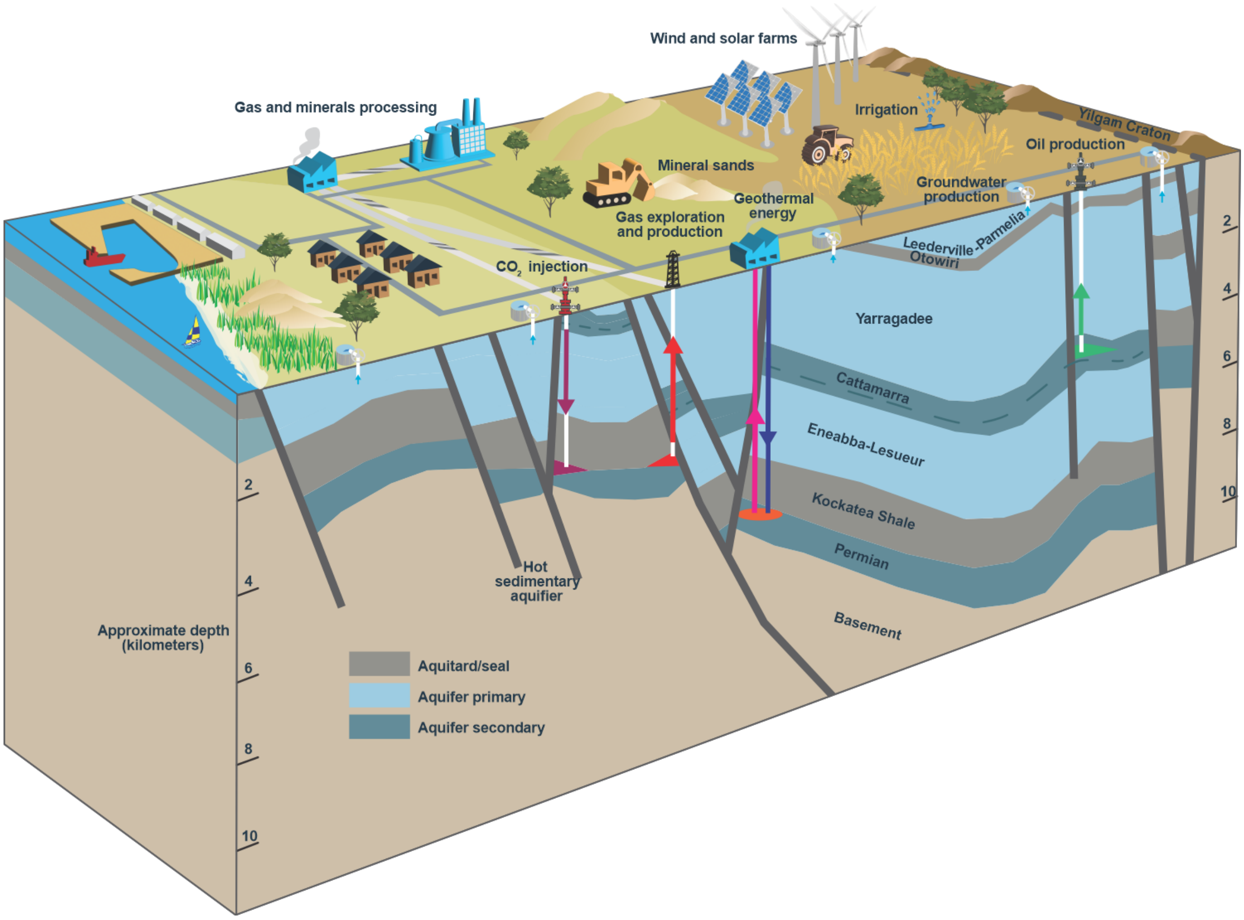


Figure 1. Diagrammatic representation of subsurface resources development in the northern Perth Basin.

1.1. Project description

The area of interest is the northern region of the Perth Basin, which hosts multiple subsurface resource developments (Figure 2). The study area stretches along the Western Australian coast from Gingin to Geraldton and is surrounded by the Darling Hills to the east. Major towns in the area include Dongara, Leeman, Eneabba and Cervantes. The primary objective of this project was to provide a framework for data-driven decision-making and for managing the economic, environmental and social aspects of developing subsurface resources in the northern Perth Basin.

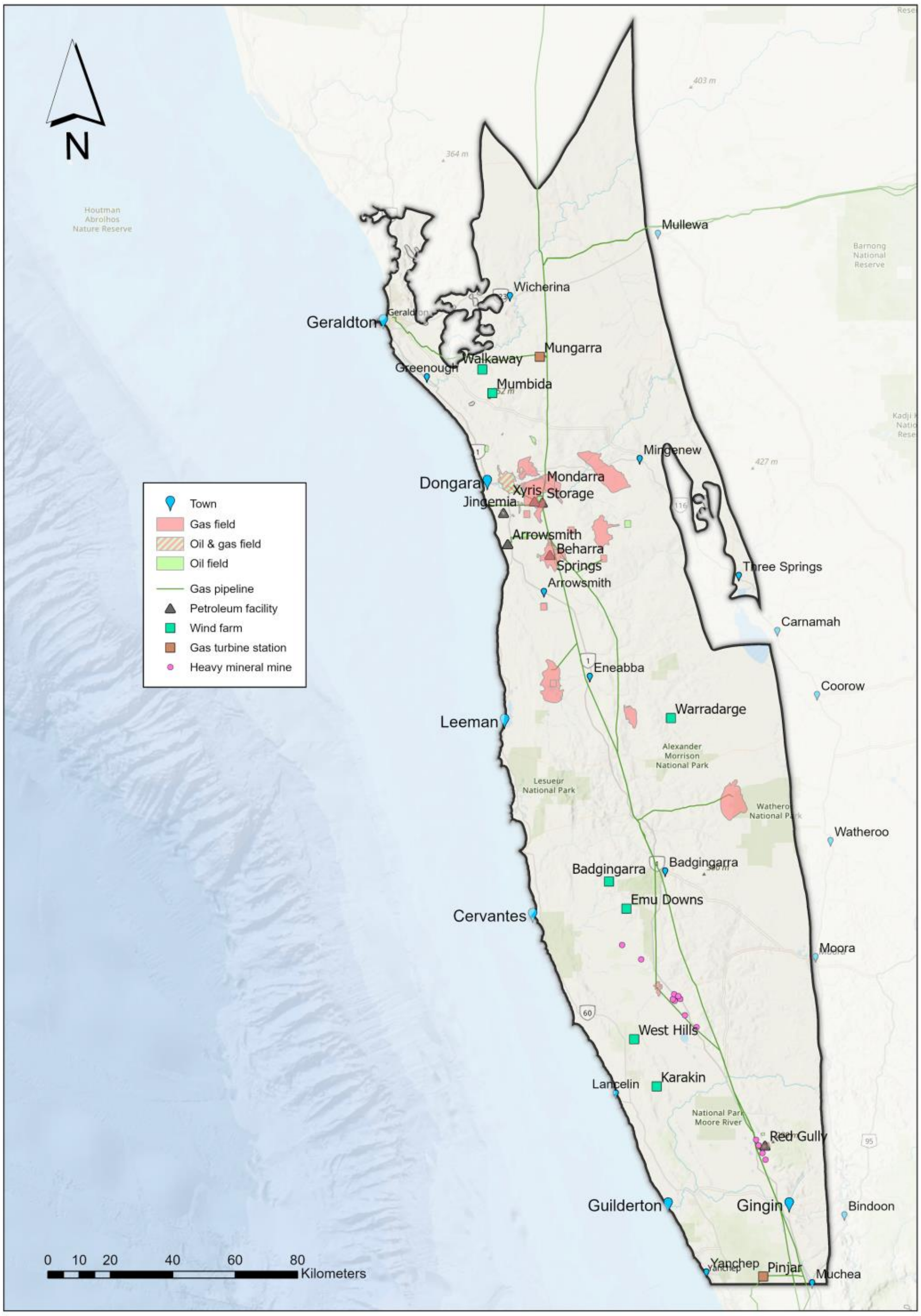


Figure 2. Map of the northern Perth Basin showing locations of petroleum fields and facilities, and electricity generation.

This project evaluated potential resource interactions at the basin scale by modelling the distribution of each subsurface resource, then identifying their overlap or interaction, either in specific geological intervals or cumulatively over the basin.

By identifying key natural resources, stakeholders, potential interactions and risks, this project aimed to:

- Assess the likelihood of different industry activities to coincide to understand possible interactions and mitigate basin resource conflicts.
- Equip community groups and regulators with the necessary tools and information to prioritise and stage future projects involving onshore gas and related activities, with a focus on the potential impacts on groundwater resources.
- Offer a systematic approach to assess and manage the risks associated with subsurface resource development, including potential contamination of groundwater resources.
- Provide an assessment to support the development of subsurface and above-ground resources in a mutually beneficial and sustainable way, emphasising the preservation of quality and availability of the region's groundwater resources.

The workflow for evaluating resource interactions in the northern Perth Basin builds on methodology developed by Michael *et al.* (2013) for basin resource management strategies associated with the development of large-scale carbon dioxide (CO_2) geological storage within pre-existing and future activities in a region.

Surface elements, including industrial facilities (Figure 2), aboriginal heritage sites, legislated lands, and agricultural areas (Figure 3), will likely influence the feasibility and planning of future subsurface resource developments in the northern Perth Basin. While these elements play a critical role in determining land access, regulatory constraints, and environmental considerations, the current study focuses solely on subsurface resource interactions. It does not incorporate surface land-use factors into the assessment. However, understanding the spatial distribution of these surface constraints is essential for future integrated resource management, helping to align economic development with cultural, environmental and land-use priorities.

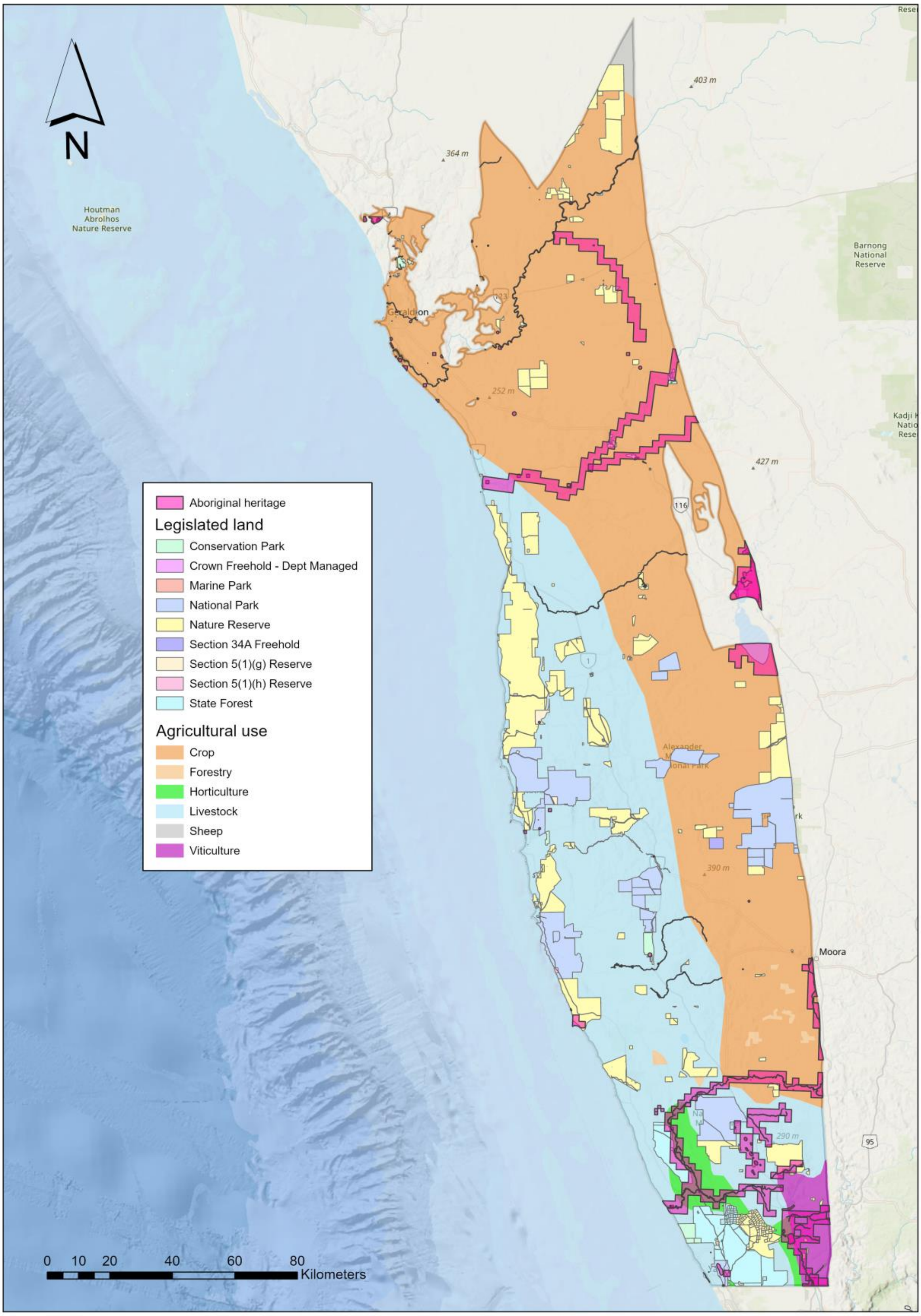


Figure 3. Distribution of Aboriginal heritage sites, legislated lands, and agricultural areas.

1.2. Northern Perth Basin framework

Geologically, the zone of interest for this resource interaction assessment encompasses the area from the Beermullah Trough in the south to the Irwin Terrace in the north (Figure 4). The Coolcalalaya Sub-basin is excluded from this assessment.

1.2.1. Geology

The northern part of the Perth Basin is characterised by an intracratonic rift basin that developed through multiple phases of rifting and sedimentation. The description below is based on work by Geoscience Australia (2020 and 2023), Thomas (2014), and Mory and Iasky (1996).

During the late Carboniferous to early Permian intervals (Figure 5), initial rifting led to the deposition of fluvial and glaciogenic sediments. Key formations deposited at this time include the Irwin River Coal Measures and the Carynginia Formation. These units reflect the interplay between glacial, fluvial, and deltaic processes in a cold-temperate climate setting. The end of early Permian rifting is marked by a regional uplift, followed by late Permian to Early Triassic early post-rift subsidence, and the deposition of alluvial fans, fan-deltas, deltaic and coastal sediments forming the Wagina and Dongara sandstones (Mory and Iasky, 1996).

During the Triassic interval (Figure 5), continued rifting and subsidence resulted in deposition of the Kockatea Shale and the Lesueur Sandstone. The Kockatea Shale is particularly significant as a major hydrocarbon source rock, while the Lesueur Sandstone serves as a regional aquifer without significant hydrocarbon accumulation. The depositional environment during this period varied from fluvial and deltaic to shallow marine settings, influenced by the region's tectonic evolution.

The Mesozoic era (Figure 5), particularly from the late Triassic to early Jurassic interval, was marked by rifting associated with the break-up of Gondwana. This tectonic activity led to the formation of major structural features and influenced the deposition of formations such as the Cattamarra Coal Measures and the Eneabba Formation. These formations represent a range of environments, from coal-forming swamps to shallow marine conditions. The final rifting phase in the onshore Perth Basin occurred in the Late Jurassic to Early Cretaceous interval, preceding continental break-up between Australia and Greater India (Norvick, 2004). It coincides with the deposition of the Yarragadee Formation and the onset of major extensional faulting.

The northern Perth Basin's structural framework (Figure 4 and Figure **6**) is defined by several prominent features, including the Dandaragan Trough, Beagle Ridge, and Eneabba Terrace. Major faults such as the Darling Fault and the Urella Fault have significantly influenced the Basin's development, creating accommodation space for sediment deposition and forming structural traps for hydrocarbons.

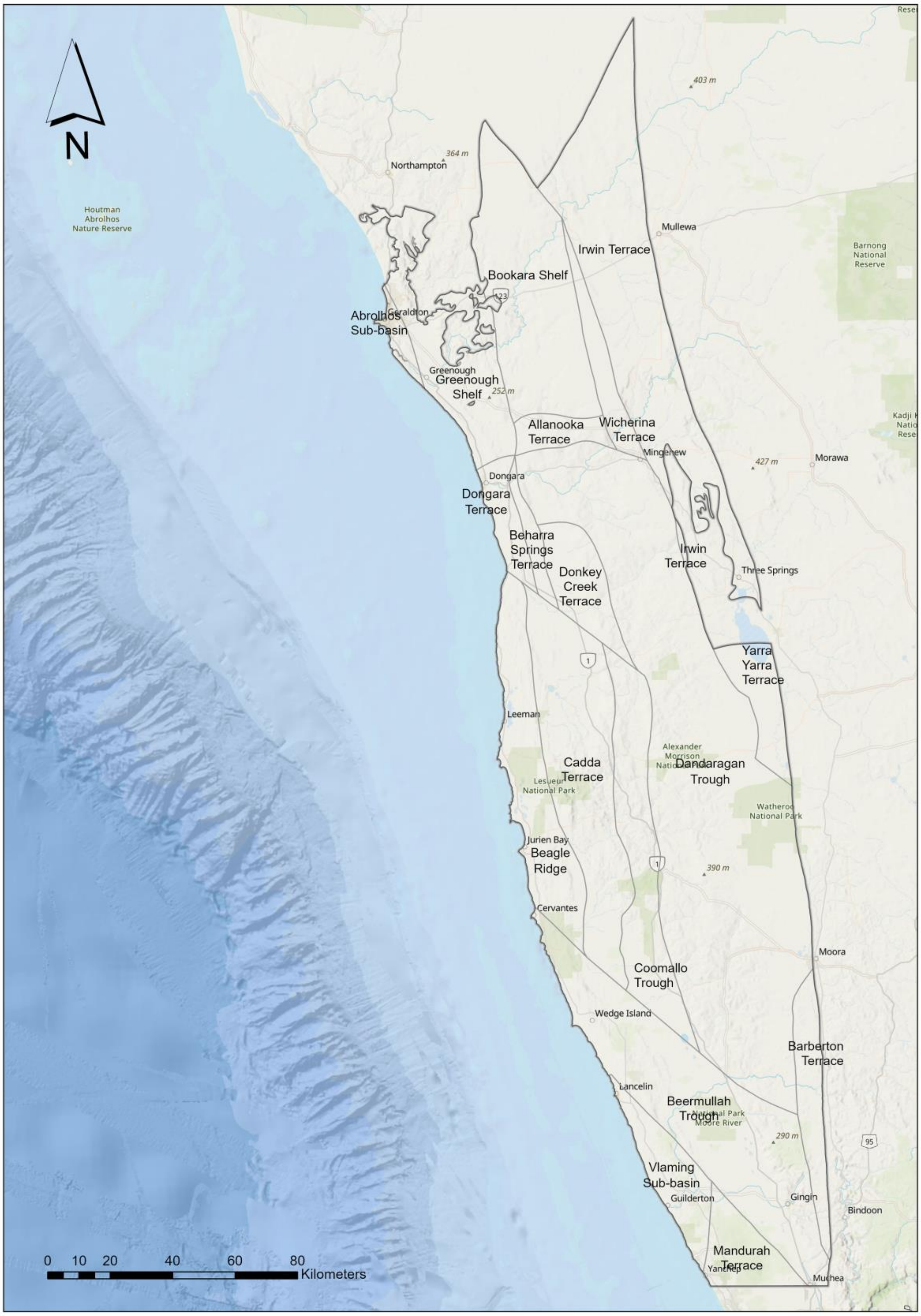


Figure 4. Project area of interest in the northern Perth Basin with tectonic units.

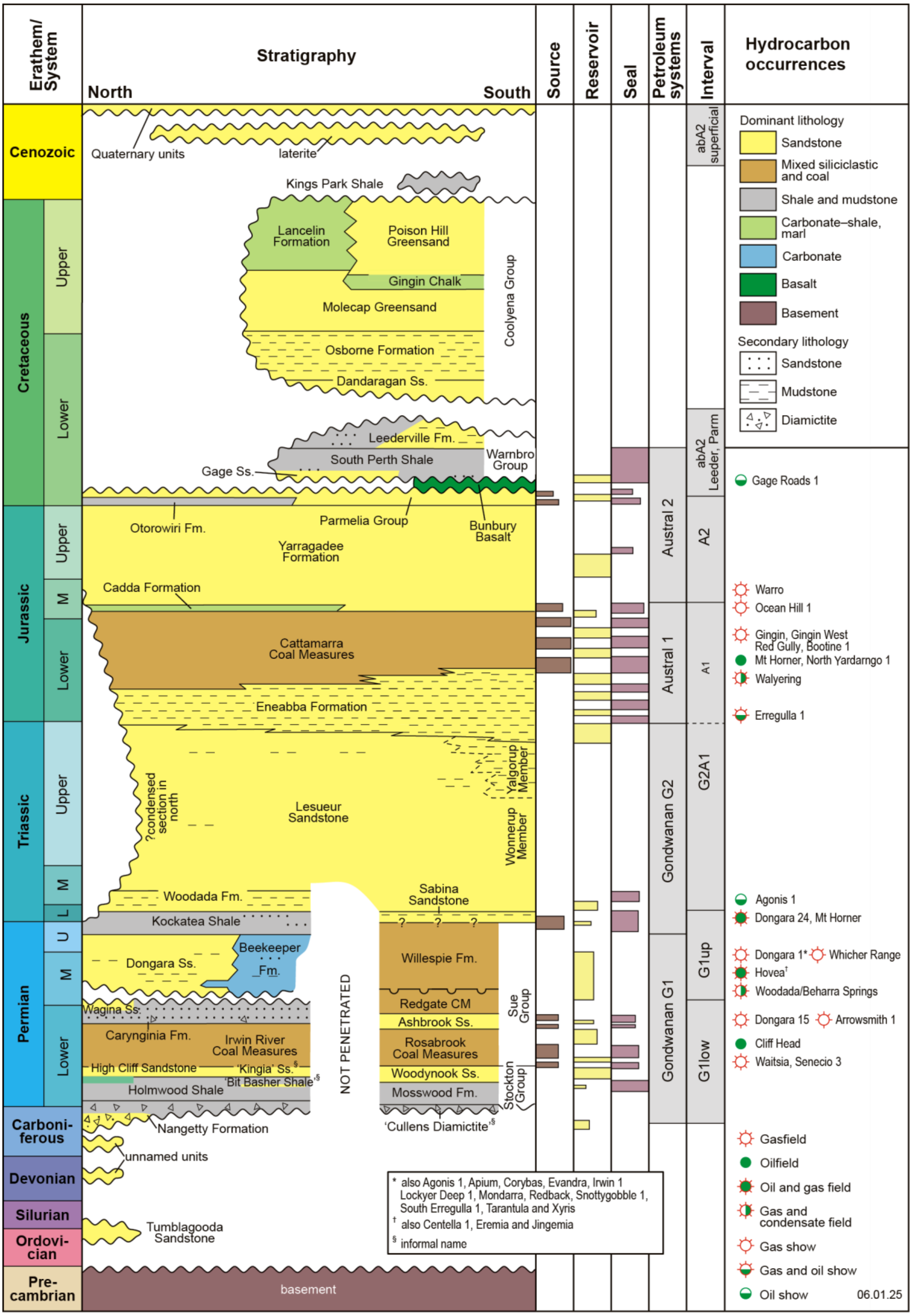


Figure 5. Stratigraphy and petroleum systems of the Perth Basin (modified from A. Mory personal communication, 2025). The interval column shows the main stratigraphic intervals used for the evaluation of resource interactions.

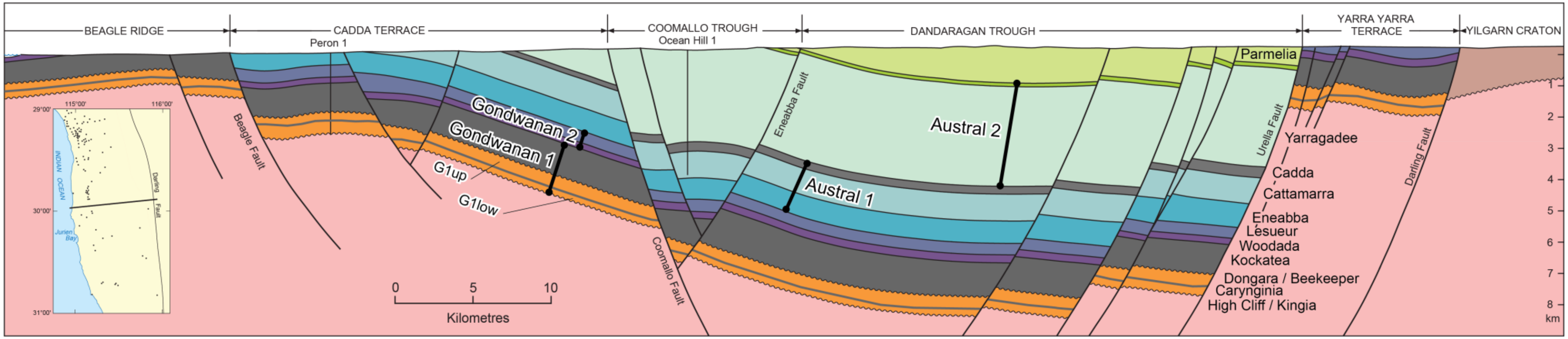


Figure 6**. Cross-section of the northern Perth Basin showing the distribution of the sedimentary sequences above the Precambrian basement. The intervals used for the suitability and interaction maps are labelled. Modified from Mory and Iasky (1996).**

Structural framework

The project area in the onshore northern Perth Basin is divided into 18 tectonic units (Figure 4). Table 1 present a short description of the main structural elements in the project area, from north to south. A full description can be found in Thomas (2014).

Table 1. Description of tectonic units.

Tectonic Unit	Structure	Main Fault Boundaries	Stratigraphy / Age
Abrolhos Sub-basin	Mostly offshore sub-basin	Poorly mapped onshore	Permian to younger
Greenough Shelf	Shallow basement shelf; progressive onlap northward	Allanooka Fault (S), Mountain Bridge Fault (E)	Permian to younger
Bookara Shelf	Structured shelf; bounded by E–W and NW-trending faults	Bookara Fault (S), Wicherina Fault (E), Mountain Bridge Fault (W)	Permian and possibly older
Irwin Terrace	Narrow, NNW half-graben	Urella Fault (W), Darling Fault (E)	Ordovician–Devonian to Middle Permian
Wicherina Terrace	Narrow half-graben bounded by westerly dipping faults	Wicherina Fault (W), Urella Fault (E), Allanooka Fault (S)	Permian and possibly older
Allanooka Terrace	Bounded block with eastward thickening Permian strata	Allanooka Fault (S), Bookara Fault (N), Wicherina Fault (E), Mountain Bridge Fault (W)	Permian
Dongara Terrace	Faulted block	Mountain Bridge Fault (E), Geraldton Fault (W)	Jurassic and older
Beharra Springs Terrace	Broad dome; 'intermediate' terrace	Between Dongara and Donkey Creek Terraces, Mountain Bridge Fault (E)	Permian
Donkey Creek Terrace	Asymmetric graben	Eneabba Fault (E & N), Abrolhos Transfer Fault (S)	Early Permian
Dandaragan Trough	Deepest onshore N–S trending half-graben	Urella Fault (E), Darling Fault (E), Muchea Fault (E), Eneabba Faults (W)	Permian to Cenozoic
Yarra Yarra Terrace	N-S trending half-graben	Urella Fault (W), Darling Fault (E)	Mesozoic
Beagle Ridge	NNW–SSE trending horst	Beagle Faults (E), Geraldton Fault (W), Abrolhos Transfer Fault (N), Cervantes Transfer Fault (S)	Likely Carboniferous–Permian
Cadda Terrace	Fault-bounded N-S terrace with uplift/erosion after Early Triassic	Beagle Faults (W), Eneabba Faults (E)	Triassic and older
Coomallo Trough	Fault bounded N-S Graben	Coomallo Fault (W), Eneabba Fault (E)	Likely Permian to Cenozoic
Barberton Terrace	Elongate N-S half-graben	Darling Fault (E), Muchea Fault (W)	Triassic -Jurassic
Beermullah Trough	Structurally low NW-trending depocentre	Darling Fault (E), Muchea Fault (E), Cervantes Transfer Fault (N), Turtle Dove Ridge (W)	Mesozoic (implied)
Vlaming Sub-basin	Mostly offshore sub-basin	Turtle Dove Ridge (E)	Likely Permian to Cenozoic
Mandurah Terrace	Structurally intermediate block	Darling Fault (E), Turtle Dove Ridge (E)	Likely Permian to Cenozoic

Potential leakage mechanisms and pathways

One major risk in the exploration of the offshore northern Perth Basin is the loss of petroleum accumulations due to trap breach over time. This is associated with the region's main Permian-

Triassic oil/gas play, where evidence of past leakage (such as palaeo-oil columns) has been identified (Nicholson *et al.,* 2012; Kempton *et al.,* 2011). These features indicate that some traps may have been breached in the past, leading to the dissipation of hydrocarbons long before present-day exploration. Importantly, this refers to ancient geological processes and does not imply an ongoing or current leakage risk.

Palaeo-oil columns were found in Permian reservoir sandstones below the Triassic Kockatea Shale regional seal in 14 of the 18 wells analysed from the Abrolhos Sub-basin. Further evidence from the Houtman Sub-basin, where a palaeo-oil column in Houtman-1 was discovered, indicates an effective oil-charge system in Jurassic strata. The breach of these palaeo-accumulations in the offshore northern Perth Basin is primarily attributed to fault reactivation and structuring associated with several geological events:

- **Jurassic-Early Cretaceous extension and continental breakup in the Valanginian**: Fault movements during this period caused significant structural reconfigurations, which could have compromised the integrity of petroleum traps.
- **Tilting and thermal subsidence of the margin post-breakup**: Following the Valanginian breakup, tilting of the margin may have further disrupted the traps, causing leakage.
- **Inversion of faults during the Miocene**: The collision of the Australian and Eurasian plates during the Miocene resulted in fault inversion, which could have breached existing traps, allowing hydrocarbons to escape.

While these examples are from offshore, the petroleum systems in the onshore northern Perth Basin share many similarities in stratigraphy, source and reservoir intervals. However, the degree and timing of fault reactivation and structural deformation are more site-specific and may vary between offshore and onshore settings.

It is important to understand the sealing behaviour of faults for the containment of stored gas in the northern Perth Basin, as it is controlled by the stress state on fault planes, which influences strain and reactivation under varying formation pressures. Additionally, the geological history of the fault (including burial and cementation processes), and the characteristics of the fault rock (created by deformation and incorporation of materials during displacement), fundamentally control cross-fault and upfault flow.

Faults can act as membrane seals by impeding cross-fault flow between juxtaposed permeable units due to the petrophysical properties of the fault rock. Conversely, they can also provide fault-parallel conduits for flow between vertically separate flow units (Manzocchi *et al.,* 2010). The type of fault-zone rock depends on the composition of the faulted sequence, the burial and temperature conditions during and after faulting (Yielding *et al.*, 2010).

These geological processes and fault characteristics significantly impact the preservation and containment of fluids in the subsurface, making fault sealing behaviour a critical factor in the exploration and development of resources in the northern Perth Basin.

1.2.2. Basin hydrogeology

Hydrogeology describes the origin, flow and quality of subsurface groundwater and how it interacts with the geological layers. In the northern Perth Basin, there are 3 major flow systems:

1. **Local flow systems** driven by meteoric (rainfall) recharge in areas of local topographic highs and discharge in smaller rivers and lakes. These are typically active at depths of < 200 m and involve fresh groundwater in the sub- or outcrop areas of Parmelia-Leederville, Yarragadee, and Eneabba-Lesueur aquifers (Figure 7). More details are provided in Section 3.5 Groundwater resources.
2. An **intermediate flow system** down to ~ 2000 m depth, with meteoric recharge in the eastward and westward regional flow of relatively fresh formation water towards the coast.
3. A **deep, stagnant to sluggish flow system** of > 2000 m depth, with slow westward flow of brackish to saline formation water.

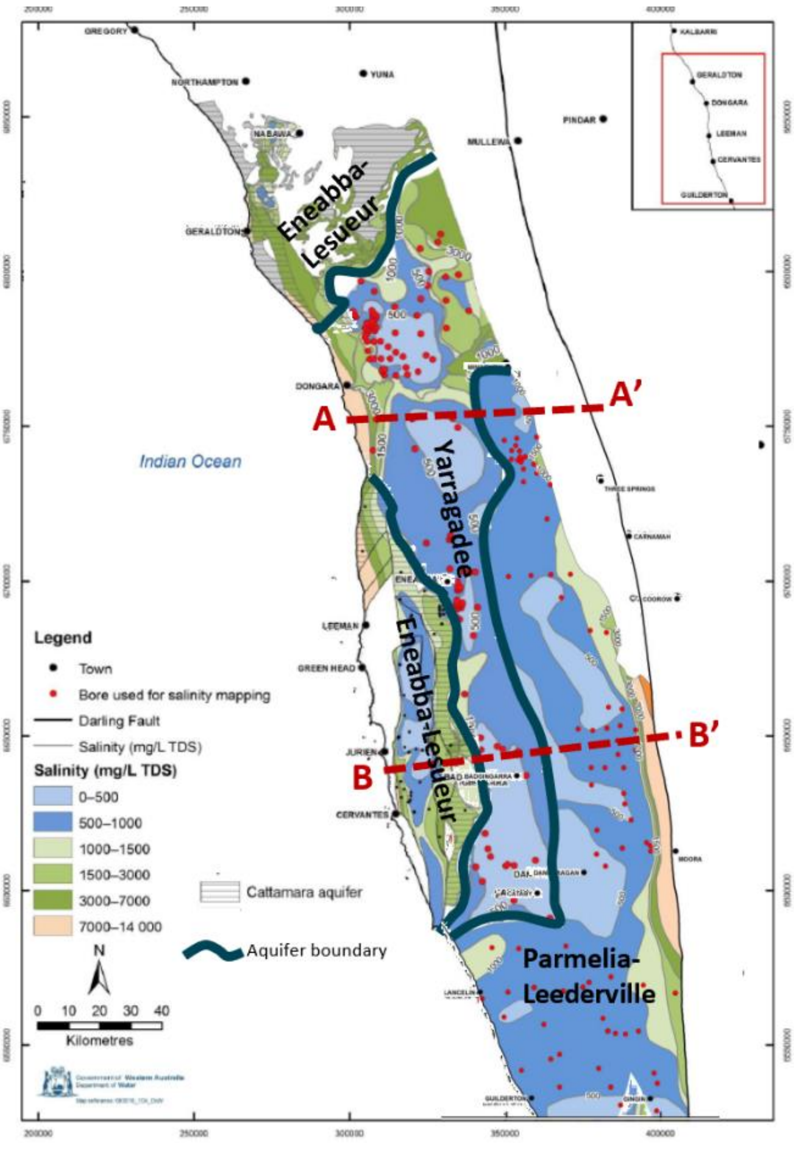


Figure 7. Salinity distribution in near-surface aquifers in the northern Perth Basin (modified from Department of Water, 2017). The red lines depict the approximate location of the cross-sections AA' and BB' shown in Figure 8 and Figure 9, respectively.

The geological structure and distribution of aquifers and aquitards in the northern Perth Basin lead to local differences in the shape and depth of the 3 flow systems as depicted in the cross-sections in Figure 8 and Figure 9. In the northern part of the study area, fresh, usable groundwater with salinity < 1000 mg/l is restricted to the upper 200 m in the Dandaragan Trough, and the intermediate flow system is largely active above the Cattamarra Coal Measures (Figure 8). In the area of the Northampton Uplift, higher salinities (> 7000 mg/l) are observed at shallow depths along the coast, likely due to incursion and mixing with seawater.

The highest salinities (> 30,000 mg/l) in the northern Perth Basin are observed offshore, in the coastal region directly affected by seawater (~35,000 mg/l), and in the deeper parts of the basin, largely in the Permian aquifers below the Kockatea Shale. In these deep parts of the basin, water that was trapped in the rocks during sedimentation, known as connate water, has not been significantly affected by mixing with fresh meteoric water. Maximum salinities measured in deep petroleum wells (> 2000 m depth) are in the order of 40,000 mg/l.

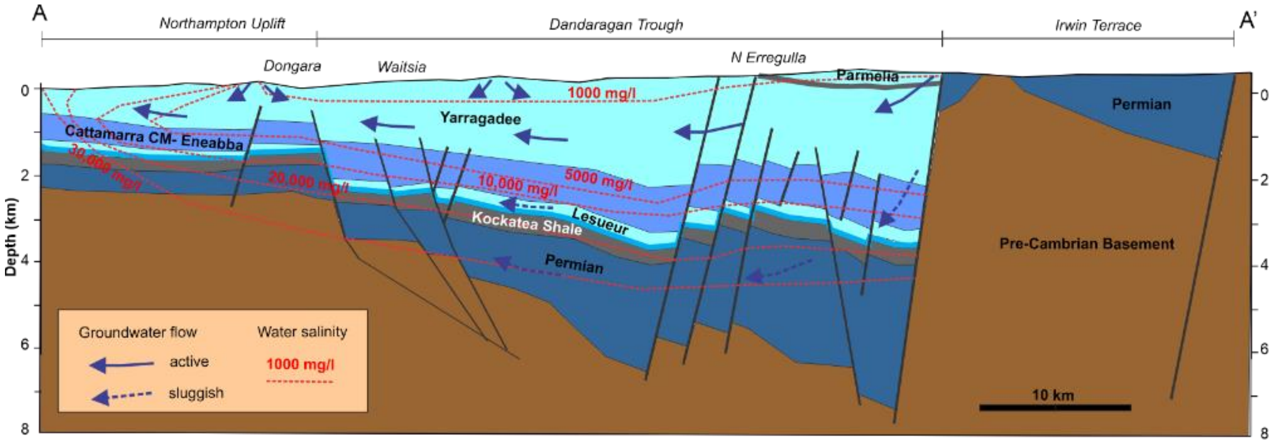


Figure 8. Conceptual hydrogeological W-E cross-section showing salinity distribution and flow directions of formation water in the northern part of the northern Perth Basin. The cross-section location is shown as line AA' in Figure 7. The salinity distribution and flow in the upper ~ 1000 m are based on maps and data from the Department of Water (2017). Deeper interpretations are highly uncertain and are based on less abundant pressure and salinity observations in petroleum wells.

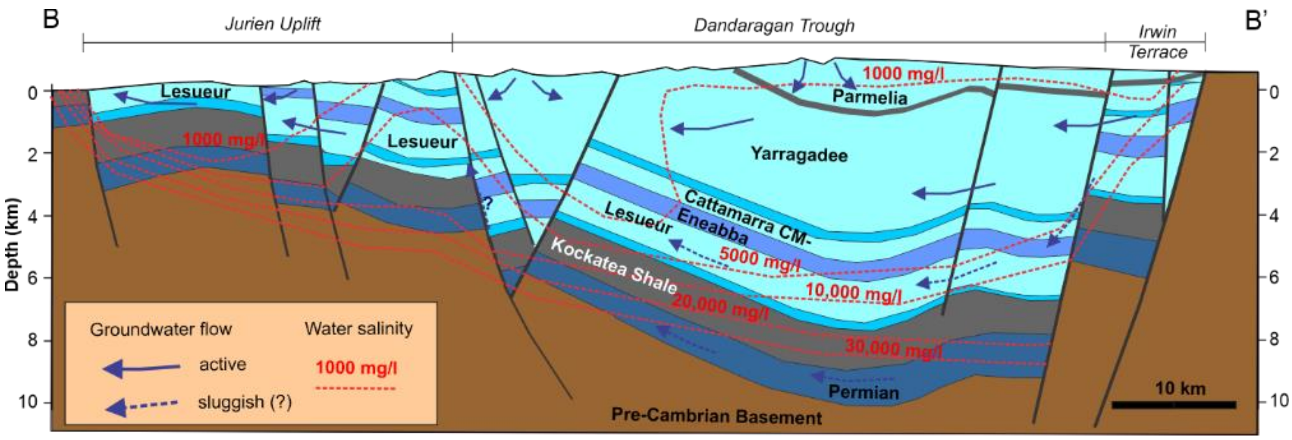


Figure 9. Conceptual hydrogeological W-E cross-section showing salinity distribution and flow directions of formation water in the central part of the northern Perth Basin. The cross-section location is shown as line BB' in Figure 7. The salinity distribution and flow in the upper ~ 1000 m are based on maps and data from the Department of Water (2017). Deeper interpretations are highly uncertain and are based on less abundant pressure and salinity observations in petroleum wells.

1.3. Interaction of subsurface resources development

The subsurface contains various resources valuable to our economy, in the form of mineral deposits or coal, or as fluids within the pore space (for example, groundwater, oil and gas). Energy can be produced in the form naturally heated groundwater water, and the pore space itself can be a commodity for natural gas, carbon dioxide or hydrogen storage. These resources are typically found at different depth ranges (Figure 10), however, they can overlap both geographically and vertically in the same geological formation in some instances.

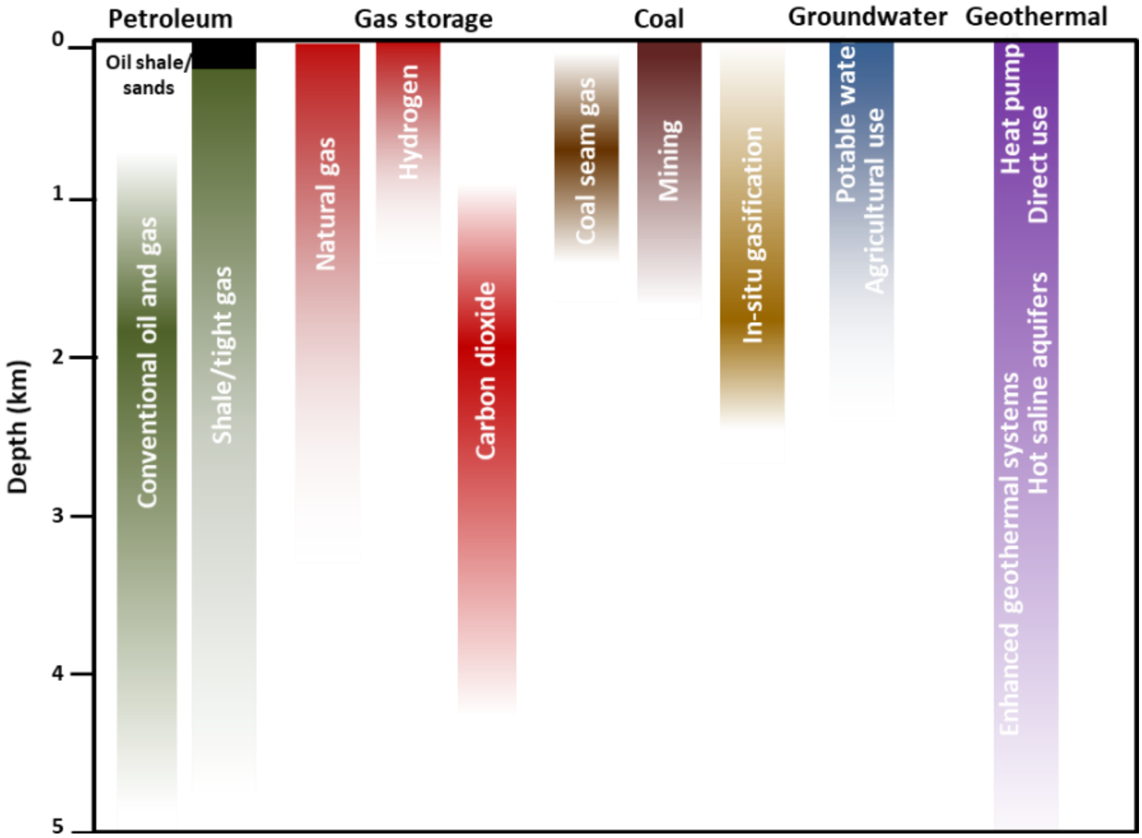


Figure 10. Typical depth ranges for various subsurface resource activities (modified from Michael *et al.,* 2016).

Interaction between subsurface resources can be in the form of (Michael *et al.*, 2016 and Field *et al.*, 2017):

1. **Direct contact, with:**
    a. Positive impacts
        i. CO_2 injection in oil or gas fields for enhanced recovery.
        ii. Storage of natural gas, hydrogen or CO_2 in depleted gas fields.
        iii. Geothermal use of co-produced water from hydrocarbon production.
    b. Negative impacts
        i. Contamination of oil or gas reservoirs.
        ii. Contamination or sterilisation of future resources.
        iii. Contamination of potable or usable groundwater.

2. **Pressure communication, with:**
   a. Positive impacts
      i. Fluid injection providing reservoir pressure support.
      ii. Fluid injection counteracting regional pressure decline or subsidence.
   b. Negative impacts
      i. Regional production-induced pressure drawdown, affecting production of neighbouring resources.
      ii. Displacement of brines into neighbouring reservoirs or into groundwater aquifers induced by fluid (i.e. CO_2) injection.
      iii. Reactivation of faults/induced seismicity.

The general potential for interaction between specific resources was investigated by Field *et al.* (2017) and is summarised in Figure 11.

In many instances, petroleum-related activities are compatible and can be deployed concurrently (for example, CO_2 enhanced oil/gas recovery (EOR/EGR) or sequentially (for example, gas storage in depleted fields). The highest potential for conflict or competition between resources is for fluid storage or disposal, since formations suitable for natural gas and hydrogen storage would also be suitable for CO_2 storage and liquid waste disposal.

	Oil and gas	EOR/EGR	Natural gas/ H_2 storage	Deep tight gas	CO_2 storage	Usable groundwater	Geothermal
Oil and gas		C	S	C	S	D	C
EOR/EGR			S	C	C	D	
Natural gas/H_2 storage				I	S	D	
Deep tight gas					I	D	
CO_2 storage						D	C
Usable groundwater							
Geothermal							

Legend:				
	No potential	Generally low potential; unlikely	Likely to be in competition	Likely to be compatible

Figure 11. Typical concurrent and sequential uses of subsurface resources. [D: mainly at different depths; I: injectivity issues; S: sequential use potential, prioritise; C: Potential for concurrent use resources (adapted from Field *et al.*, 2017)].

In general, it is unlikely for subsurface resource development to compete with potable groundwater production because the latter is usually found at much shallower depths (like in the northern Perth Basin) and is hydraulically separated from deeper formations by sealing formations (Figure 12a). Resource development activities are more likely to compete in basins with large, contiguous sloping aquifers (for example, the Great Artesian Basin in Queensland). In the Great

Artesian Basin, usable groundwater is present at depths of more than 2 km, and deeper parts of the same aquifer are suitable for CO_2 geological storage and hydrocarbon production (similar to the configuration in Figure 12b). In this case, the state government prohibits CO_2 geological storage in the basin (*MEROLA Act 2024*) due to potential contamination of future groundwater resources. While usable groundwater aquifers are typically hydraulically separated from deeper zones through the development of other subsurface resources, resource operators need to demonstrate to the public and environmental regulators that their operations do not contaminate groundwater resources through the leakage of hazardous substances.

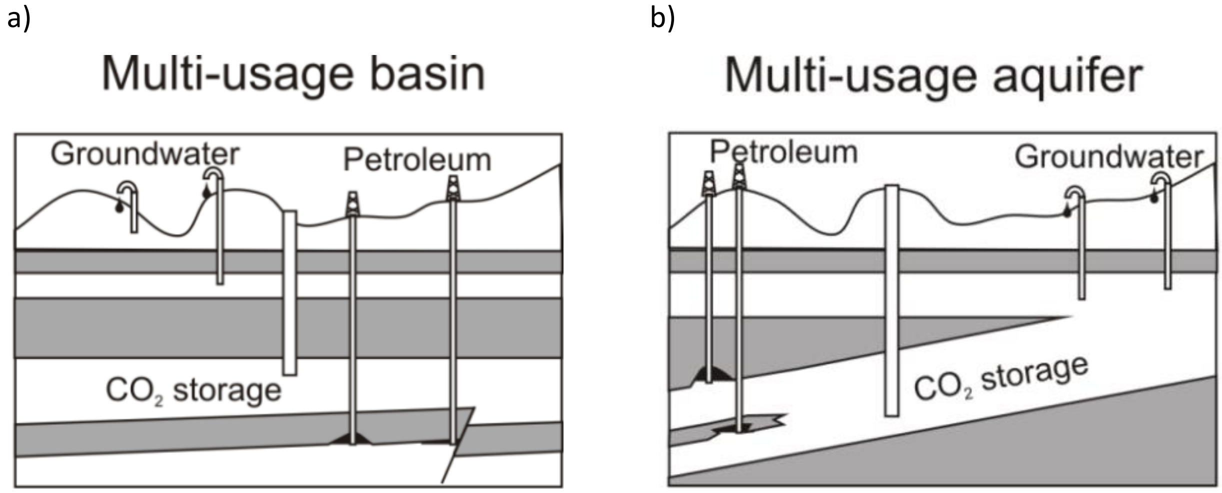


Figure 12. Illustration of a) multi-usage basin and b) multi-usage aquifer resource development scenarios (modified from Michael *et al.,* 2016).

Even if the development of different resources is compatible, complications can still occur when legislations consider commodities like natural gas and geothermal energy separately. This results in an overlap of exploration and production licenses from different owners. Guidelines and regulations need to be in place to manage the concurrent or subsequent development of these resources with minimal detrimental impacts to either party or to the environment.

The physical location and distribution of fluid in the subsurface are usually well constrained by the structural geometry of the reservoir it is contained in (for example, an oil or gas trap) or by numerically simulating the migration of an injected CO_2 plume. These fluids would need to be contained within and regulated under their respective lease areas (for example, petroleum production lease, greenhouse gas injection lease). However, pressure changes induced by fluid production or injection have a larger radius of impact (Figure 13) and could extend beyond the lease area despite decreasing away from the point of production/injection. If these pressure changes have the potential to negatively impact resource development, parties (under guidance from the regulator) would need to agree on how to measure and attribute the impacts, and how they translate into lost revenue for compensation. In the event of disagreements, the regulator may need to step in as arbitrator.

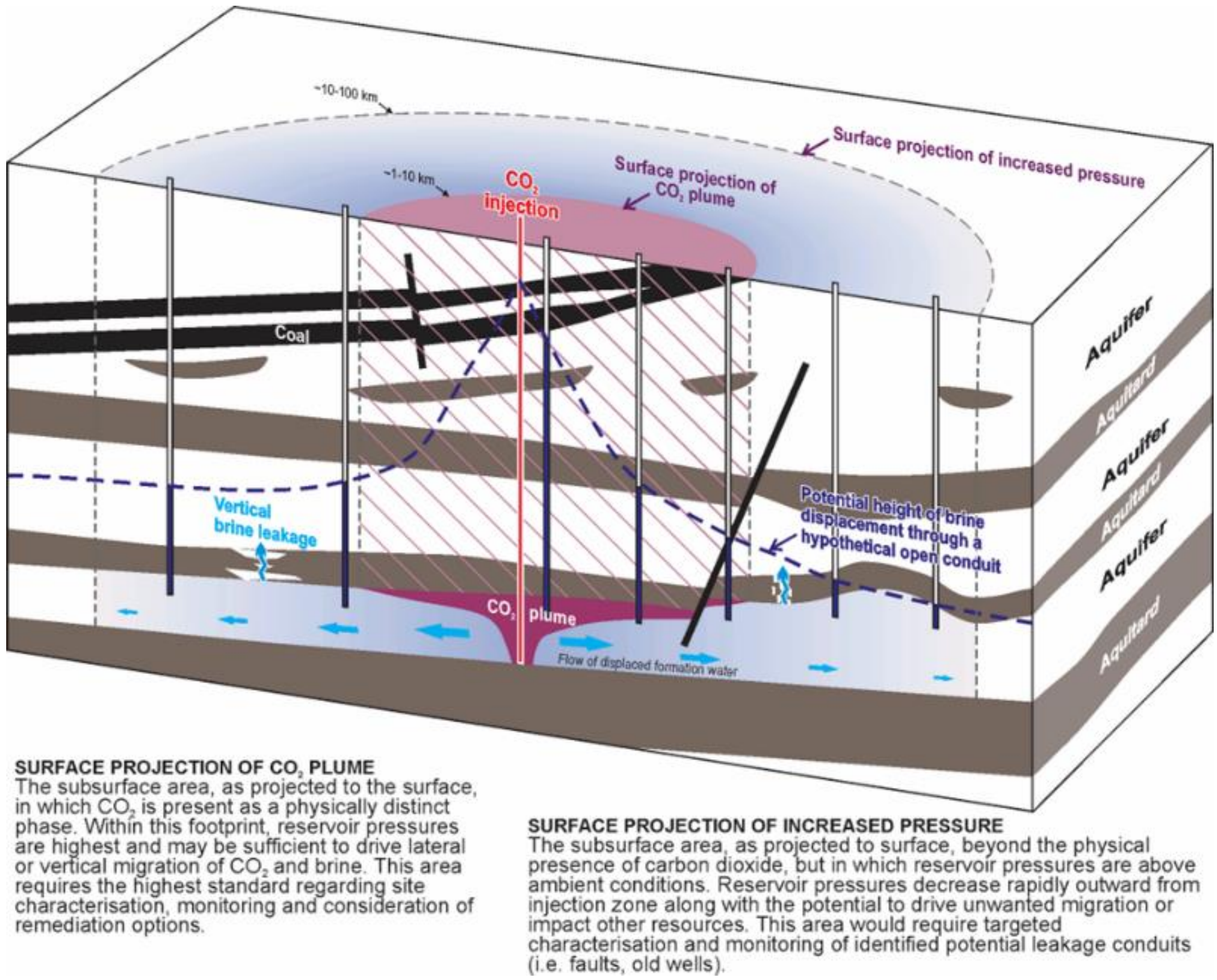


Figure 13. Schematic representation of potential impacts related to CO_2 injection (Michael *et al.,* 2016). The degree of pressure increase is reflected in the relative height of the dashed blue line, representing the potential height of displaced formation water in a hypothetical open conduit.

In a homogenous aquifer, the area of pressure change around an injection well is shaped as a cone with an exponentially increasing radius (Figure 14A). Injection pressure dissipates approximately logarithmically with distance from the well site. When there are 2 injection wells, the individual pressure cones merge, as shown in Figure 14B. In the case of fluid production, the shape of the cone would remain the same, but its direction would be inverted (in other words, pressure changes would be negative).

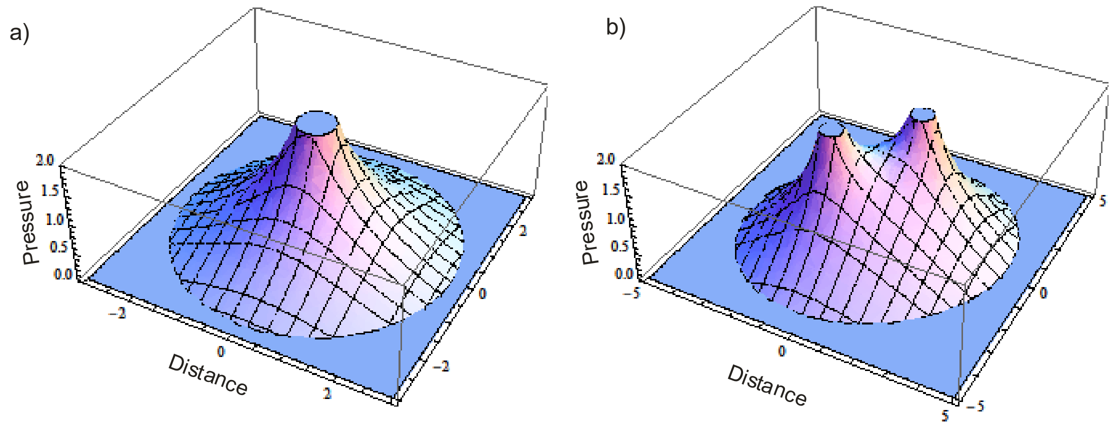


Figure 14. Steady-state pressure distribution in the vicinity of a) a well with a constant injection rate and fixed pressure at an outer radius, and b) 2 wells with equal injection rates. Axes values are dimensionless. IEAGHG (2010).

The detailed pressure distribution is governed by the injection rate, fluid viscosity, aquifer permeability, aquifer thickness, well radius and the effective reservoir radius. The pressure in bounded reservoirs (for example, fault compartments or depleted fields) with no connection to regional aquifers increases more rapidly in response to fluid injection (Figure 15). This is important because maximum allowable pressures are reached earlier in bounded reservoirs compared to unbounded reservoirs for the same injection rate and reservoir properties, hence allowing for a lower total injection volume.

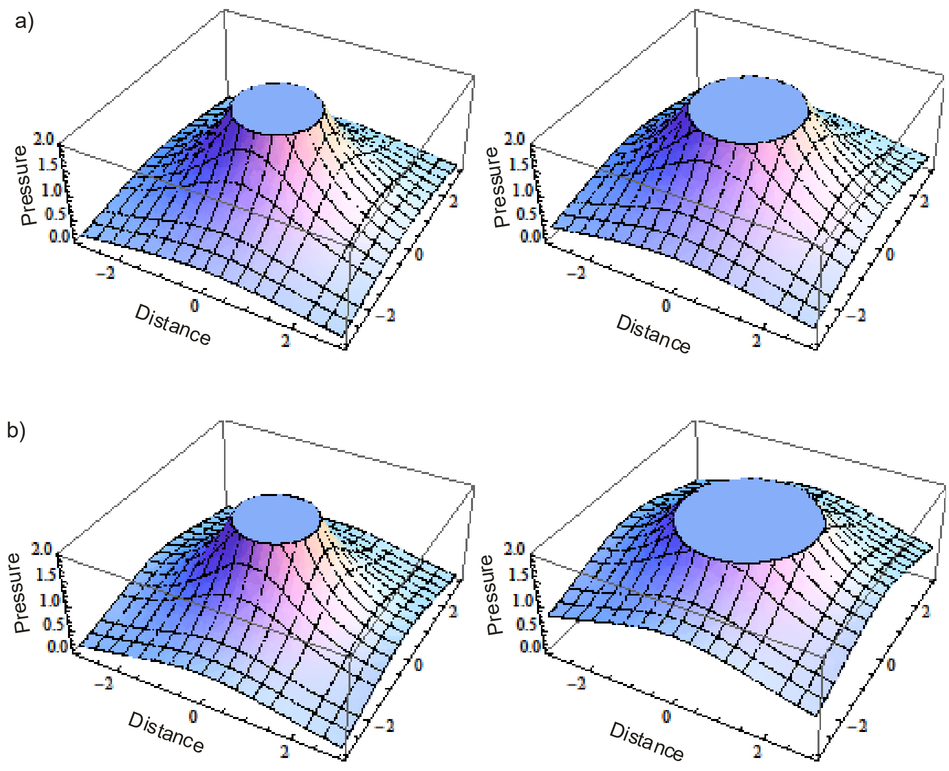


Figure 15. Pressure build-up at an early point in time (left) and later point in time (right) in a) an unbounded infinite reservoir and b) a bounded reservoir. Both a) and b) are represented at the same time steps. Pressure values are truncated at p = 2, rather than the well. IEAGHG (2010).

In sedimentary basins with multiple production and injection wells, pressure impacts are cumulative. The independent operation of CO_2 injection and petroleum production can result in significant over- or under-pressuring in a basin (Figure 16), potentially causing land uplift/subsidence, or contaminating groundwater. However, with the right development concepts, unwanted pressure changes (and associated impacts) could be significantly reduced when CO_2 injection and petroleum production are operated in conjunction (Michael *et al.,* 2013). Generally, the CO_2 storage resource for a pressure-depleted aquifer is likely to be higher than that for a normally-pressured aquifer. The difference should be related to the volumes of previous petroleum and associated water production.

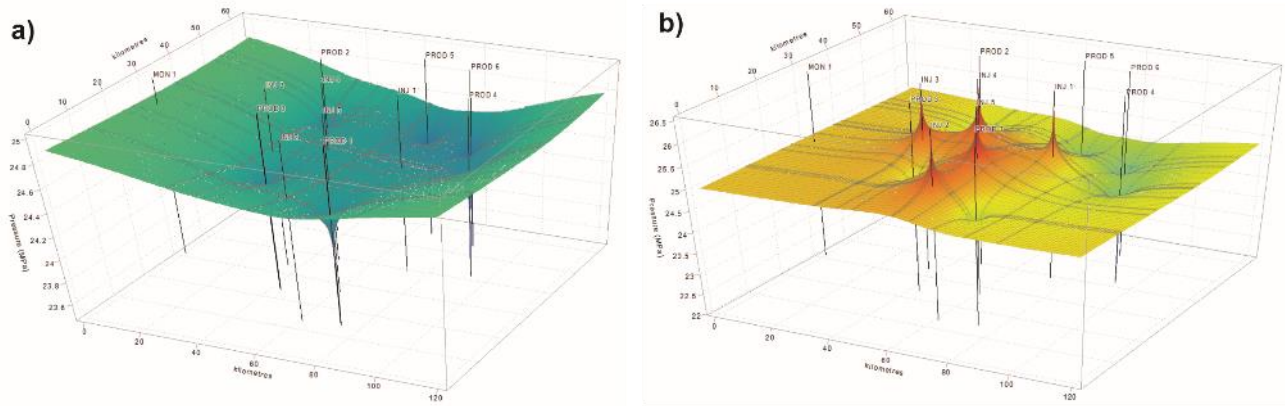


Figure 16. Results of cumulative pressure response to fluid production and injection, from basin-scale analytical simulation. The figure shows simplified models of the Gippsland Basin in Victoria, illustrating the pressure distribution in the target aquifer after fluid production for: a) 1.2 million m^3 of petroleum production, and b) concurrent petroleum production (1.2 million m^3) and CO_2 injection (2,000 Mt). Homogeneous reservoir with pre-production pressure of approximately 25 MPa. Hortle *et al.* (2014).

Basin resource management should follow a tiered approach based on how likely the impacts occur (Birkholzer *et al.,* 2014). It should focus on the degree of pressure change that could result in negative impacts on other resources. For example, the United States Environmental Protection Agency (US EPA, 2008) has proposed limiting the monitored area for a CCS project based on the minimum pressure increase at which a sustained flow of brine rises through a hypothetical conduit into an overlying drinking water aquifer occurs. Other considerations are the pressure required to reactivate faults, induce fractures in the seal, or reduce productivity of other natural resources.

1.3.1. Examples of resource conflict management from other jurisdictions

This section discusses how other jurisdictions have addressed basin resource overlap issues. While the resources in these examples are not necessarily present in the northern Perth Basin, they still provide useful insights into how other regulators respond to conflicts about the parallel development of different resources and pressure impacts.

Gas-over-bitumen (Alberta, Canada)

In Alberta, oil sands and natural gas are considered distinct commodities that can be leased separately and require separate production licenses (www.alberta.ca/gas-over-bitumen). This can be problematic when associated gas overlies a bitumen accumulation that will be exploited through an in-situ oil production process (for example, steam-assisted gravity drainage (SAGD)). SAGD involves drilling 2 wells into the bitumen zone: one well to inject steam to heat the bitumen, and the second well to recover the oil. In late 1996, the regulator, the Alberta Energy and Utilities Board (EUB), received submissions from several oil sands leaseholders with concerns that gas companies producing associated gas before bitumen production would result in potential adverse effects on the eventual recovery of bitumen. Pressure depletion in the gas reservoir could negatively impact sustained steam pressures during the SAGD process, thereby partially sterilising the bitumen resource. A subsequent hearing by the EUB established, largely based on reservoir simulation studies, that gas production could have negative impacts on SAGD in bitumen zones. While this could not be confirmed by actual data, the risk of sterilisation of valuable bitumen resources was deemed too high for all cases, and the regulator ordered the shut-in of production from 146 natural gas wells in the Surmont oil sands area in 2000, with some compensation for the gas producers (McLarty and Lepine, 2004). As a result, the *Oil Sands Conservation Act 1988* was revised in 2000 to prioritise bitumen development over natural gas production. Following the *Alberta Oil Sands Tenure Guidelines,* released in 2020, the state regulator can grant bitumen leases to existing holders of a petroleum license through a 'direct purchase' agreement outside the public offering process. This avoids 'split rights' and facilitates common ownership of subsurface resources in a specific geographic area and geological formation. The process for assessing and managing potential conflicts between natural gas and bitumen resources is depicted in Figure 17.

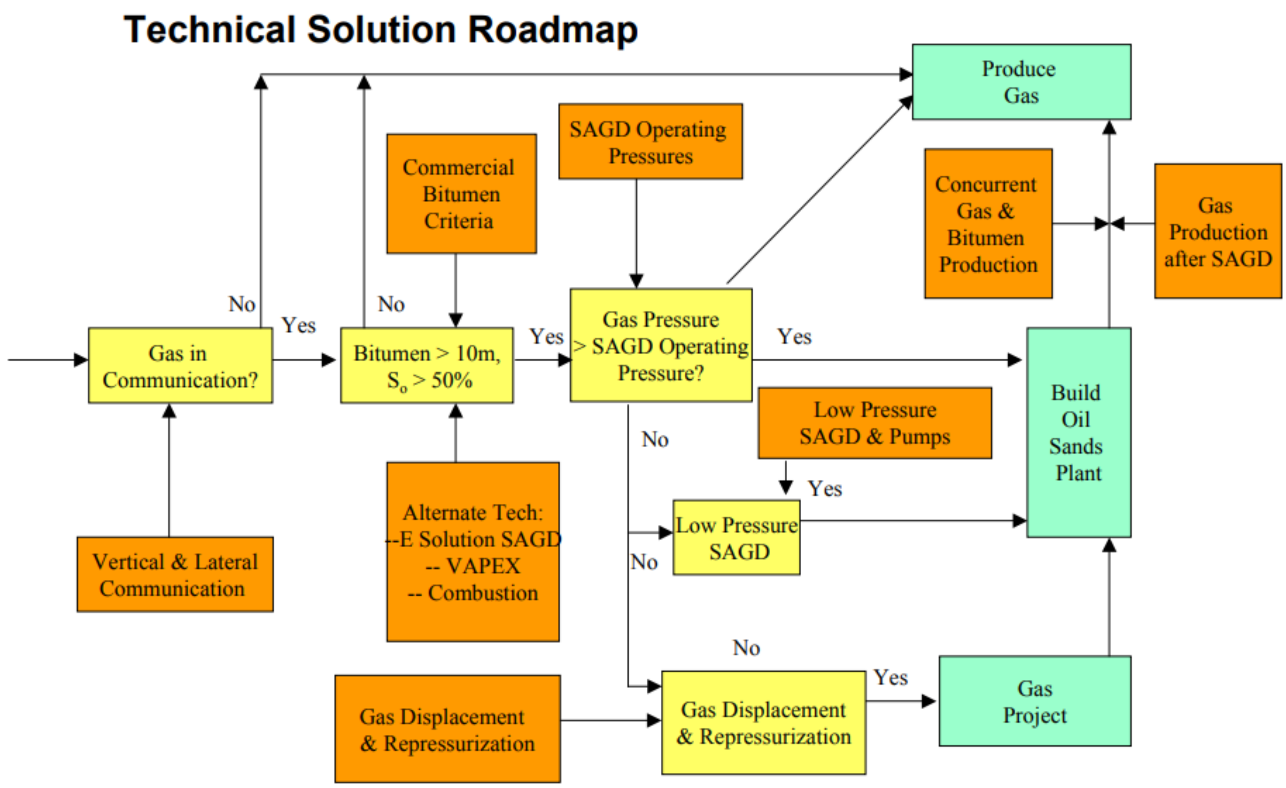


Figure 17. Flow diagram outlining a technical solution to optimise gas and bitumen recovery in Alberta, Canada. www.alberta.ca/system/files/custom_downloaded_images/gas-bit-flow-techroadmap.pdf).

Coal and coal seam gas (Queensland)

The overlap of coal mining areas and coal seam gas (CSG) production in Queensland is regulated by Chapter 4 of the *Mineral and Energy Resources (Common Provisions) Act 2014.* The Act was revised to facilitate the co-existence of Queensland's coal and CSG industries, and to ensure their cooperation to optimise the development and use of both resources (Adkins and Clague, 2014). It reflects, to a large extent, 4 principles proposed by the industry in a white paper:

1. **Direct path to grant:** Providing all other requirements are satisfied, an application for a production license can be granted without requiring ministerial preference decision, even if it overlaps with an existing exploration or production tenure for another resource.
2. **Right of way for coal:** The rights of a CSG tenure holder can be temporarily suspended within pre-determined areas of a coal mining lease, where sole occupancy is required for safe and efficient coal mining operations.
3. **Information exchange:** To optimise the co-development of coal and CSG resources.
4. **Freedom to negotiate bespoke agreements.**

The Act provides a framework for independent arbitration in the case of disputes (for example, acceleration notices given by a coal mining operator, compensation payments, changes to joint development plans, etc.). Two industry experts with coal and CSG expertise must be involved in the arbitration process, and the arbitrator's decision must be consistent with mining safety and health requirements. It must also result in the optimal development of coal and CSG resources.

For groundwater impacts on petroleum activities, the Queensland *Water Act 2000* defines trigger thresholds for production-induced pressure impacts. These thresholds are set as 5 m and 2 m hydraulic-head drawdown for consolidated (i.e. sandstone) and unconsolidated aquifers (i.e. sand), respectively. The responsible petroleum tenure holder must conduct an impact assessment that identifies boreholes of other users within the affected area and enter into an agreement with the owners of those bores.

CO_2 geological storage and groundwater (Great Artesian Basin, Queensland)

In 2020, the Carbon Transport and Storage Company (CTSCo), a subsidiary wholly owned by Glencore, started exploration and appraisal of a greenhouse gas storage permit (EPQ7) in the Surat Basin, under Queensland's *Greenhouse Gas Storage Act 2009*. CTSCo submitted a first draft of their Environmental Impact Statement (EIS) in 2022 to support a test CCS project, which proposed to inject up to 330,000 tonnes of CO_2 from Glencore's Millmerran Power Station into the Precipice Sandstone in the Surat Basin over 3 years, at a depth of approximately 2300 m. While not potable, formation water at that location in the Precipice Sandstone is relatively fresh, with a salinity of approximately 4000 mg/l. Approximately 60 km to the west, oil is produced from updip in the Precipice Sandstone at a depth of ~ 1200 m and 3000 mg/l salinity. Following objections from landholders in the region, who were concerned about future use of Precipice water as stock water, various independent technical experts and organisations reviewed the EIS and a final amended EIS was submitted to the regulator in March 2024. Ultimately, the Minister rejected CTSCo's proposal based on Section 41 of Queensland's *Environmental Protection Regulation 2019*, on the basis that CO_2 is considered a 'waste', and CTSCo's injection target, the Precipice Sandstone, is not a 'confined aquifer' (defined as contained entirely within impermeable strata).

As a result, injected CO_2 was likely to deteriorate the environmental values of the receiving groundwater.

Queensland Environmental Protection Regulation 2019, Section 41: Activity involving direct release of waste to groundwater.

(1) This section applies to the administering authority for making an environmental management decision relating to an activity that involves, or may involve, the release of waste directly to groundwater (the receiving groundwater). Example of direct release of waste to groundwater – an activity involving the release of contaminated water to groundwater through a well, deep-well injection or a bore

(2) The administering authority must refuse to grant the application if the authority considers:

> **(a) for an application other than an application relating to an environmental authority for a petroleum activity – the waste is not being, or may not be, released entirely within a confined aquifer; or**
>
> **(b) the release of the waste is adversely affecting, or may adversely affect, a surface ecological system; or**
>
> **(c) the waste is likely to result in a deterioration in the environmental values of the receiving groundwater.**

(3) In this section, confined aquifer means an aquifer that is contained entirely within impermeable strata.

While initial concerns regarding CO_2 storage in the Great Artesian Basin were largely economic (for example, the contamination or sterilisation of a future water source for cattle farmers and agricultural use), it was the enactment of Queensland's environmental legislation that rejected CTSCo's CO_2 storage project. Consequently, legislative changes through the *Mineral and Energy Resource and Other Legislation Amendment Act 2024* (MEROLA Act 2024) were introduced to permanently ban all greenhouse gas storage and injection activities in Queensland's Great Artesian Basin with the aim "…to protect its unique environmental, social, economic, and cultural values from the potential safety and environmental risks posed by carbon dioxide injection."

Lessons learned

The examples from Alberta and Queensland show different ways of managing the co-development of, and potential conflicts between, various subsurface resources. Each example is based on different drivers that lead to varying forms of prioritisation (Table 2).

Table 2. Summary of resource conflict examples.

Case	Resources	Conflict type	Resolution	Basis	Outcome
Alberta gas over bitumen	Oil from bitumen – natural gas	Pressure communication	Prioritisation of more valuable oil resource	Economics	Natural gas can only be produced after development of bitumen resource
Queensland coal-CSG	Coal – coal seam gas	development of vertically separated resources in overlapping leases;	Co-existence of both resource developments; 'right of way' for coal	Economics/ safety	Both resources can be developed in parallel, but CSG production may be temporarily suspended/delayed (with compensation provisions) if it prevents safe coal mining
Queensland CO_2 storage	CO_2 storage – water resources	Direct contact, contamination of water resource	Prioritisation of future water resource	Environmental/ social	Ban of CO_2 geological storage in the Great Artesian Basin

In Alberta's gas-over-bitumen and Queensland's coal-CSG examples, the management of resource development is largely informed by economics. Oil produced from bitumen is considered to have higher value than natural gas, now and in the foreseeable future. As gas production (whether before or during) may be detrimental to bitumen development, the latter is clearly prioritised under the current regulations in Alberta. However, the priorities could change if natural gas becomes more valuable in the future.

In Queensland, coal and CSG are considered equally important for the state's economy and regulations attempt to enable co-development of the 2 resources in the most efficient and safe way.

The Great Artesian Basin is a special case, because the conflict between geological storage of CO_2 and water resources is not purely based on economics, but also on environmental and social aspects. Although the groundwater in question is not potable and located at depths too deep to be economically produced at present, CO_2 geological storage was deemed too risky due to potential contamination of a future water resource for cattle farming. The development of coal, CSG and other petroleum resources also falls under environmental regulations and cannot have detrimental effects on potable groundwater or other environmentally sensitive areas.

One advantage of having a clear ban or prioritisation of one resource over the other is that it provides certainty, avoiding lengthy and costly arbitration hearings. However, economics and priorities can change, which may require an update of regulations in the future.

Generally, direct impacts (like contamination of one resource by the operations of another) are relatively easy to identify. Compensation can be paid based on lost revenue if the impacts are impossible to mitigate. Pressure impacts, on the other hand, are harder to predict and more difficult to attribute to a source. They are not necessarily detrimental, and may even be favourable. Again, having clear trigger values provides certainty and helps parties agree on monitoring and compensation solutions before any conflict arises (for example, the 5 m and 2 m hydraulic-head values in Queensland for acceptable drawdown induced by CSG production in a neighbouring well). This works particularly well when the pressure impact is detrimental, such as in cases where both parties rely on pressure reduction (or pressure increase) for developing their respective resources.

1.4. Regulatory environment in Western Australia

1.4.1. Western Australian groundwater legislation and regulations

In Western Australia, the Department of Water and Environmental Regulation (DWER) is responsible for water planning, management and quality protection. The *Rights in Water and Irrigation Act 1914* provides the statutory basis for planning and allocation of water in Western Australia. The objectives of the legislation include the management, sustainable use and development of water resources to meet the needs of current and future users, as well as the protection of ecosystems and the environment in which water resources are situated. DWER approves different types of licences and permits to authorise various activities related to groundwater abstraction, including:

a) a licence to take groundwater or surface water

b) a licence to construct or alter a groundwater well.

The *Country Areas Water Supply Act 1947* provides for the allocation of reticulated water to country areas and safeguards water supplies. The *Metropolitan Water Supply, Sewerage and Drainage Act 1909* provides the legal definition of boundaries for metropolitan water, sewerage and drainage areas. The Acts define legal boundaries of surface and groundwater drinking water sources and include bylaws that protect the water quality of these sources. They also include provisions for the establishment of protection zones (for example, wellhead protection zones and reservoir protection zones). Any intention to take groundwater or inject into aquifers is covered under the above 3 Acts. Occasionally, DWER develops specific management plans that further define the circumstances under which water can be taken from an aquifer, and guidelines for the protection of water resources from any activity that has the potential to affect their quality.

The responsibility for the public water supply in Western Australia lies with the various water service providers, which in the case of the northern Perth Basin, is the Water Corporation.

1.4.2. Environmental assessment and regulatory system

The regulatory and policy requirements of the resources sector (including minerals, petroleum, geothermal and geological storage of natural gas, hydrogen and carbon dioxide) are overseen by the Resource and Environmental Regulations Group in the Department of Energy, Mines, Industry Regulation and Safety (DEMIRS) of the Western Australian Government.

The legal framework for the exploration and recovery of petroleum in Western Australian onshore and State waters areas is provided within the *Petroleum and Geothermal Energy Resources Act*

1967 (PGER) and the *Petroleum (Submerged Lands) Act 1982*. Three sets of regulations determine the management and administration of activities related to the exploration for, and the recovery of, below-ground energy resources in Western Australia:

- the Petroleum and Geothermal Energy Resources (Occupational Safety and Health) Regulations 2010 and the Petroleum and Geothermal Energy Resources (Management of Safety) Regulations 2010
- the Petroleum and Geothermal Energy Resources (Environment) Regulations 2012
- the Petroleum and Geothermal Energy Resources (Resource Management and Administration) Regulations 2015 (the 'onshore' regulations) and the Petroleum (Submerged Lands) Resource Management and Administration) Regulations 2015.

DEMIRS assesses environmental proposals for petroleum and geothermal energy resources in accordance with the *Petroleum and Geothermal Energy Resources Act 1967*, and the *Mining Act 1978* for mining-related activities. Mining, petroleum and geothermal activity proposals that may have a significant environmental impact will be referred to the Environmental Protection Authority (EPA) for environmental impact assessment under the *Environmental Protection Act 1986*.

The Western Australian Environmental Protection Authority (WA EPA) is an independent entity, and its operations are governed by the Environmental Protection Act 1986. WA EPA's functions include:

- conducting environmental impact assessments
- preparing statutory policies for environmental protection
- preparing and publishing guidelines for managing environmental impacts
- providing strategic advice to the Minister for Environment.

Overlapping petroleum, geothermal (and carbon storage) titles

Under the PGER Act 1967, petroleum and geothermal titles can exist under the same title block. In June 2023, DEMIRS published a draft of the 'Guide note on the management of subsisting petroleum and geothermal titles,' containing the following assessment considerations and principles:

1. Prior to making an application, either as part of an acreage release or for a Special Prospecting Authority (SPA), applicants should undertake the following:
    1. Make themselves aware of any existing petroleum or geothermal title.
    2. Be aware that proposals for work may be restricted due to potential impacts on existing operations. Applicants should identify any potential impacts and demonstrate how these are to be mitigated or managed.
    3. Demonstrate that the proposed work program and expenditure are achievable without interference with subsisting titles or rights, or potential excluded areas.
    4. Note that in the case of applications received as part of an acreage release, work programs cannot be changed by the applicant post-bid; however, the Minister may approve an alternative work program.

2. The following principles will be applied when assessing tenure applications that would create subsisting petroleum or geothermal titles:
    a. Avoidance of potential impacts to existing recovery operations and declared locations will be prioritised over exploration operations and leads or prospects.
    b. Discovered resources are given priority over prospective resources.
3. To assess potential impacts when assessing applications that subsist with existing petroleum or geothermal titles, DEMIRS will follow this process (Figure **18**):
    a. Identify potential impacts to existing petroleum or geothermal recovery and exploration operations.
    b. Review information about the mitigation or management of impacts submitted as part of the application.
    c. If appropriate, request that the applicant provide further information regarding any potential impacts. Whilst not exhaustive, this may include requests for:
        i. a description of discovered petroleum pools or geothermal energy resources within subsisting titles, or where there may be an impact on another title
        ii. the outcomes of any consultations undertaken with existing title holders
        iii. whether the applicant intends to explore in the same geologic intervals as any declared locations, petroleum pools or geothermal energy resources within subsisting titles or another title.
    d. DEMIRS may also seek information from existing petroleum or geothermal title holders on what they consider to be potential impacts on their operation, and how these might be mitigated or managed best.
    e. DEMIRS' assessment will consider:
        i. the degree to which the proposed exploration (as per the proposal for work and expenditure) or recovery operations interfere with exploration or recovery operations in subsisting petroleum or geothermal titles
        ii. where applicable, how the proposed work program demonstrates that the extraction of petroleum or geothermal energy will not affect the extraction of the other in future.

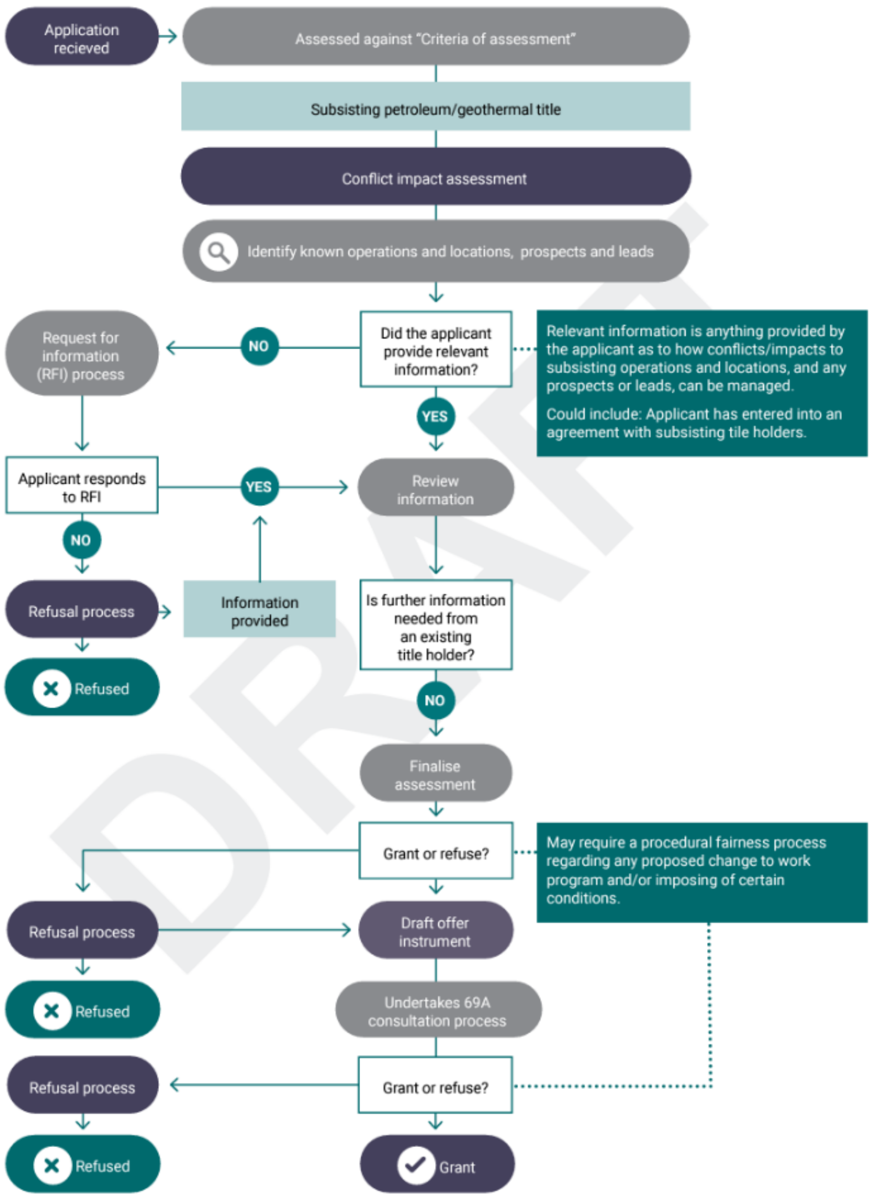


Figure 18. Draft schematic workflow of the assessment process for subsisting petroleum or geothermal titles (DEMIRS, 2023).

CO_2 geological storage

In May 2024, the Carbon Capture and Storage Bill (an amendment to the *Petroleum and Geothermal Energy Resources Act 1967*, *Petroleum Pipelines Act 1969 and Petroleum (Submerged Lands) Act 1982*) passed Western Australian Parliament. This amendment provides a legislative framework for the transport and geological storage of greenhouse gases, and it also enables exploration for naturally occurring hydrogen. Regulations associated with this Bill are currently under development and are needed before any activity related to carbon geological storage or natural hydrogen can commence.

Regulations and guidelines are currently being updated under the *Petroleum Legislation Amendment Bill (B) 2023* to include subsisting titles for geological storage of CO_2 and natural hydrogen activities in a similar way as for petroleum and geothermal titles. In *Response to Submissions Petroleum Legislation Amendment Bill (B) 2023*, DEMIRS proposes that petroleum and geothermal lessees and licensees will be able to apply for a greenhouse gas retention lease or a greenhouse gas injection license, without going through the acreage release process. This will avoid the delay of greenhouse gas storage projects. However, this greenhouse gas lease cannot extend beyond the blocks of the existing petroleum or geothermal license areas. Petroleum and geothermal permittees, and holders of petroleum and geothermal drilling reservations, will not be eligible to make an application for a greenhouse gas retention lease to minimise the risk of 'land banking'. Land banking refers to the practice of acquiring undeveloped land, often in areas with potential for future development, with the goal of selling it later at a higher price.

2. Methodology

2.1. Overview

The methodology for identifying and delineating resources and potential interaction in the northern Perth Basin relies primarily on Geographic Information Systems (GIS). This approach leverages open-source and proprietary geospatial data related to subsurface and surface resources in the region. The scope of this work does not include further geological modelling or interpretation of geophysical data, as the existing data is deemed sufficient for a basin-scale resource interaction assessment.

The first phase of the project involves comprehensive data gathering, review, curation, and initial assessment. This phase sets the foundation for subsequent detailed analyses.

Geospatial datasets related to the overall geology of the northern Perth Basin, the petroleum resources, geothermal resources, carbon geological storage (CGS), underground gas storage (UGS) and groundwater resources are added to a GIS project that represents the foundation of the interaction assessment.

In general terms, the assessment follows a structured workflow designed to evaluate how multiple subsurface resources may coexist or compete across the northern Perth Basin (Figure 19). The process begins by identifying key *suitability factors* for each resource type: petroleum, CGS, UGS, geothermal, and groundwater. These suitability factors define the geological and spatial conditions under which a given resource is considered viable or developable.

Using these factors, *suitability maps* are created for each resource at key stratigraphic intervals. These suitability maps quantify and visualise where each resource is most likely to occur and be viable for development.

The next step involves combining the suitability maps of coexisting resources to generate *interaction maps*. These interaction maps highlight areas of potential overlap or competition between specific pairs or groups of resources. *Thematic interaction* maps are then derived to focus on specific interactions of interest, such as petroleum vs CGS, or groundwater vs other resources.

To provide a comprehensive view, a *cumulative interaction map* is constructed. The cumulative interaction map aggregates interaction signals across all major intervals to highlight broad spatial trends and areas where resource competition is most likely.

Finally, the cumulative interaction map is integrated with 2 additional factors:

- groundwater demand, using bore density as a proxy for usage pressure
- potential migration pathways, using fault and well density as indicators of vertical connectivity.

These *integrated cumulative maps* refine the assessment by identifying dual-stress zones where high-interaction potential coincides with high water demand or elevated risk of deep-shallow fluid movement.

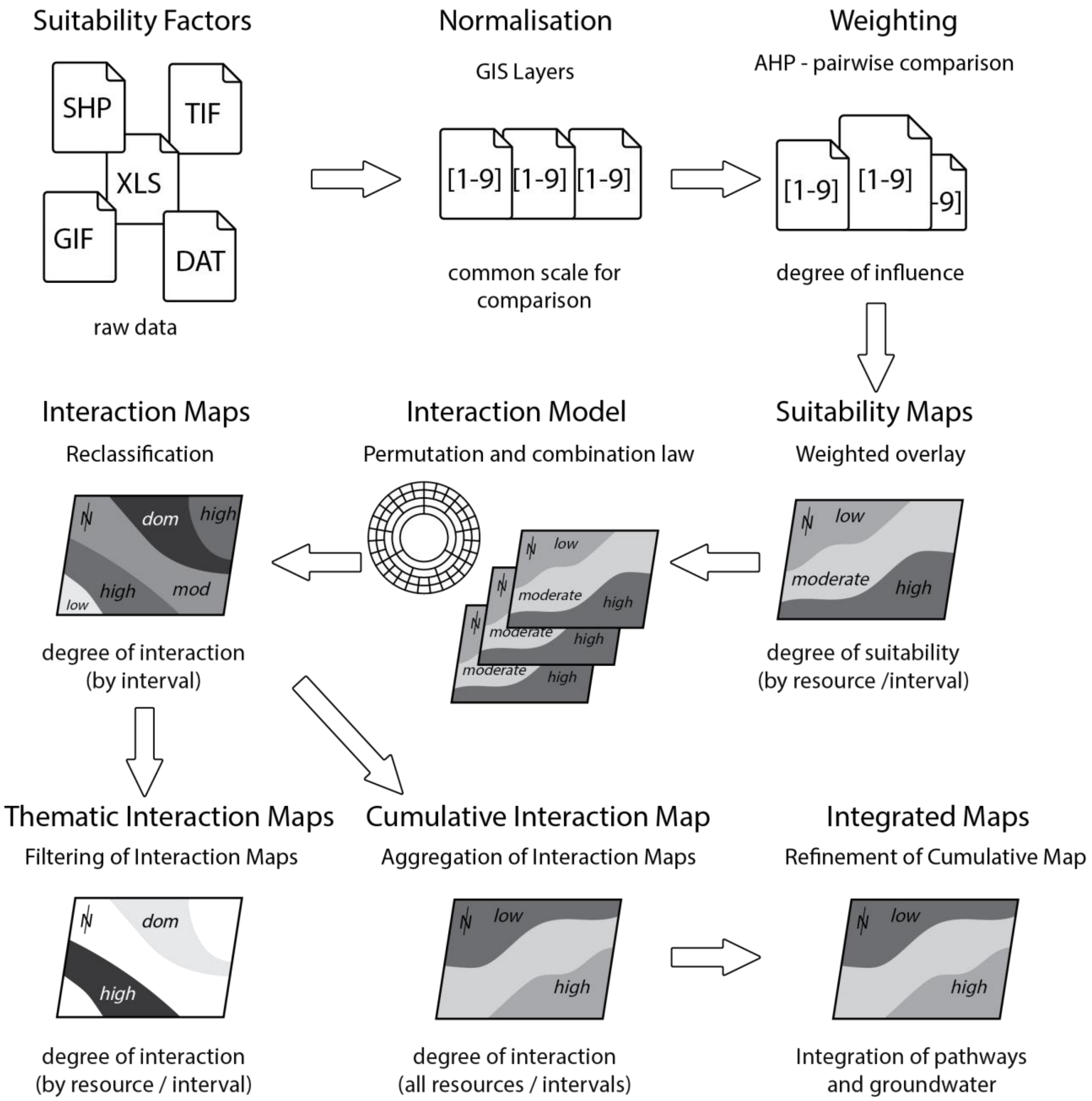


Figure 19. Schematic workflow for evaluation of resource interactions.

2.2. Identification and assessment of resources

The assessment of resource interactions in the northern Perth Basin applies a variant of the Multi-Criteria Evaluation (MCE) and Analytic Hierarchy Process (AHP) (Saaty, 1980; Belton and Stewart, 2002). These methodologies support 2 key objectives:

1. Evaluating the suitability of subsurface resources using a structured approach that integrates multiple factors influencing resource presence and viability.
2. Assessing potential resource interactions by quantifying spatial overlaps and competition for pore space, as well as ‘soft’ interactions resulting from indirect connectivity through geological pathways such as faults or wellbores.

The resulting suitability maps are combined into interaction maps that quantify resource overlap and competition. These maps facilitate decision-making for land and subsurface management by highlighting areas where multiple resources may coexist, compete, or require regulatory intervention.

The intervals considered in the assessment (Figure 5 and Figure **20**) include:

- G1low (Lower Permian, under the Carynginia Fm)
- G1up (Upper Permian, under the Kockatea Shale)
- G2A1 (Triassic-Lower Jurassic under the Cadda Fm)
- A1 (Lower Jurassic)
- A2 (Upper Jurassic)
- abA2 – Leeder, Parm (Cretaceous, including Leederville and Parmelia Fm)
- abA2 – Superficial (Cenozoic, including the Superficial formations).

<table>
<tr><th>Erathem</th><th>Stratigraphy</th><th>Petroleum System</th><th>Assessment Interval</th></tr>
<tr><td>Cenozoic</td><td>Superficial</td><td></td><td>abA2
Superficial</td></tr>
<tr><td rowspan="3">Createaceous</td><td colspan="3">Eroded</td></tr>
<tr><td rowspan="2">Leederville
Parmelia</td><td></td><td rowspan="2">abA2
Leeder, Parm</td></tr>
<tr><td rowspan="2">Austral 2</td></tr>
<tr><td rowspan="2">Jurassic</td><td>Yarragadee</td><td>A2</td></tr>
<tr><td>Cadda
Cattamarra</td><td>Austral 1</td><td>A1</td></tr>
<tr><td>Triassic</td><td>Eneabba
Lesueur</td><td>Gondwanan 2</td><td>G2A1</td></tr>
<tr><td rowspan="2">Permian</td><td>Kockatea
Dongara, Wagina</td><td rowspan="2">Gondwanan 1</td><td>G1up</td></tr>
<tr><td>Carynginia
High Cliff, Kingia</td><td>G1low</td></tr>
</table>

Figure 20. Key assessment intervals used in the assessment of resource interaction.

2.3. Suitability factors

Suitability factors are the geological and technical criteria used to assess the likelihood of a particular resource being present or developed in a specific location. These factors include the presence and effectiveness of reservoir and seal formations, and the depth, structure, temperature, and proximity to known resources. Georeferenced datasets (such as facies maps, borehole locations, and petroleum field outlines) are used to represent these factors spatially and are integrated into the suitability mapping process to visualise where conditions are most favourable for each resource. The complete set of evaluation factors for the resources is provided in Appendix 1: *Suitability* .

These factors are derived from proprietary and publicly available databases, as well as digitised records. They are classified within a GIS environment as either polygon layers with categorical value classes, point layers with categorical value classes, or raster grids with continuous pixel values.

The datasets supporting this work were accessed from multiple public agencies and proprietary sources, each contributing critical geological, hydrological and energy-related information relevant to the northern Perth Basin. Key data providers include DEMIRS Data Centre (2025), WAPIMS (2025), GeoView (2025), DWER (2025), the Bureau of Meteorology (2025), S&P Global (2024), Geoscience Australia (2025), and several peer-reviewed and industry reports, including 3D-GEO (2013), Craig *et al.* (2022), Ellis *et al.* (2024), and Mory and Iasky (1996).

To quantitatively assess these factors, original geospatial datasets must often be processed to a uniform resolution through resampling, ensuring comparability across layers. Many of these factors are then calculated or derived using spatial analysis techniques in GIS, including spatial interpolation (for example, inverse distance weighting), density estimation (for example, kernel density), distance and proximity analysis, hotspot detection, spatial clustering evaluation (for example, average nearest neighbour), and overlap analysis.

Normalisation of suitability factors

Since suitability factors are measured on different scales (nominal, ordinal, interval, and ratio), normalisation is required to convert them to a common scale for comparison (Figure 19).

Following the Land-Use Conflict Identification Strategy (LUCIS) (Carr and Zwick, 2007), all suitability factors are standardised using a 1–9 scale, where:

- 1 = lowest suitability
- 9 = highest suitability.

A 5-rank system (1, 3, 5, 7, 9) is applied to express how likely it is that resources are present for each factor. The choice of normalisation method is factor-dependent and can include regular intervals, natural breaks in data distribution or expert domain input.

Factors may be binary (for example, presence/absence) or exhibit gradual variations with up to 5 ranks.

Weighting of suitability factors

Because different factors influence resource suitability to varying degrees, they are weighted to reflect their relative importance (Figure 19). This weighting process is guided by the Analytic Hierarchy Process (AHP) (Saaty, 1980) and implemented using pairwise comparison matrices that compare each factor against another to establish relative importance. A consistency check is applied by computing the consistency index (CI) and consistency ratio (CR) to verify logical consistency. A CR < 0.10 is considered acceptable (Saaty, 1980).

2.4. Suitability maps

The suitability maps integrate normalised and weighted suitability factors into a single suitability representation for each resource (Figure 19). To ensure consistency, all suitability maps:

- are resampled to a 500 m x 500 m grid
- use a 1–9 scale, reclassified into 3 suitability categories:
    - low suitability (1–4)
    - moderate suitability (5–6)
    - high suitability (7–9).

This process results in 15 suitability maps, corresponding to different resources and stratigraphic intervals (Figure 21, Figure 42, A–D and Figure 45A–C).

<table>
<tr><th>Erathem</th><th>Stratigraphy</th><th>Assessment Interval</th><th>Suitability Map</th><th>Interaction Map</th><th>Thematic Interaction Map</th><th></th></tr>
<tr><td>Cenozoic</td><td>Superficial</td><td>abA2
Superficial</td><td>Suitability Groundwater (abA2 Superficial)</td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Creataceous</td><td colspan="3">Eroded</td><td></td><td></td><td></td></tr>
<tr><td>Leederville
Parmelia</td><td>abA2
Leeder, Parm</td><td>Suitability Groundwater (abA2 Leederville Parmelia)</td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Jurassic</td><td>Yarragadee</td><td>A2</td><td>Suitability Groundwater (A2)</td><td></td><td></td><td></td></tr>
<tr><td>Cadda
Cattamarra</td><td>A1</td><td rowspan="2">Suitability Groundwater (A1)
Suitability Petroleum (G2A1)
Suitability CGS (G2A1)
Suitability UGS (G2A1)</td><td rowspan="2">Interactions in Triassic Lower-Jurassic (G2A1)</td><td rowspan="2">Petroleum resource vs other (G2A1)
CGS resource vs other (G2A1)
Groundwater resources vs other (G2A1)</td><td rowspan="4">Cumulative Interaction</td></tr>
<tr><td>Triassic</td><td>Eneabba
Lesueur</td><td>G2A1</td></tr>
<tr><td rowspan="2">Permian</td><td>Kockatea
Dongara, Wagina</td><td>G1up</td><td>Suitability Petroleum (G1up)
Suitability CGS (G1up)
Suitability UGS (G1up)
Suitability Geothermal (G1up)</td><td>Interactions in Upper Permian (G1)</td><td>Petroleum resource vs other (G1up)
CGS resource vs other (G1up)</td></tr>
<tr><td>Caryngina
High Cliff, Kingia</td><td>G1low</td><td>Suitability Petroleum (G1low)
Suitability CGS (G1low)
Suitability UGS (G1low)
Suitability Geothermal (G1low)</td><td>Interactions in Lower Permian (G1)</td><td>Petroleum resource vs other (G1low)
CGS resource vs other (G1low)</td></tr>
</table>

Figure 21. Outputs of resource assessment for the northern Perth Basin. Suitability maps, interaction maps, thematic interaction maps and the cumulative interaction map are shown with their respective assessment interval.

2.5. Interaction maps

An interaction map combines suitability maps for multiple resources within a specific assessment interval to highlight where those resources co-occur (Figure 19). It identifies areas of potential competition or overlap to support assessments of subsurface resource interactions.

Interactions can occur within the same stratigraphic interval, leading to direct competition for pore space (the natural empty space within underground rocks that can hold fluids like water, gas, or CO_2) when multiple resources coexist in the same subsurface unit. This is typically observed among petroleum, CGS, UGS, and geothermal resources in the Permian to Lower Jurassic intervals.

The development of interaction maps is based on permutation and combination laws (for example, Jing *et al.*, 2021). The suitability maps are combined for each assessment interval (Figure **20**), and interaction intensity is categorised as follows (Figure 22):

- **high interaction:** at least 2 resources exhibit high suitability
- **moderate interaction:** 2 or more resources show moderate suitability, or one resource has high suitability while others are moderate
- **low interaction:** at most one resource has moderate suitability, with no high-suitability resources
- **resource dominance:** one resource exhibits high suitability while all others remain low.

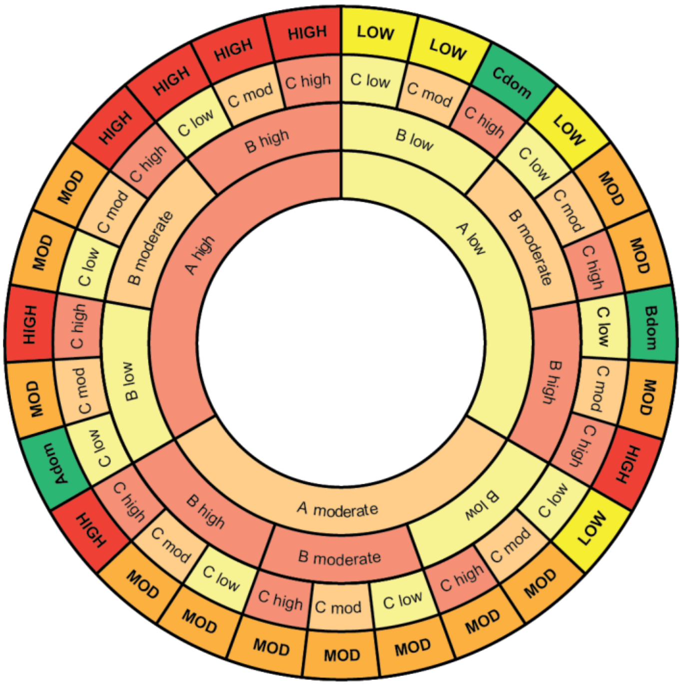


Figure 22. Schematic empirical permutation and combination laws for interaction maps of 3 resources. The first 3 rings from the centre represent resources A, B and C and their suitability (low, moderate, high). The outside ring represents the interaction intensity (low, moderate, high and dominant resource (#dom).

To improve granularity, interaction zones are further classified based on:

- the number of high-suitability resources
- the specific combinations of moderate and high-suitability resources
- the dominant resource, where applicable.

A detailed breakdown of resource-specific interactions is recorded, capturing the relationships between different resources and their suitability levels (for example, petroleum = high, geothermal = moderate, and CGS = low). This enables a more comprehensive understanding of how multiple resources interact within a given area.

This process produces:

- 3 general interaction maps for the Lower Permian, Upper Permian, and Triassic-Lower Jurassic intervals
- 7 thematic interaction maps (resource-specific maps showing the interaction of petroleum, CGS, and groundwater with all other resources).

2.6. Cumulative interaction map

A cumulative interaction map integrates all resource interactions across the Permian-Lower Jurassic intervals (Figure 48). The cumulative interaction map:

- Aggregates suitability values from suitability maps for petroleum, CGS, UGS, and geothermal resources.
- Computes a cumulative interaction value by adding the individual suitability values at each sample location to approximate the intensity of resource interaction across the Permian-Lower Jurassic intervals.

This cumulative interaction map offers a comprehensive view of overlapping resources. It provides a detailed representation of the resources that typically underlie groundwater aquifers.

2.7. Integrated cumulative interaction maps

Building on the cumulative interaction map, a series of integrated cumulative maps is developed to refine the assessment of resource interactions by incorporating additional information on groundwater demand and potential migration pathways (Figure 19). These integrated cumulative interaction maps enhance understanding of dual-resource stress zones and connectivity risks, supporting regional-scale risk assessment and resource management planning.

In addition to direct competition for the same pore space, interactions between resources can also be ‘soft,’ where they occupy different stratigraphic intervals but are still indirectly connected. This is particularly relevant for deeper resources (such as petroleum, CGS, UGS, and geothermal developments in the Permian to Lower Jurassic intervals) and shallower groundwater systems hosted in Jurassic to Cenozoic aquifers. Pathways, such as faults or deep boreholes, may allow vertical connectivity between these otherwise separated systems. The integrated cumulative interaction maps explicitly address this issue by incorporating proxies for both groundwater demand and the likelihood of vertical connectivity. As such, they provide a valuable tool for identifying areas where soft interactions may occur, supporting more informed decision-making regarding groundwater protection, resource coexistence and long-term development planning.

2.7.1. Integration of groundwater demand and resource interaction

A complementary integrated cumulative interaction map (Figure 49) is developed by combining the cumulative interaction map with water bore density data, which serves as a proxy for groundwater demand. This map illustrates how deep resource interactions (petroleum, CGS, UGS and geothermal) intersect spatially with areas of intensive groundwater use, highlighting zones where competing demands may arise.

This map contributes to a more comprehensive understanding of how groundwater and deep subsurface development intersect, supporting informed decision-making in the northern Perth Basin.

2.7.2. Integration of potential migration pathways

The integrated cumulative interaction map integrates faults and petroleum well infrastructure, which could act as vertical migration pathways between deep resource-bearing formations and overlying groundwater aquifers. The pathways are weighted based on their potential to enhance subsurface permeability and influence fluid movement across stratigraphic barriers. This process produces a pathway-integrated map (Figure 50), which adjusts cumulative interaction values based on the likelihood of vertical connectivity. This map helps to visualise regions with high fault displacement or well densities that experience elevated interaction values, emphasising areas where structural permeability could enhance vertical fluid movement and warrant further assessment. Regions with low fault or low well density see reduced interaction values, indicating a lower likelihood of migration pathways and a greater degree of separation between deep and shallow formations.

This integrated approach helps identify areas where resource interactions may extend beyond their primary depth intervals, informing risk assessments and management strategies for subsurface resource development in the Northern Perth Basin.

3. Northern Perth Basin resources

3.1. Petroleum resources

The northern Perth Basin is the second highest petroleum-producing province under Western Australian jurisdiction, following the Northern Carnarvon Basin in the state's territorial waters. The description below is based on information from DEMIRS (2024), Geoscience Australia (2020 and 2023), and Mory and Iasky (1996).

Petroleum-system analysis indicates the presence of widespread mature source rocks, abundant reservoirs, and favourable timing of structures for hydrocarbon entrapment. However, seal integrity is considered the biggest uncertainty due to the intense faulting and high sand-to-shale ratio of the post-Lower Triassic succession. Major play types in the basin include Permian-Triassic and Jurassic anticlines, Permian-Triassic tilted fault blocks and stratigraphic traps. Viable deeper plays (for example, Lower Permian) also exist, as evidenced by the Waitsia gas field. While oil and gas production have declined as fields deplete, deep gas resources have the potential to offset this decline.

Four petroleum systems have been identified within the northern Perth Basin (Figure 5):

1. Gondwanan 1 with a Permian source
2. Gondwanan 2 with a mostly Triassic source
3. Austral 1 with Jurassic sources
4. Austral 2 with an Upper Jurassic-Lower Cretaceous source.

3.1.1. Petroleum system elements

These petroleum systems are composed of key geological elements—source rocks, reservoirs, seals, traps, and generation histories—that together determine the location and productivity of hydrocarbon accumulations. The following summaries highlight the main components and their distribution.

Sources:

- Permian: Gas-prone shales and coals, particularly the Irwin River Coal Measures (IRCM) and Carynginia Formation, are sources of gas.
- Triassic: Oil- and gas-prone marine shales, notably the Kockatea Shale, especially the Hovea Member, serve as primary oil sources.
- Jurassic: Marine and non-marine oil-and gas-prone shales and coals from formations like the Eneabba Formation, Cattamarra Coal Measures, and Cadda Formation.

Reservoirs:

- Permian: Fluvio-deltaic and marine sandstones, including the High Cliff Sandstone and Dongara Sandstone, provide significant reservoir potential.

- Triassic: Shallow marine sandstones, notably from the Woodada Formation and Lesueur Sandstone, serve as reservoirs.
- Jurassic: Fluvial and deltaic sandstones from the Cattamarra Coal Measures and Yarragadee Formation provide reservoir potential.

Seals:

- Regional seals: Marine shales of the Triassic Kockatea Shale and the Jurassic Cadda Formation provide regional sealing capabilities.
- Intraformational seals: These are present throughout the Triassic-Jurassic interval, ensuring containment within various stratigraphic levels.

Traps:

- Structural: Large stratigraphic pinch-outs, fault block plays, and rollover anticlines are common. Sub-unconformity plays also exist, particularly under the Valanginian unconformity.

Generation:

- Permian source rocks generated significant amounts of gas, with peak generation occurring in the Triassic interval.
- The Hovea Member of the Kockatea Shale entered the main oil window in the Triassic, with maturity increasing during the Jurassic and Early Cretaceous interval.
- Oil and gas expulsion from Jurassic source rocks occurred primarily in the Early Cretaceous interval, with additional generation and expulsion from multiple source rocks after Valanginian break-up.

3.1.2. Petroleum wells and infrastructures

The northern Perth Basin hosts 355 petroleum wells, 18 gas pipelines and 6 petroleum facilities, most of which are dedicated to production (Figure 23).

3.1.3. Petroleum fields and permits

The northern Perth Basin includes 48 petroleum fields (Figure 24) across a range of operational states and development stages. There are 13 fields (27.1%) currently shut-in, which are not producing hydrocarbons but are maintained for potential future use. Five fields (10.4%) are actively producing hydrocarbons. Twenty-three fields (47.9%) are undeveloped, meaning they have been discovered but not yet developed for production. Additionally, 7 fields (14.6%) are depleted, having exhausted their economically recoverable hydrocarbons.

The northern Perth Basin includes 53 petroleum permits (Figure 25).

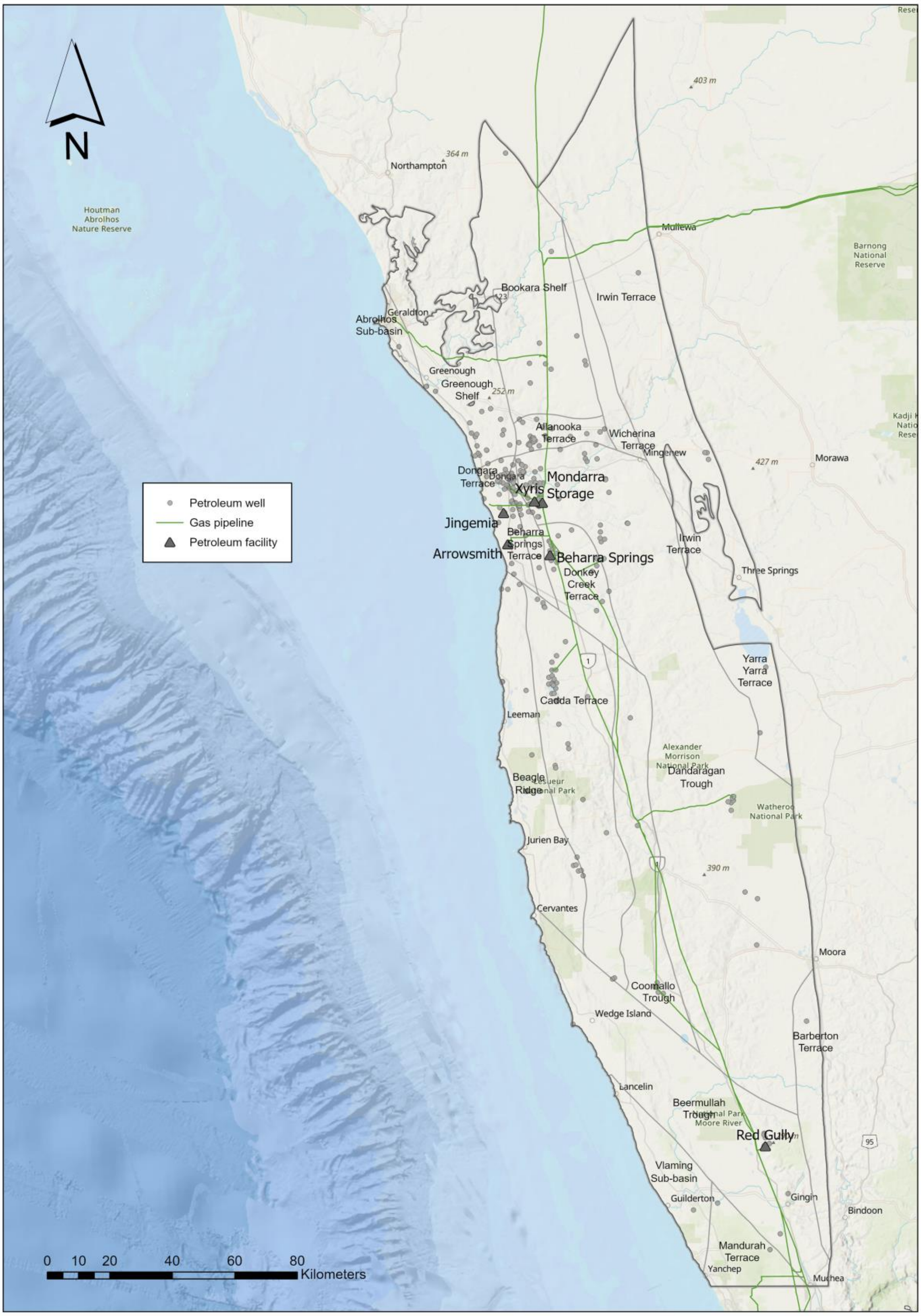


Figure 23. Petroleum wells, gas pipelines and petroleum facilities in the northern Perth Basin.

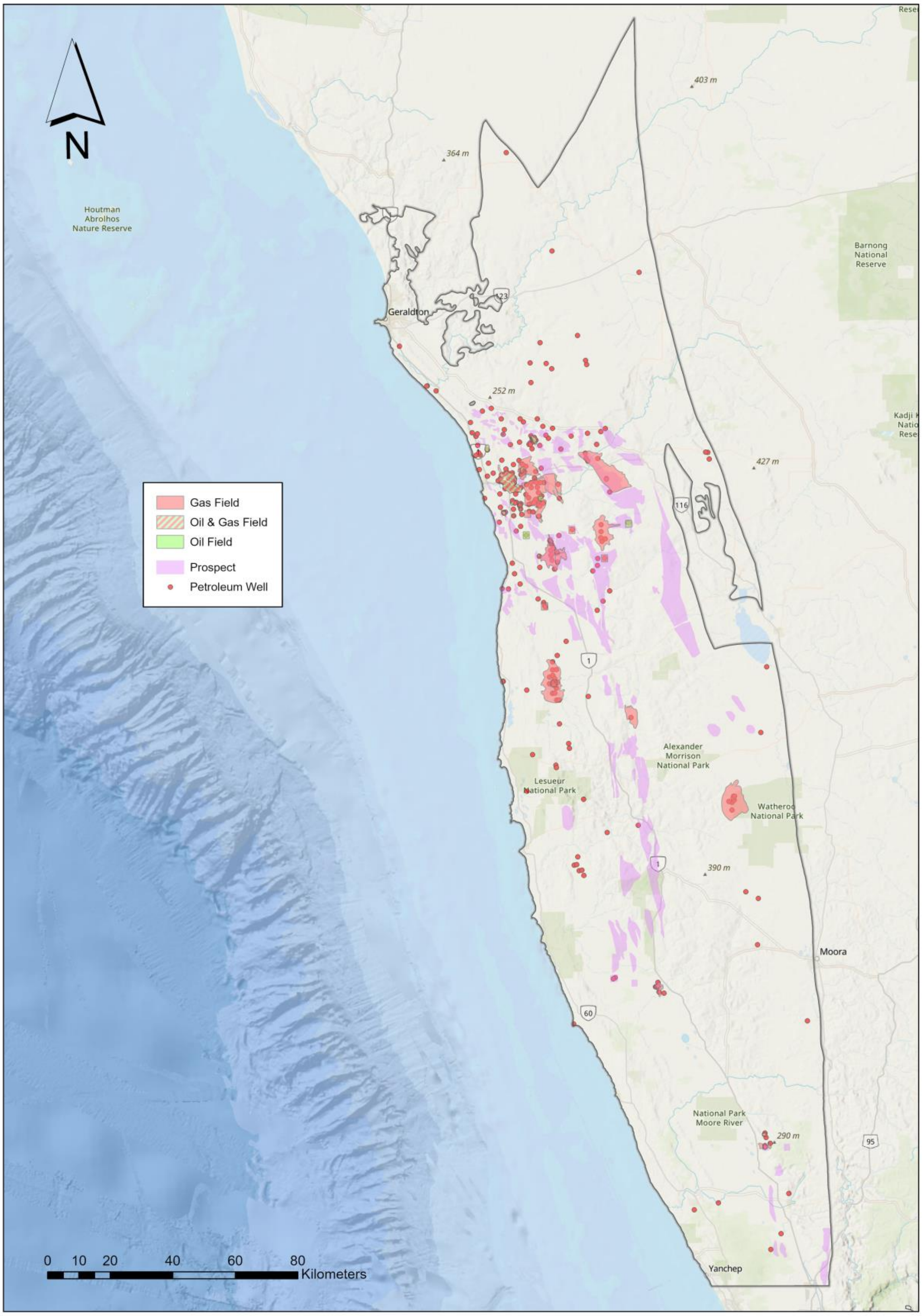


Figure 24. Petroleum fields and prospect distribution in the northern Perth Basin.

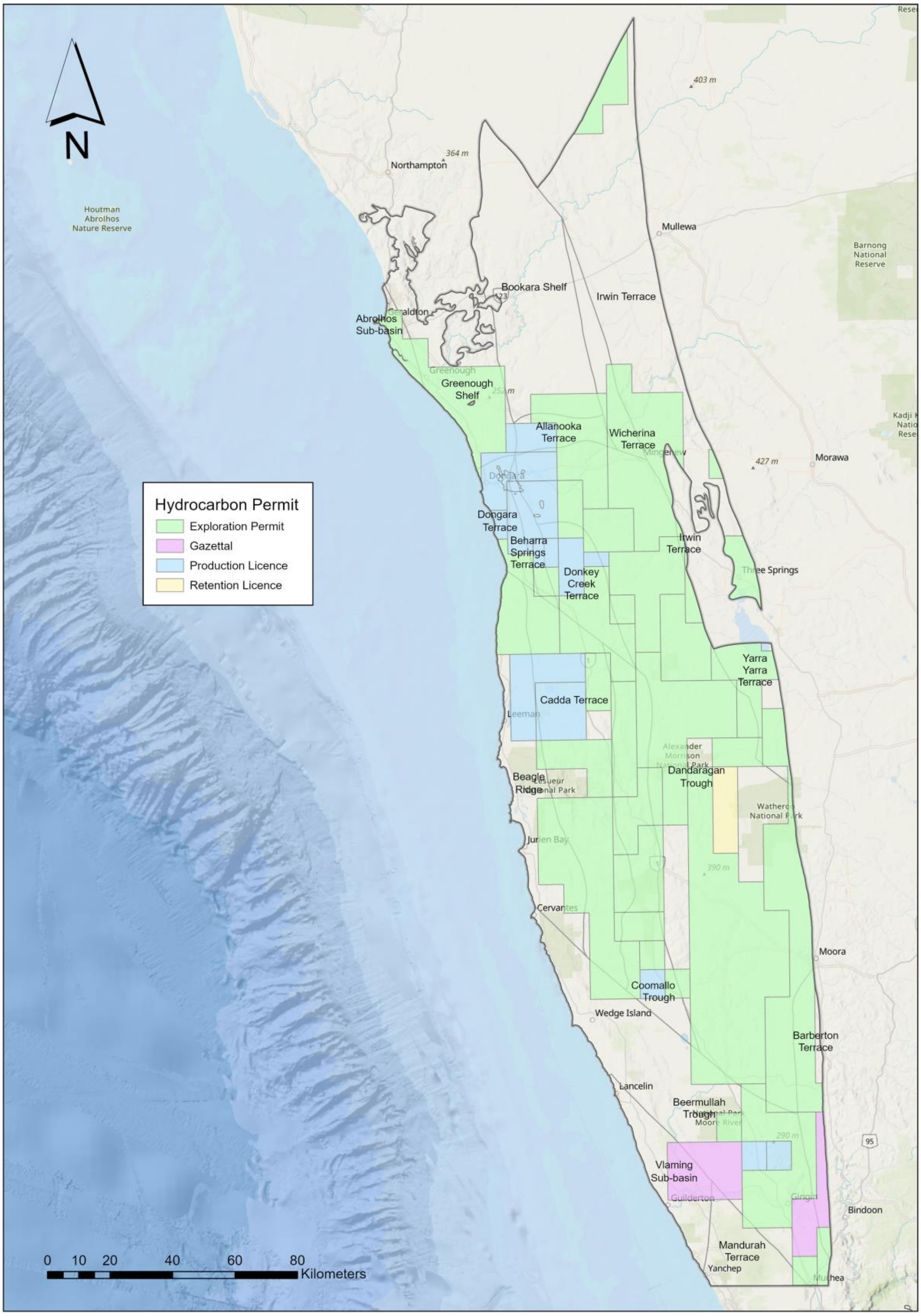


Figure 25. Petroleum permits distribution in the northern Perth Basin.

3.1.4. Natural hydrogen

Hydrogen has been detected in petroleum well samples across the northern Perth Basin, with reported concentrations reaching tens of percent (Haines, 2023). However, the source, migration and trapping mechanisms of natural hydrogen remain highly uncertain (for example, Stalker *et al.,* 2022 and Langhi, 2024). It is unclear whether the hydrogen detected in wells originates from natural subsurface generation processes or is an artifact of drilling or operational conditions (Langhi and Strand, 2023).

Unlike petroleum systems, where the source, migration pathways and trapping mechanisms are relatively well understood, the dynamics of natural hydrogen generation, movement, and containment in the subsurface remain largely uncharacterised. Current evidence suggests that the hydrogen is mixed with hydrocarbon accumulations, implying that it may not form independent, conventional accumulations. The potential caprock effectiveness for hydrogen retention is also unknown, adding further uncertainty to its long-term containment (Stalker *et al.,* 2022).

Given these uncertainties and knowledge gaps, no suitability map can or should be applied at this stage. Under the current state of understanding, the most reasonable assumption is that if a natural hydrogen resource exists in the northern Perth Basin, it would behave similarly to petroleum: trapped within conventional porous reservoirs and sealed by low-permeability caprocks. Until further data and research provide a clearer understanding of its generation, migration and accumulation mechanisms, natural hydrogen must be treated as a potential but unconfirmed subsurface resource that shares fundamental geological principles with conventional hydrocarbons.

3.2. Geothermal resources

3.2.1. Background: geothermal energy

Geothermal energy is a low-emissions resource that can be exploited for direct use or to generate electricity, depending on the temperature of the geothermal operation's target depth (Figure 26, left).

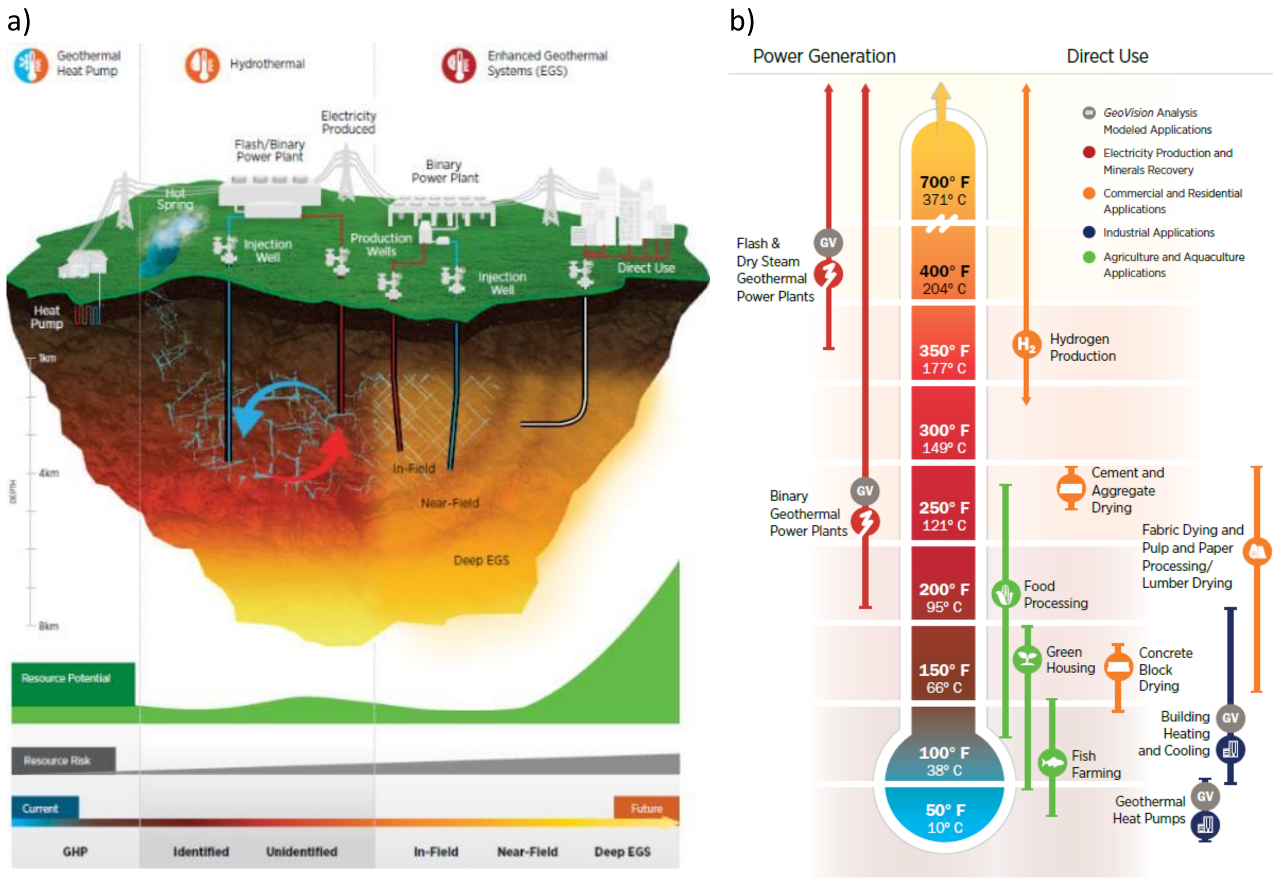


Figure 26. a) Application types for geothermal resources and b) temperature ranges for typical use of geothermal resources (US DOE, 2019).

While there is a large variety of geothermal energy systems, all have 3 basic components (Huddlestone-Holmes, 2014):

a) the geothermal resource (the heat)

b) the method with which this heat is accessed

c) the component that uses the heat.

Geothermal resource

The primary aspect of a geothermal resource is heat, originating from deep within the Earth and trapped by insulating rocks. In addition, a fluid (such as water or steam) that can easily flow through the rock must be present to develop the geothermal resource. This fluid may be naturally occurring or introduced into the system.

Heat access

The heat energy in a geothermal resource is accessed through wells drilled into the geothermal reservoir. The heat is delivered to the surface in the form of a fluid (water or steam) through production wells. After extracting the heat, cool water may be reinjected through a nearby second well, where it is heated before it is produced again through the first production well. Such a loop can be either open (where fluid flow occurs through the reservoir rock) or closed (where fluid is circulated within a connected pair of wells, without contacting the reservoir rock).

Heat utilisation

At the surface, energy is extracted from the hot fluid through a power station. Alternatively, the heat can be used directly for district heating or other industrial processes.

Commercial electricity generation is generally economical at temperatures above 150^{o}C and at depths that can be accessed by wells providing adequate flow. New technologies, such as binary plants, are being developed that use working fluids with a lower boiling temperature than water and can produce electricity at lower temperatures. The direct use of geothermal energy has a wide range of applications, including the heating of greenhouses, swimming pools and buildings, at temperatures ranging from ~ 20–140^{o}C. (Figure 26, right).

Western Australia primarily explores 2 types of geothermal technologies for electricity generation (Figure **27**):

- **Hot sedimentary aquifers (HSA):** these systems utilise naturally occurring hot water found in porous rocks at depths of 1–4 km.
- **Enhanced geothermal systems (EGS):** these systems extract heat by circulating fluids through engineered fractures in hot dry rocks found at depths of 3–5 kilometres, but their commerciality is yet to be demonstrated. This technology is particularly suited to parts of Australia that are not covered by sedimentary basins and exhibit high heat flow.

In addition to these, direct use systems leverage the Earth's natural heat for non-electric applications, like heating and cooling buildings. This method is utilised in some residential developments and public swimming pools, providing an efficient and sustainable heating solution.

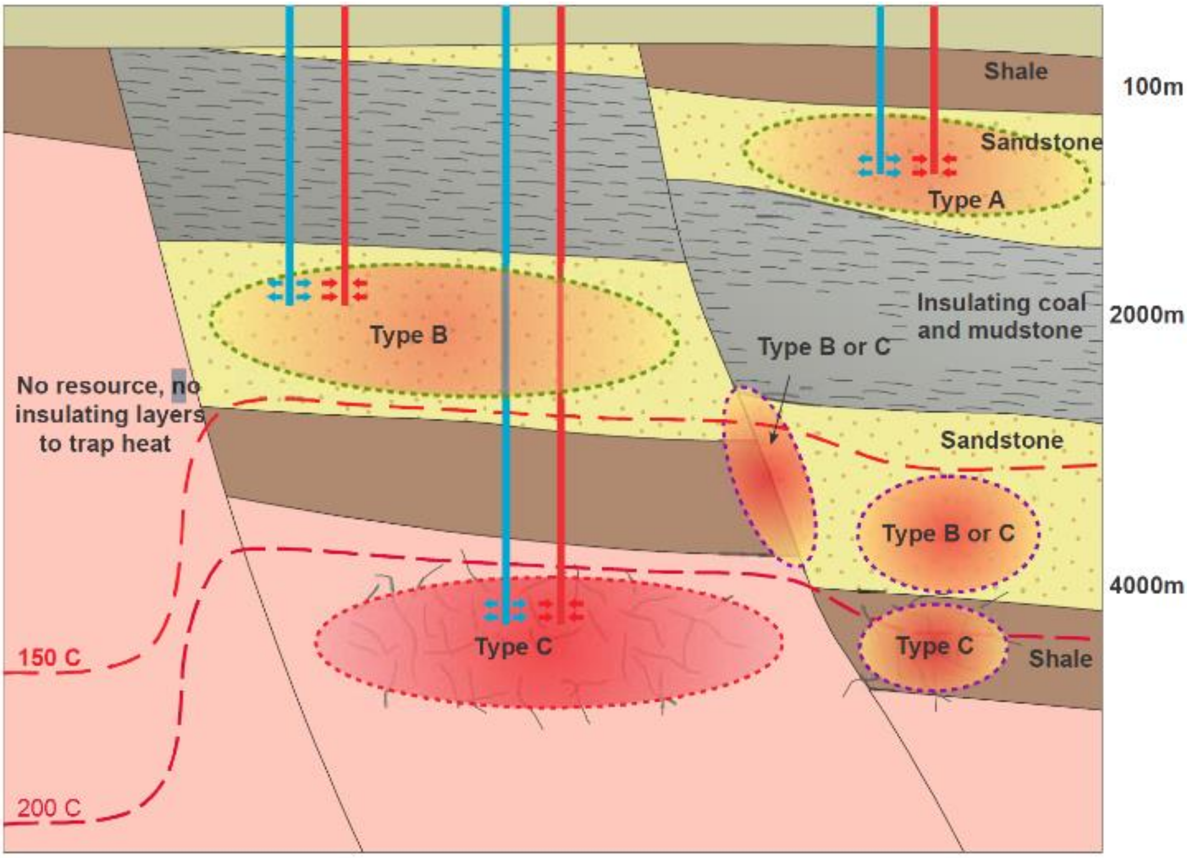


Figure 27. **Schematic representation and hypothetical geological settings of different geothermal resource styles as a function of depth (approximates temperature) and enhancements required to produce the required flow rates. 'Type A' represents shallow, direct use; 'Type B' represents hot saline aquifer (HSA); and 'Type C' represents EGS. Huddlestone-Holmes (2014).**

3.2.2. Northern Perth Basin heat flow and geothermal reservoirs

The northern Perth Basin exhibits a range of heat flow values and geothermal gradients, reflecting its complex geological structure. The heat flow values range from 30 to 140 mW/m² (Ghori, 2009), with higher values observed in the northwest where the sedimentary section is thinner. In contrast, lower values are present in the eastern part over the Dandaragan Trough.

The average geothermal gradient in the northern Perth Basin ranges between 10 to 55 °C/km (Mory and Iasky, 1996). However, greater depths show less consistent gradients due to the basin's complex geological structure. Both conductive and convective heat transport mechanisms are present, with conductive being predominant.

Key formations within the Perth Basin that hold potential as geothermal reservoirs include granitic basement rocks and sedimentary layers with high porosity and permeability. Specific formations of interest are those intersected by petroleum exploration wells, which have high temperature gradients and suitable reservoir properties. The focus is on shallower depths (2.5–3.5 km) with temperatures of 150–160 °C and adequate fluid flow rates from natural faults and fractures.

Figure 28 shows the temperature at the top of the Kockatea Shale (and equivalent strata) as well as the location of geothermal titles and applications in the northern Perth Basin.

The Kingia Sandstone (Figure 29) stands out as a key formation for geothermal energy (Ballesteros *et al.,* 2020) due to its favourable heat flow and temperature characteristics:

- **Heat flow:** Exceeds 90 mW/m^2 locally.
- **Geothermal gradient:** Approximately 37 °C/km.
- **Aquifer temperatures:** Exceeds 115 °C, making it suitable for power generation using binary Organic Rankine Cycle (ORC) technology.
- **Depth and temperature:** Temperatures can exceed 150 °C at depths generally greater than 3500 m.
- **Fluid flow rates:** While there is current gas production from Kingia Sandstone reservoirs, permeability values are not well constrained. Additionally, there is large uncertainty around the presence of permeability sufficient for maintaining fluid flow rates adequate for geothermal applications.

The Kingia Sandstone is distributed on the Dongara Terrace, Beharra Spring Terrace, Dandaragan Trough, Donkey Creek Terrace, Beagle Ridge, Cadda Terrace and Coomallo Trough, with the hotter part located on the Cadda Terrace, Donkey Creek Terrace and Dandaragan Trough.

Other formations reach temperatures exceeding 150^{o}C, mostly at depths greater than 4000 m.

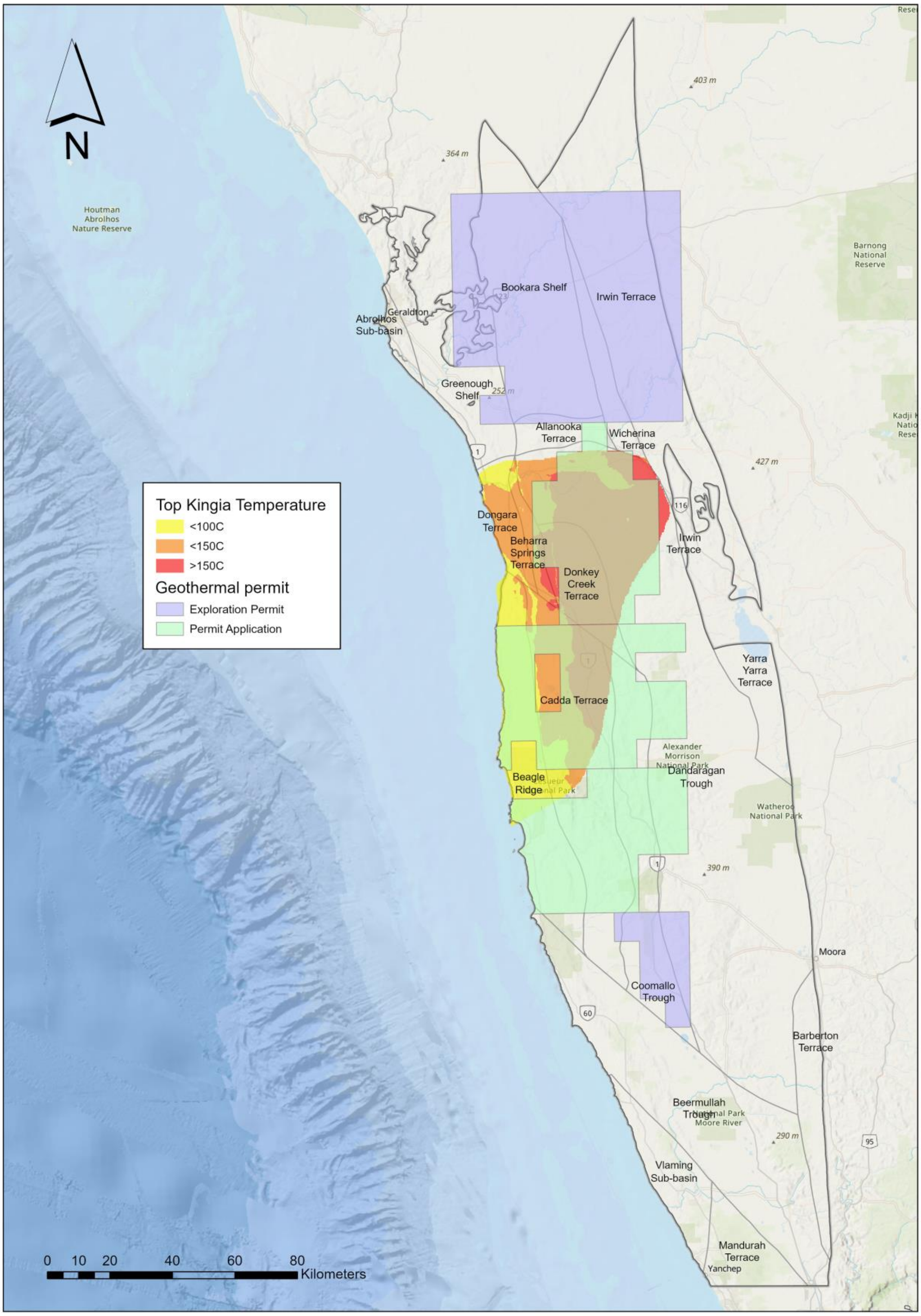


Figure 28. Temperature at the top of the Kockatea Shale (and equivalent strata) and location of geothermal titles and applications.

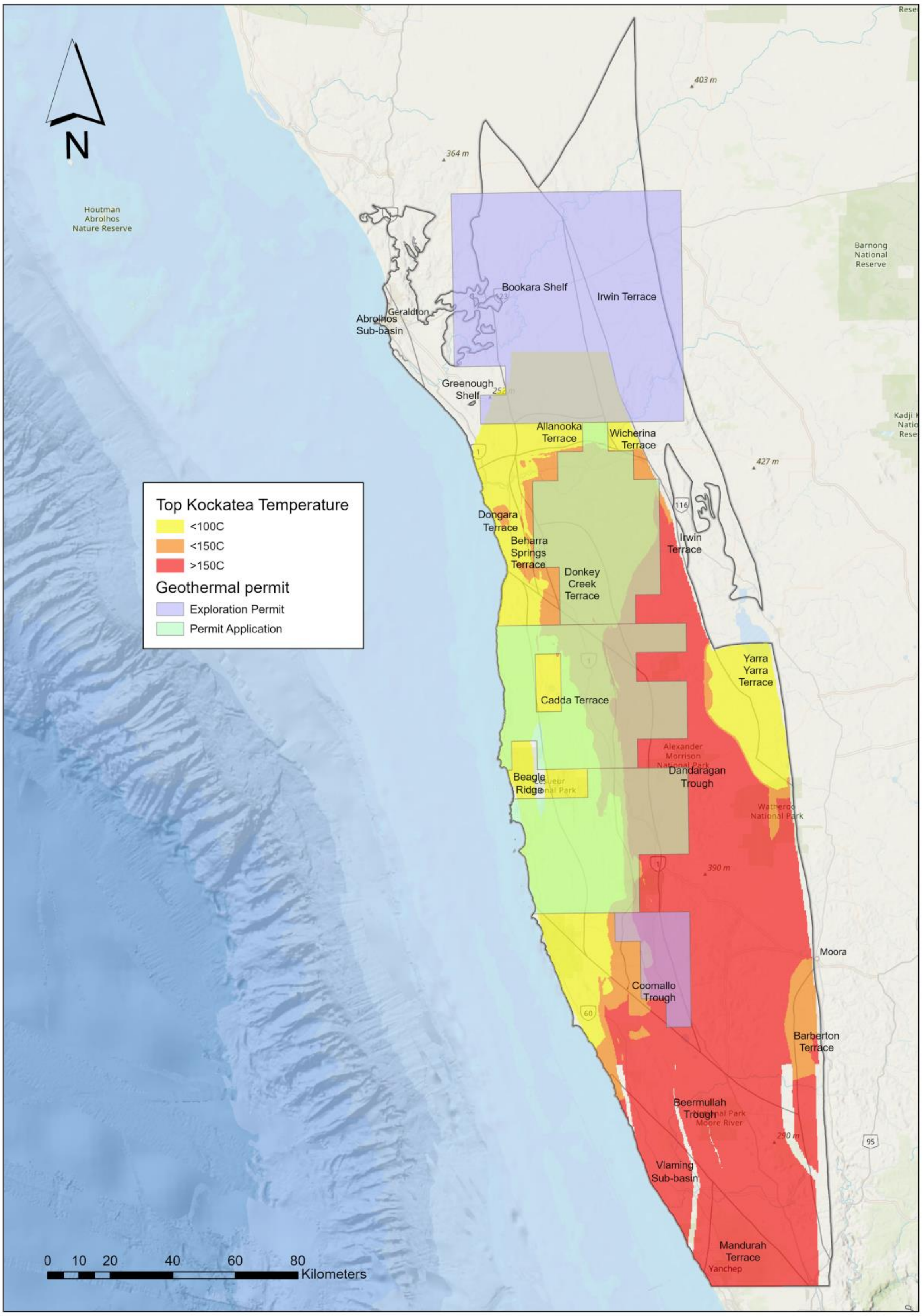


Figure 29. Temperature at the top of the Kingia Sandstone and location of geothermal titles and applications.

3.2.3. Western Australian geothermal development

Western Australia has experienced considerable growth in direct-use geothermal projects, notably for heating public swimming pools and leisure centres. Several leisure centres utilise geothermal energy, primarily sourced from the Yarragadee Formation in the Perth metropolitan area (Pujol *et al.*, 2015).

Currently there is no active geothermal energy production in the northern Perth Basin. However, several exploration licences have been issued in recent years (Western Australia Government, 2023). For instance, in late 2021, Strike Energy Ltd applied for the first new geothermal exploration license in 10 years and received a significant grant for its northern Perth Basin project. Following the acquisition of Mid West Geothermal Power Pty Ltd in 2021, Strike Energy Ltd announced a geothermal resource of 203 petajoules (PJ) within the Permian Kingia Sandstone at depths of approximately 4000 m and temperatures around 170 °C for its Mid West Geothermal Power Project (www.mwgp.com.au/) under the GSPA 2 AO permit.

VRX Silica Ltd, a pure-play silica sand company listed on the ASX, has received Geothermal Exploration Permit (GEP) 44, covering 8 blocks in Dandaragan (www.australiangeothermal.org.au/post/vrx-silica-granted-geothermal-exploration-permit-in-north-perth-basin-wa). This permit aims to explore geothermal technology for producing renewable energy for the Mid West region, specifically to support VRX's Arrowsmith Silica Sand Projects and the production of green hydrogen for glass manufacturing. VRX Silica has partnered with Hydro X (now Steam Resources) through a farm-in and joint venture agreement to develop GEP 44.

GEP 45 is held by Energy Resources Ltd, a wholly owned subsidiary of Mineral Resources. The permit is for a 6-year period, commencing in July 2023. However, detailed information about the geothermal project under GEP 45 has not been publicly disclosed.

3.3. Carbon geological storage resources

3.3.1. Background: carbon capture and storage

Carbon capture and storage (CCS) has been identified as one option within a portfolio of technologies to mitigate greenhouse gas emissions into the atmosphere, thereby limiting climate change. Carbon geological storage is the process of storing CO_2 extracted from a pre- or post-combustion process in deep geologic reservoirs.

At temperatures and pressures above 31.1 °C and 7.39 MPa, respectively, CO_2 is a supercritical fluid with the density of a liquid and viscosity of a gas. These temperature and pressure conditions generally correspond to a depth of approximately 800 m, depending on the local geothermal and pressure gradients. Therefore, CO_2 geological storage preferably occurs at depths of 800 m or more below the ground surface, where the CO_2 has a relatively high density (~ 200–700 kg/m^3), which reduces required subsurface storage volumes and buoyancy-driven migration potential.

Carbon geological storage requires a series of operations (Figure 30) that includes the injection of CO_2 through a well. The liquid or supercritical CO_2 is delivered via pipeline to the wellhead, where additional compression and heating may be required to ensure continuous CO_2 injection (Figure 30).

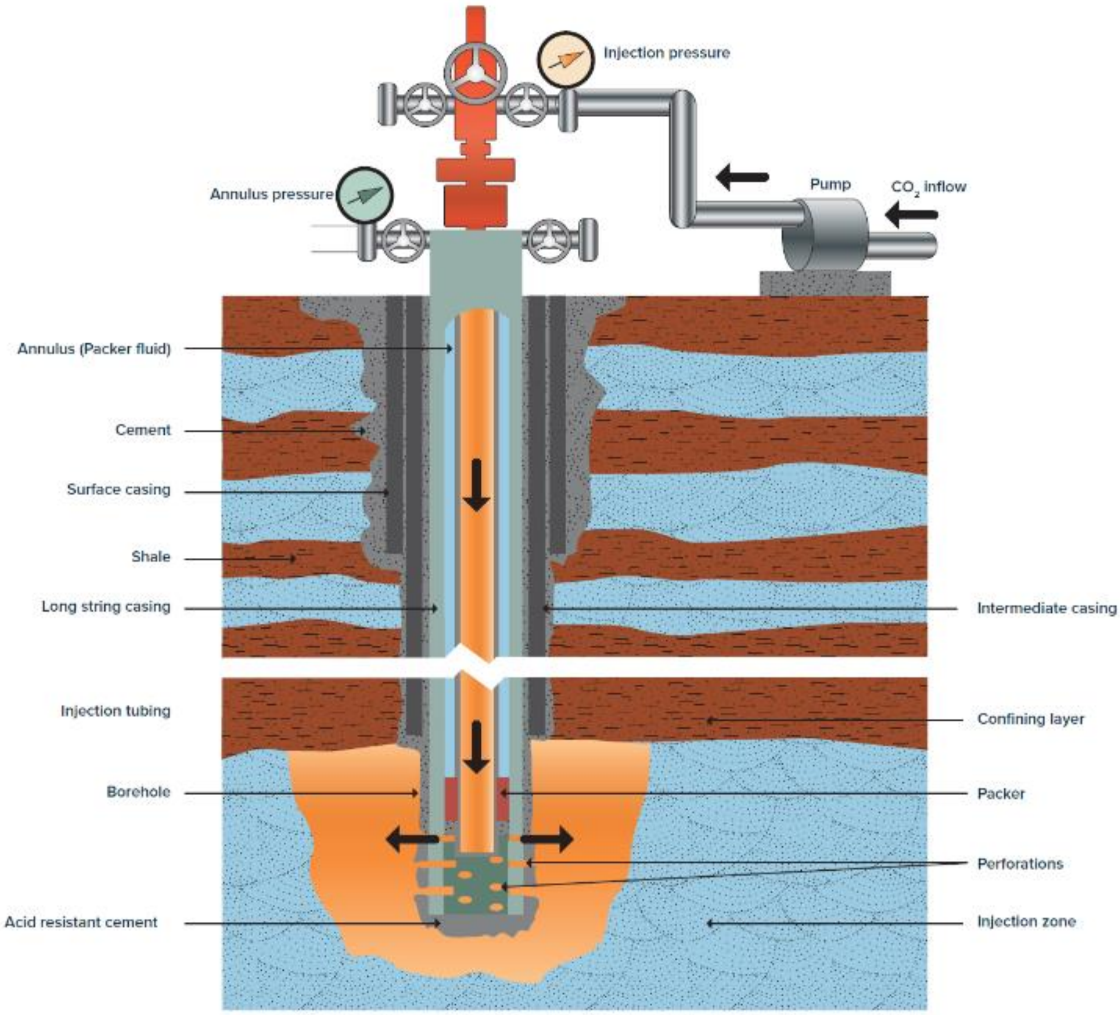


Figure 30. Schematic showing compression and injection of CO_2.

A CO_2 geological storage complex consists of a porous reservoir formation (for example, sandstone or carbonate) and a low-permeability sealing formation (for example, shale or evaporite). It must have the following requirements to prevent leakage to shallower formations or the atmosphere:

1. The reservoir formation needs to have sufficient storage capacity for the anticipated volume of CO_2.
2. The reservoir formation needs to have adequate injectivity (as defined by permeability and thickness of the reservoir rock) for accepting CO_2 at the desired injection rate. The most important constraint is that the bottomhole injection pressure should remain below the formation fracture pressure.
3. The sealing formation and geological structure of the reservoir complex need to ensure that the injected CO_2 is contained within a defined volume and that there are no material impacts on other resources or the environment.

Containment of the CO_2 can occur in various ways and over various time scales, with storage security generally increasing over time (Intergovernmental Panel on Climate Change (IPCC), 2005). Structural trapping is the process of trapping free-phase CO_2 by buoyancy in a closed structure below an impervious seal, similar to naturally occurring oil and gas fields. As the supercritical CO_2 moves through the reservoir rock, small droplets of the CO_2 will remain trapped in the centre of each pore and become immobilised by imbibition of formation water; a process termed residual trapping.

When CO_2 is injected into a deep aquifer, it will gradually dissolve into the formation water, resulting in CO_2-enriched water. This solution is slightly denser than CO_2-free water, forcing the CO_2-saturated water to migrate downwards due to its negative buoyancy. This process, referred to as solubility trapping, occurs when the CO_2 is contained within a structural trap or when it is migrating along the aquifer as it rises from the injection point. CO_2 dissolved in water can also react with the rock framework in the form of mineral dissolution or precipitation. Some of these geochemical processes (for example, dissolution and precipitation of calcite) can occur early in the injection process and impact on injectivity. However, trapping large volumes of carbon permanently via mineral trapping of CO_2, will take hundreds to thousands of years, depending on the mineralogy of the reservoir rock.

3.3.2. CO_2 geological storage in the northern Perth Basin

The northern Perth Basin was assessed for its potential for carbon geological storage in saline aquifers by the Carbon Storage Taskforce (2009), the CCS Atlas by 3D-GEO (2013) and Varma *et al.* (2013). An update of the 2013 CCS Atlas is currently being conducted by the Geological Survey of Western Australia (GSWA) and preliminary results were presented by Ellis *et al*. (2024) (Figure 31).

In the onshore northern Perth Basin, potential reservoirs are sandstones of the Beekeeper, Dongara/Wagina, Kingia/High Cliff and Lesueur formations and total P90, P50 and P10 prospective storage capacities were estimated to be 1.4 Gt, 2.9 Gt and 5.3 Gt, respectively (Carbon Storage Taskforce, 2009).

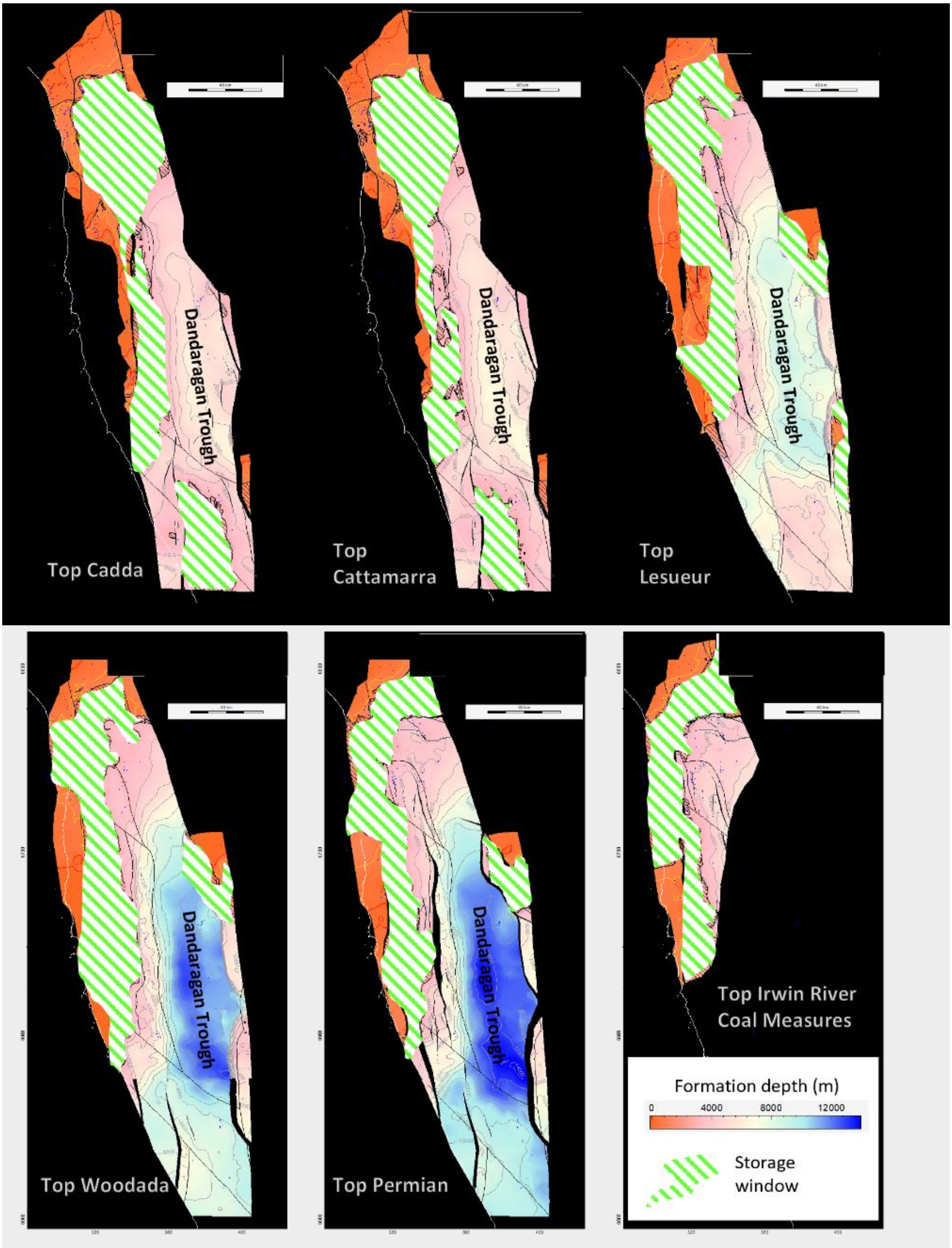


Figure 31. Preliminary delineation of optimum storage windows (1000–3000 m depth; green hashed areas) in various northern Perth Basin formations (From Ellis *et al.,* 2024).

Five possible storage leads were identified by 3D-GEO (2013) in the northern Perth Basin (Figure 32), which partly overlap with sites assessed in more detail by Varma *et al.* (2013).

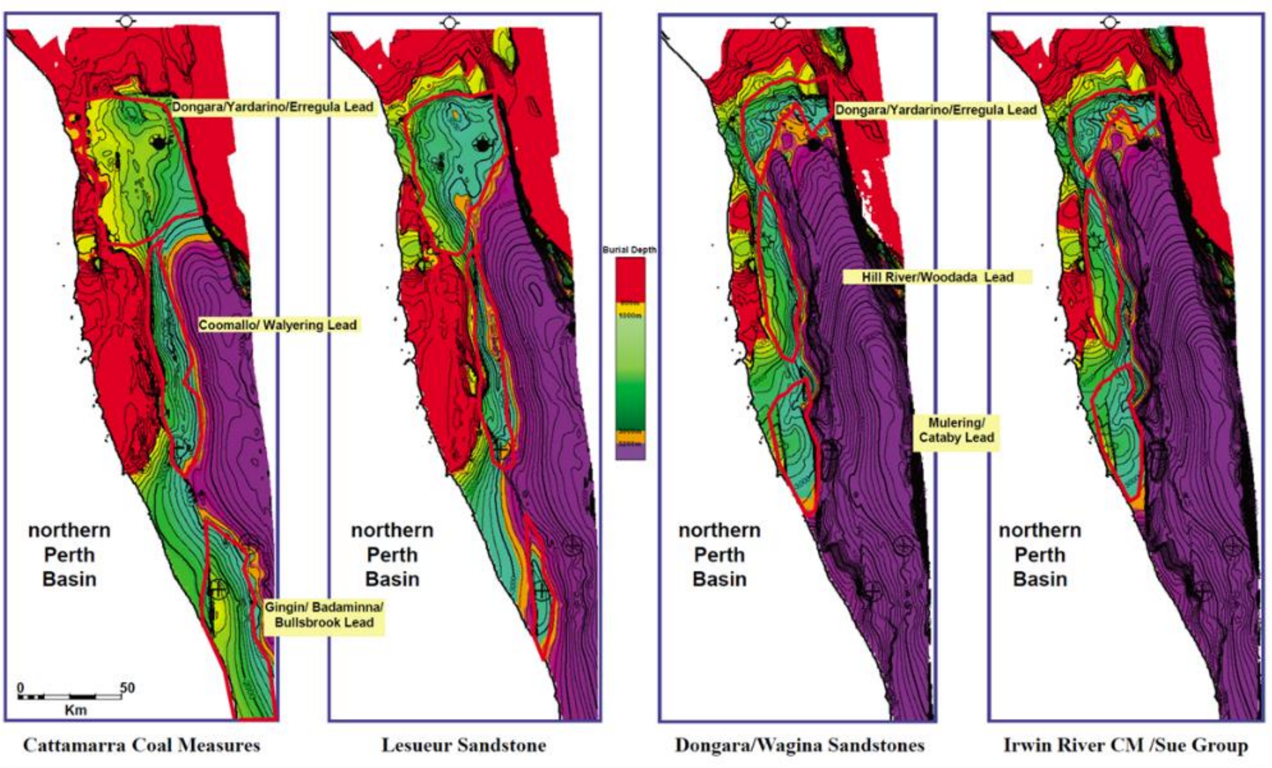


Figure 32. Burial depth of potential storage formations and location of prospective areas (red outline) for CO_2 geological storage identified by 3D-GEO (2013).

The Dongara/Yardarino area in the northern part of the basin has the highest overall prospective CO_2 storage resources (approximately 2 Gt in multiple reservoirs). A more detailed prospect analysis of several smaller areas (Figure 33A) results in a CO_2 storage resource of approximately 50–160 Mt (Varma *et al*., 2013). The area also contains hydrocarbon fields with prospective storage resources of up to 52 Mt in the Dongara field (Figure 33B and Figure 33C). Geological data and operational experience from these fields reduce the overall uncertainty for containment and reservoir properties, but may delay geological storage implementation until reservoir depletion. A hybrid model of combining storage in a depleted gas field with storage in underlying aquifers is shown in Figure 34. While it would be difficult to exceed the full aquifer volume for storage, extending the storage reservoir, beyond the part of the structure previously filled with natural gas, may provide an option to increase storage capacity of a depleted gas field.

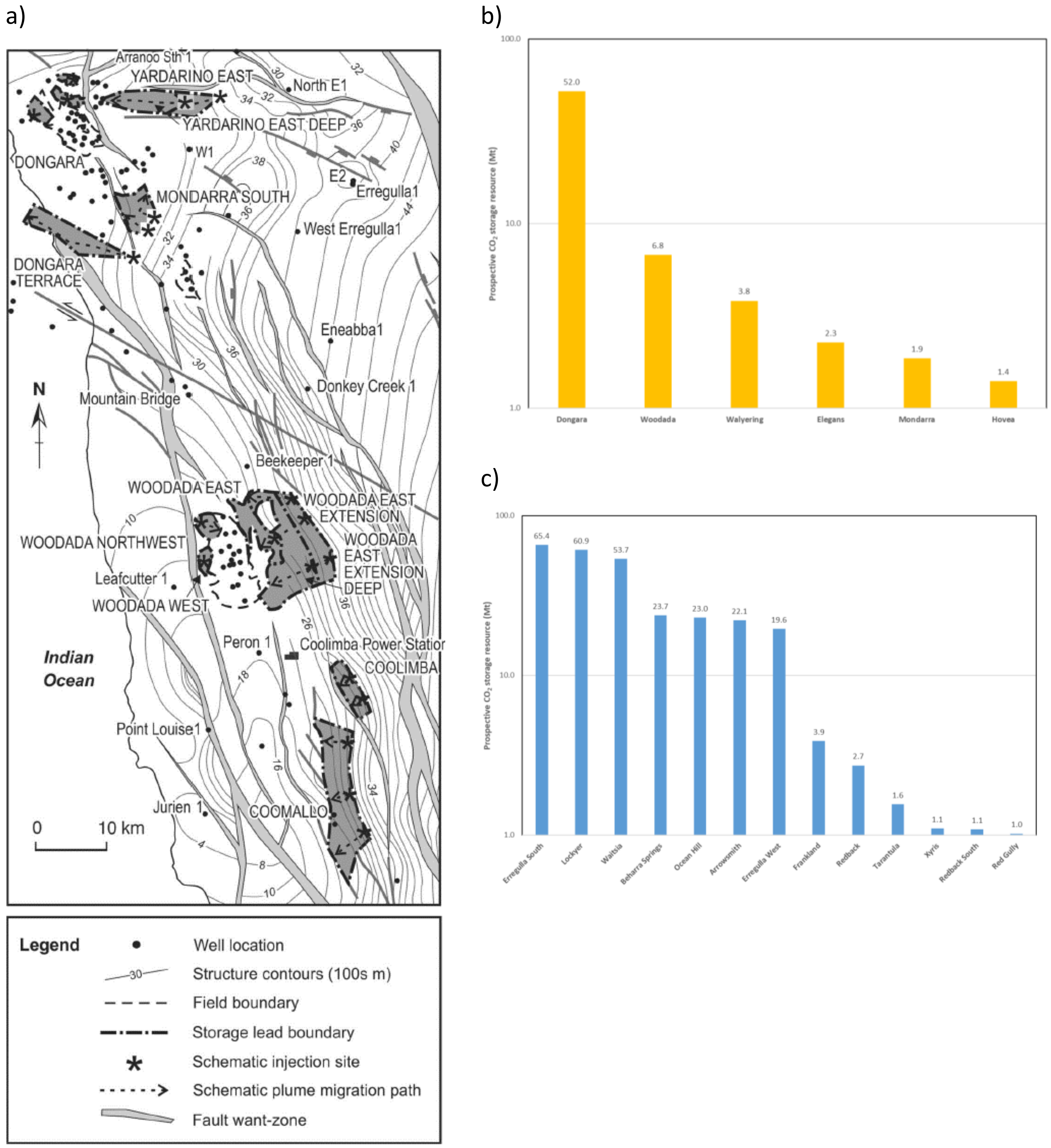


Figure 33. a) Potential CO_2 storage prospects in the northern Perth Basin (modified from Varma *et al.,* 2013). Prospective CO_2 storage resources (> 1 Mt) in the northern Perth Basin in b) depleted gas fields, and c) producing or un-produced fields.

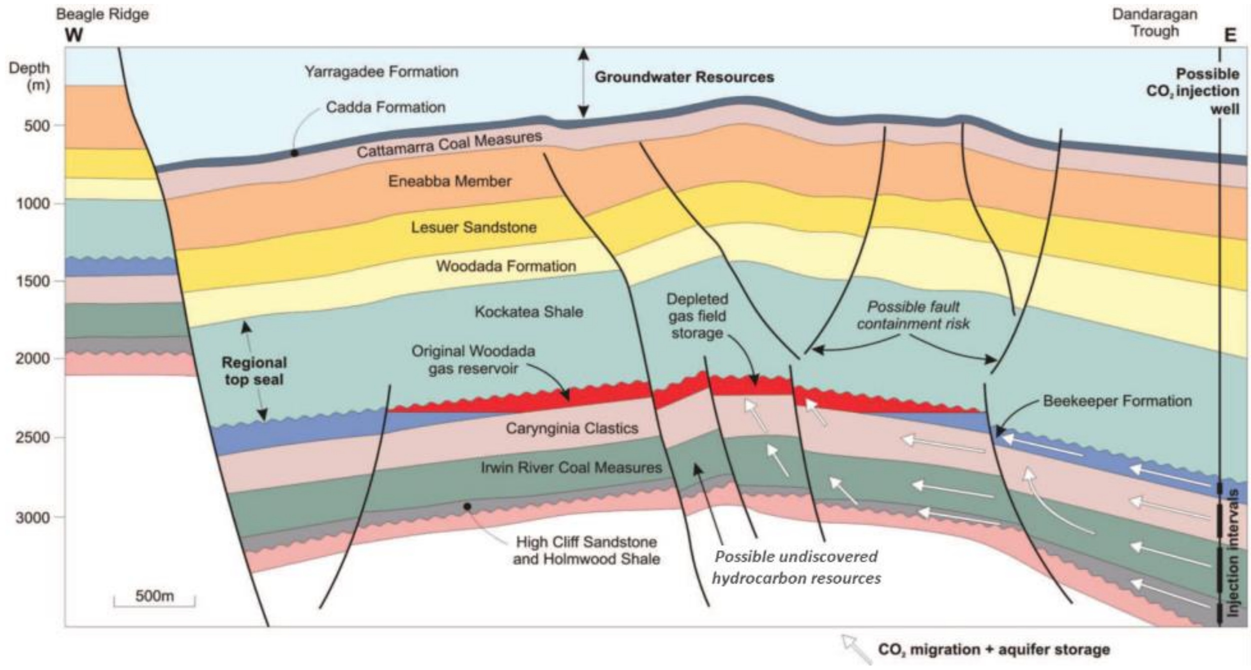


Figure 34. Hybrid CO_2 storage model in depleted Woodada gas field and underlying aquifers (Varma *et al.,* 2013).

3.3.3. Industrial projects with carbon capture and storage

Ammonia can be used as a low-emissions fuel for power generation, transportation and other applications, or to produce fertilisers and other chemicals. If CO_2 captured from the production of ammonia through steam methane reforming (SMR) of natural gas was injected and stored in a geological reservoir, this would be considered 'low-emissions ammonia,' also called 'blue ammonia'.

Building on the existing natural gas operations, blue ammonia projects are being considered by Mitsui E&P Australia (MEPAU) and Wesfarmers Chemicals, Energy & Fertilisers Limited (WesCEF), (www.mitsui.com/jp/en/topics/2021/1242033_12171.html). MEPAU has a 50% working interest, and is operating the Waitsia gas field near Dongara. MEPAU also holds up to 100% working interest in nearby depleted gas fields. As the first phase of its Cygnus CCS Hub, MEPAU conducted a small-scale CO_2 injection pilot test (~46 tonnes) in its depleted Dongara gas field in February 2024 (www.mepau.com.au/successful-co2-injection-test/).

WesCEF has an existing fertiliser plant in the Kwinana industrial area, south of Perth, and plans are being considered to capture and transport CO_2 emissions from the plant to a storage site in the northern Perth Basin, either by truck or by pipeline.

Similarly, the Pilot Energy Mid West Clean Energy Project (MWCEP) proposes hydrogen production using partial oxidation reforming with > 1 Mt/yr of integrated CCS capacity, and renewables-based hydrogen to produce up to 220,000 t/yr of blue ammonia (www.pilotenergy.com.au/mid-west-clean-energy-project). The proposed storage location is the offshore Cliff Head oil field.

3.4. Underground gas storage resources

3.4.1. Background: underground gas storage

There are 2 important criteria needed for an underground natural gas or hydrogen storage reservoir:

1. sufficient capacity to hold gas for future use
2. sufficient reservoir injectivity/productivity that allows the planned rate at which the gas can be injected and withdrawn (EIA, 2019).

There are 3 engineering and design objectives for a UGS site (Katz and Tek, 1999):

1. maximum gas storage capacity
2. minimal gas losses
3. sustainability of gas delivery rate.

The key UGS components are illustrated in Figure 35.

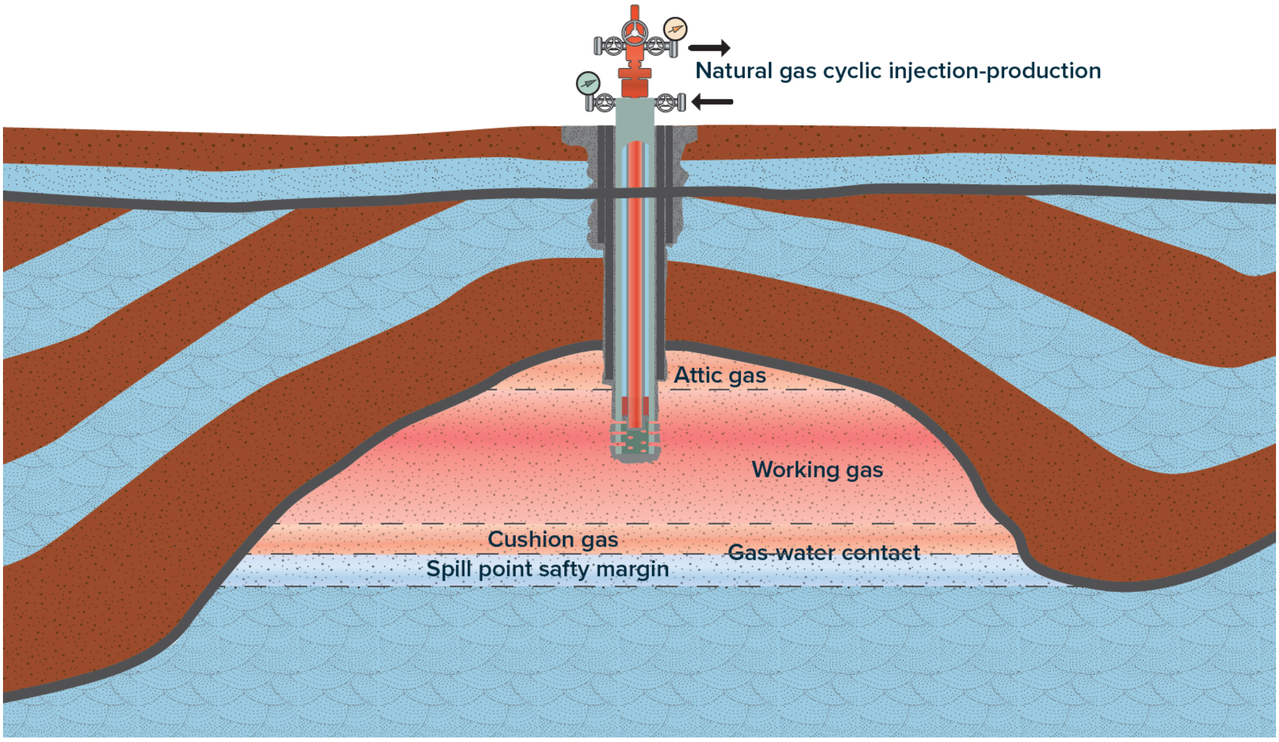


Figure 35. Schematic cross-section showing key principles for UGS.

3.4.2. Natural gas storage in the northern Perth Basin

The only natural gas storage operation in the northern Perth Basin is the Mondarra gas storage facility near Dongara, operated by the APA Group. The operation uses a depleted gas field and consists of 3 injection/production wells in the Dongara Sandstone at a depth of approximately 2700 m (Figure **36**). The storage reservoir has a total storage capacity of 15 PJ, the capability to inject gas at 70 TJ/day, and withdraw gas at 150 TJ/day (APA, 2013). This is equivalent to an approximate storage volume of 24 billion cubic feet (BCF), or 0.7 km^3.

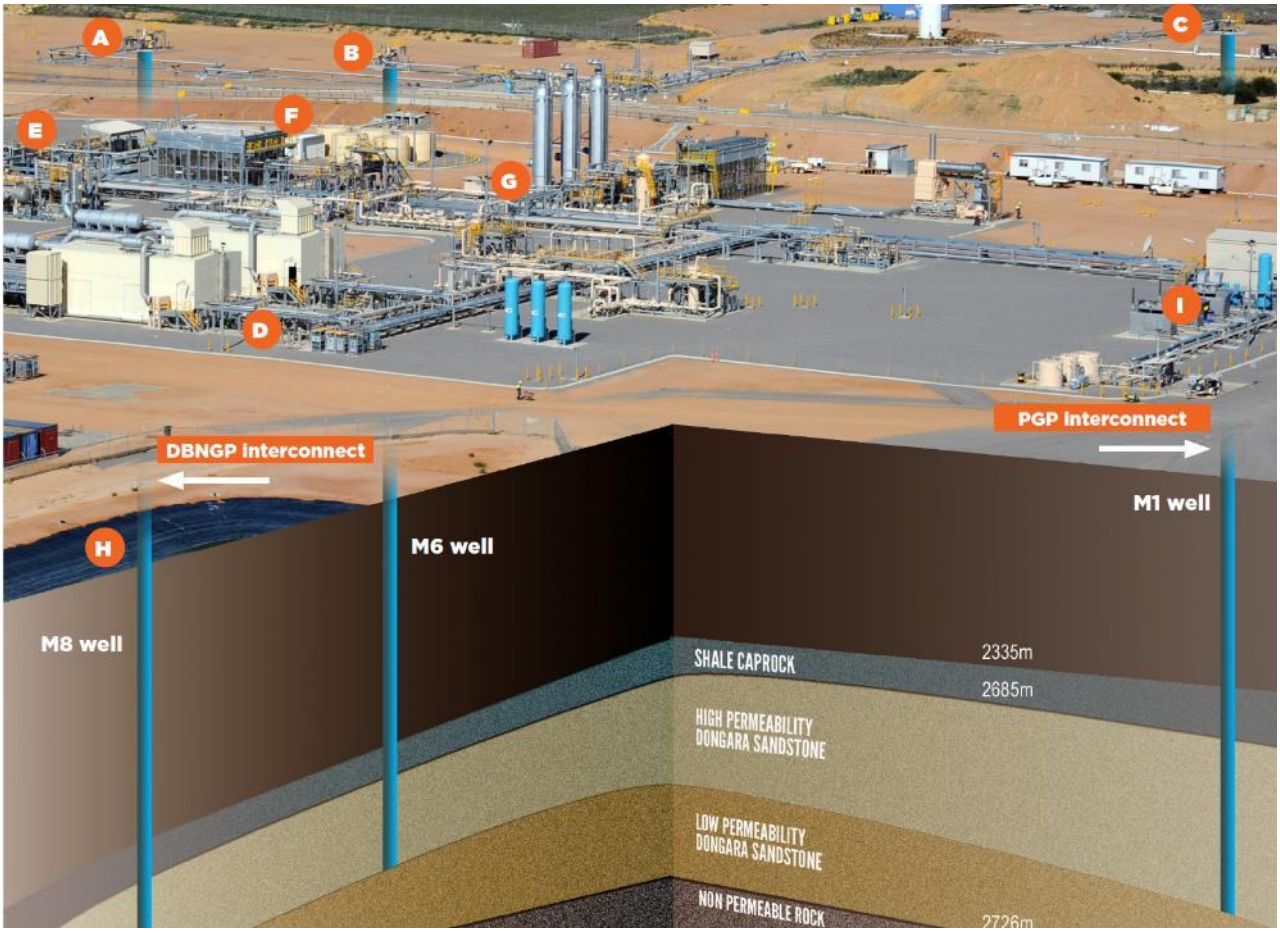


Figure 36. Schematic diagram of the Mondarra gas storage facility showing the location of: A), B), and C) injection/production wells, D) aerial reciprocating compressors, E) gas processing facility, F) cooler and separator, G) conditioning package unit, H) evaporation pond, and I) gas engine alternators. The facility is connected to the Dampier to Bunbury Natural Gas Pipeline (DBNGP) and the Parmelia Gas Pipeline (PGP). APA (2013).

3.4.3. Underground hydrogen storage in the northern Perth Basin

Currently, there is no hydrogen produced in the northern Perth Basin. However, future plans by Mitsui E&P Australia and Pilot Energy include the production of ammonia from natural gas, which involves hydrogen intermediates or by-products that may require underground storage. Also, future hydrogen production from renewable energy projects may necessitate underground storage. Therefore, the *Western Australian Renewable Hydrogen Roadmap (November 2020)* considers utilising depleted oil and gas fields for hydrogen storage. RISC (2021) performed a screening study for the Western Australian Government, evaluating the potential of depleted oil and gas reservoirs for underground hydrogen storage. Twenty-one of the assessed fields were located in the northern Perth Basin, 6 of which have been deemed as having strong storage potential, and 6 having moderate storage potential (Table 3). Potential competition with other users includes natural gas storage (i.e. Mondarra), expansion of petroleum operations (i.e. Beharra Springs) and CO_2 geological storage (i.e. Dongara).

Table 3. Underground hydrogen potential in oil and gas fields in the northern Perth Basin (RISC, 2021).

Field	Storage volume (BCF)	H_2 storage potential	Reasoning/risks
Xyris (gas)	9.3	Strong	Good storage capacity, high-quality reservoir.
Yardarino (gas)	5.1	Strong	Good storage capacity, high-quality reservoir – less production than Xyris so lower storage potential.
Beharra Springs (gas)	89	Strong	Good storage capacity, high-quality reservoir. Beharra Springs Deep under development.
Redback (gas)	22	Strong	Good storage capacity, high-quality reservoir. Beharra Springs Deep under development.
Tarantula (gas)	19	Strong	Good storage capacity, permeability low at 10–20 mD.
Mondarra (gas storage)	24	Strong	Good storage capacity. Currently used as natural gas storage facility (not currently available). High productivity.
Dongara (gas)	458	Moderate	Very high storage capacity, potentially too large for H2 requirements. Good reservoir properties. Many (47) wells.
Red Gully (gas)	4.0	Moderate	Good storage capacity, high-quality reservoir, wells watered out.
Apium (gas)	1.2	Moderate	Sufficient gas production – permeability is very low (< 5 mD), reducing potential injection and withdrawal rates.
Gingin (gas)	1.7	Moderate	Sufficient gas production – varying properties across field, poor deliverability in production wells.
Hovea (oil)	3.4	Moderate	Good storage capacity, high permeability – risk of potential H_2 dissolution and contamination in/from oil.
Mt Horner (oil)	1.0	Moderate	Limited storage capacity, high water saturation – risk of potential H_2 dissolution and contamination in/from oil.

3.5. Groundwater resources

The northern Perth Basin groundwater aquifers supply about 95% of water used for town water supply, agriculture, mining and petroleum industries (Department of Water, 2017). These aquifers also support many groundwater-dependent wetlands, watercourses, vegetation associations and cave and aquifer ecosystems in the Mid West region.

3.5.1. Background: groundwater

Groundwater is an integral part of the hydrologic cycle. The quantity and quality of groundwater resources require careful management to ensure sustainable use for domestic, industrial and environmental needs. Depending on the jurisdiction, the salinity of groundwater constrains its possible usage. For example, potable water (< 1000 mg/l), irrigation or domestic washing purposes (< 2,000 mg/l), and stock watering (< 10,000 mg/l). Groundwater with a salinity of > 10,000 mg/l is generally used only for specific industrial purposes. Thus, sedimentary basins may have multiple groundwater requirements from municipalities, households, agriculture, mining, geothermal applications, CO_2 geological storage and petroleum production, which collectively place a cumulative stress on groundwater resources. Therefore, knowledge of a basin's usable groundwater distribution, jurisdictions and existing policies is required for planning and management of potential resource interactions.

Basin-scale characterisation of the groundwater resource, along with knowledge of the regional setting (including climate, geomorphology, drainage, and land-use), is needed as a starting point for developing a basin resource management strategy. The main information required for suitable groundwater characterisation are:

- The geological distribution of aquifers and aquitards (rocks that greatly restrict or limit groundwater flow and that can be sealing rocks for storage) and their hydraulic properties, such as porosity and permeability.
- Baseline groundwater levels and flows within aquifers under natural conditions and, where possible, records of historical changes arising from climate variability, pumping and land-use.
- Baseline or current groundwater quality parameters.
- Groundwater-dependent ecosystem requirements.
- Locations and rates of basin recharge and discharge.
- Locations of subsurface features affecting flow paths or regions of cross-formational flow.
- Volume of groundwater in storage.

3.5.2. Groundwater resources in the northern Perth Basin

The primary aquifers used as groundwater resources in the northern Perth Basin are the Superficial, Leederville, Leederville-Parmelia and Yarragadee aquifers. Secondary sources are provided by aquifers in the Cattamarra Coal Measures and Eneabba-Lesueur formations (Table 4).

Table 4. Hydrostratigraphy and aquifer use in the northern Perth Basin (simplified from Department of Water, 2017).

Period	Hydrostratigraphy	Aquifer characteristics	Usage
Quaternary and Neogene	Superficial aquifer	Minor to major aquifer beneath Swan Coastal Plain; fresh to saline	Major groundwater resource
Cretaceous	Mirabooka aquifer	Minor to moderate aquifer beneath southern Dandaragan Plateau; fresh to brackish	
	Kardinya aquitard		
	Leederville aquifer	Major aquifer below the coastal plain south of Cataby (combined with Parmelia Group beneath Dandaragan Plateau to form the Leederville-Parmelia aquifer); fresh	
	South Perth aquitard		
	Leederville-Parmelia aquifer	Hydraulically connected with Yarragadee aquifer	Major groundwater resource; Minor oil and gas accumulations; Secondary potential for CO_2 storage
Jurassic	Otowiri aquitard	Extensive aquitard below Dandaragan Plateau (includes shaley part of the Carnac Formation)	
	Yarragadee aquifer	Major regional aquifer; Mostly fresh	
	Cattamarra aquifer	Interbedded aquifer-aquitard on Cadda Terrace; mostly brackish	
	Eneabba-Lesueur aquifer	Major aquifer on Beagle Ridge-Cadda Terrace; fresh to brackish	
Triassic			
	Kockatea aquitard		
Permian	Wagina aquifer	Local aquifer in north; saline	Gas production; gas storage
	Carynginia aquitard		
	Irwin-High Cliff aquifer	Poor to moderate aquifer; saline	Gas production
	Holmwood aquitard		
	Nangetty aquifer	Poor to moderate aquifer; saline	Gas production
Silurian-Ordovician	Tumblagooda aquifer	Regional aquifer in northern margin of Perth Basin. Mostly fractured rock aquifer; brackish to saline – locally fresh	
Proterozoic		Poor, fractured-rock aquifer; fresh to brackish	

Due to the structural history of the basin, aquifers can be close to the ground surface, either as outcrop or subcropping below Cenozoic superficial sediments (Figure 37). In most regions of the northern Perth Basin, the base of the Yarragadee aquifer is the lower limit for meteoric flow systems (Commander, 1981). Where the Yarragadee aquifer is absent, the base of the meteoric flow systems is usually the base of the shallowest aquifer present. Meteroic (originating from rainfall) influx of fresh water has flushed the remnants of high salinity seawater from most of these shallow aquifers above the Kockatea Shale (Department of Water, 2017). Regional flow in the northern Perth Basin is generally from east to west, with recharge in areas of topographic high along the basin margin and discharge along the shoreline and partly offshore (Figure 38). Salinity of formation water in the upper 1000 m is generally below 3000 mg/l, except for brackish formation water, which exhibits salinity of up to 10,000 mg/l due to the incursion of marine water close to the shoreline (for example, the Dongara line Well DL1 in Figure 38).

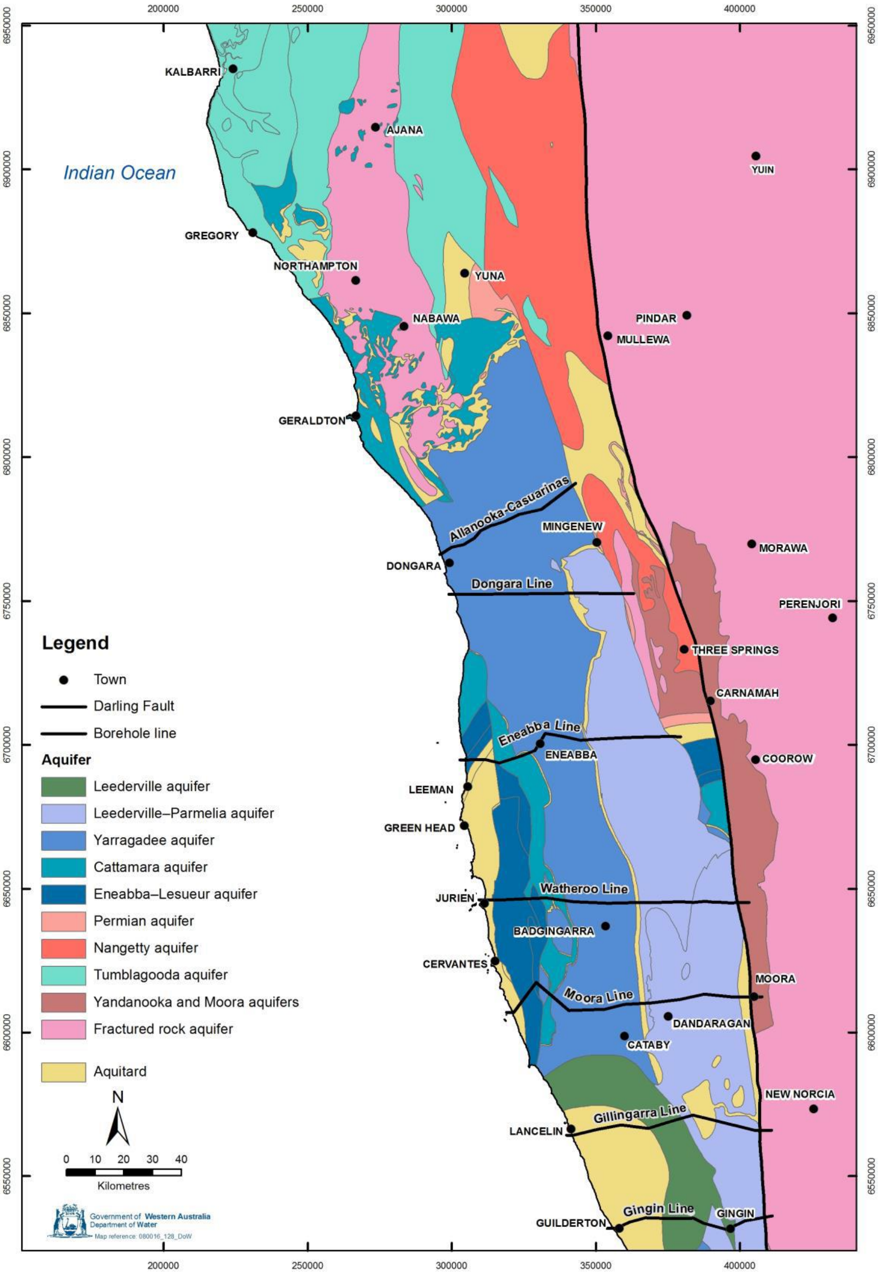
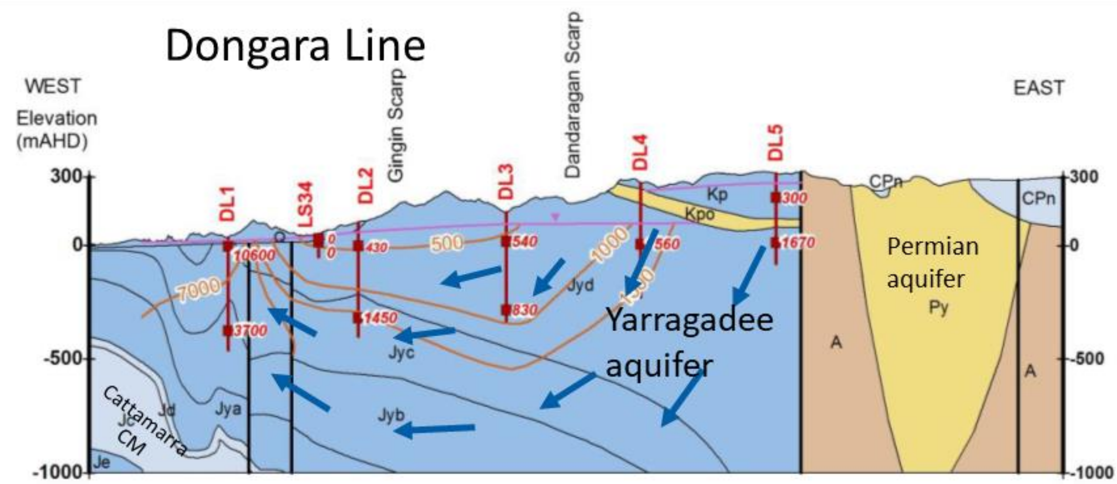
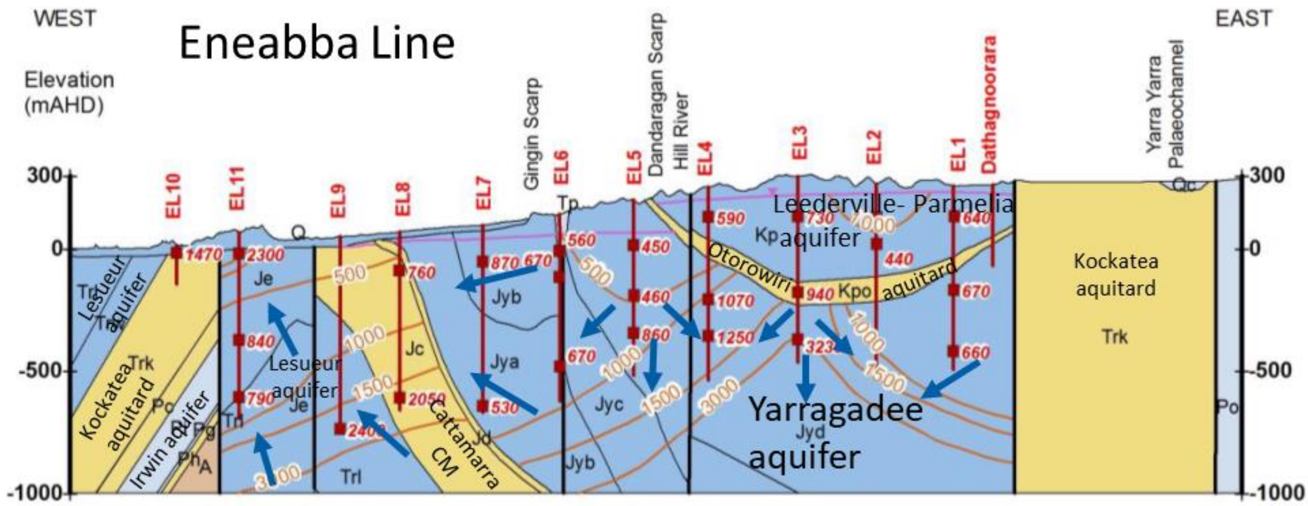


Figure 37. Shallow aquifers and aquitards below superficial formations or surficial deposits (Department of Water, 2017). Also shown are the Dongara, Eneabba and Gillingarra cross-section lines in Figure 38.

a)



b)



c)

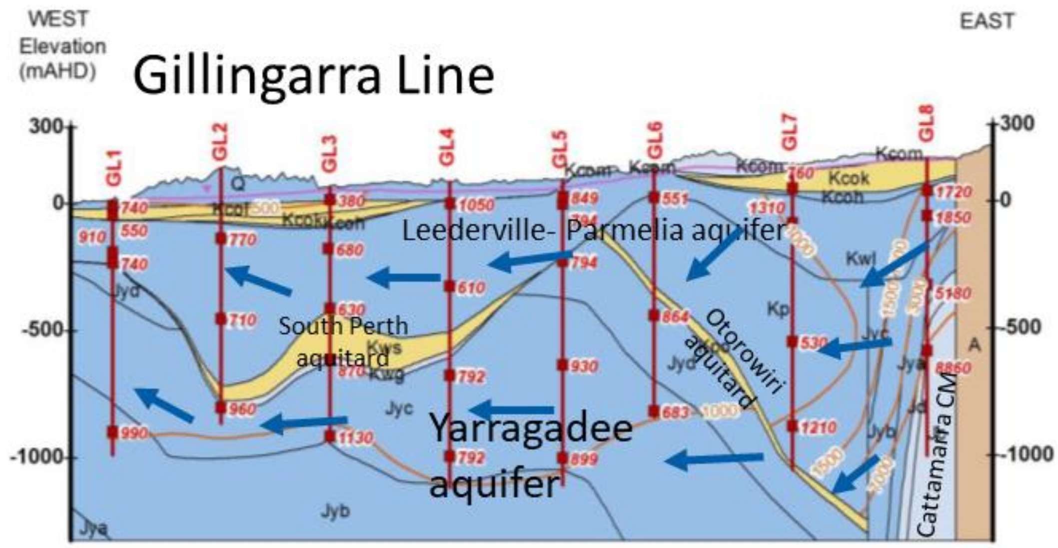


Figure 38. Hydrogeological cross-sections showing salinity (mg/l) distribution and inferred water flow directions (blue arrows): a) Dongara line, b) Eneabba line, c) Gillingarra line. See Figure 37 for location of cross-section lines. Modified from Department of Water (2017).

A natural interface between low-salinity groundwater and denser seawater forms a wedge within any unconfined aquifer along the coastline (Figure 39). The location of the interface is dynamic, moving inland if fresh groundwater flow is reduced by abstraction or low rainfall recharge (seawater intrusion). As a consequence, bores located in fresh groundwater above the seawater wedge or near the inland toe of the wedge may become saline, which poses a risk to coastal communities and groundwater-dependent ecosystems (GDEs) like wetlands (Department of Water, 2017).

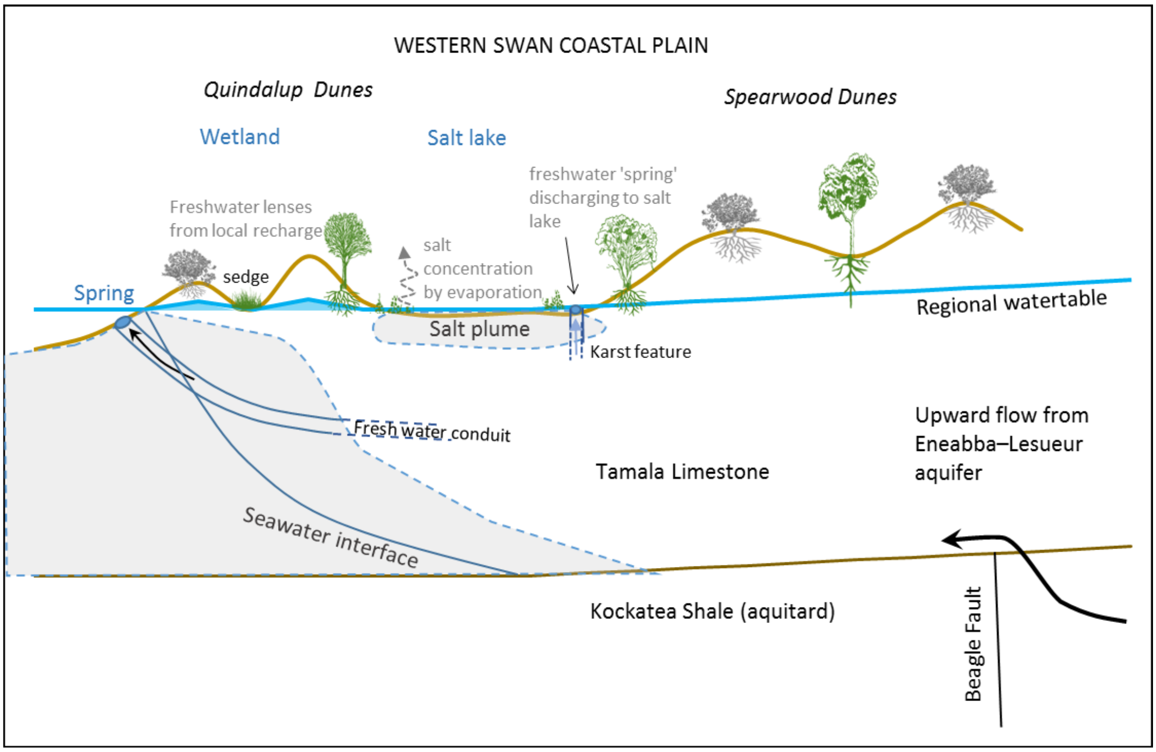


Figure 39. Schematic diagram showing the seawater-groundwater interface in aquifers along the coastline (Department of Water, 2017).

3.5.3. Groundwater management

The northern Perth Basin aquifers supply about 95% of all water used for town water supply, agriculture, mining and petroleum industries (Department of Water, 2017). Licenses to withdraw groundwater by various stakeholders are managed within 4 groundwater management areas: Gnangara, Gingin, Jurien and Arrowsmith (Figure 40).

DWER have developed Water allocation plans for each region that outline how much water can be taken from groundwater and surface water resources, while safeguarding their sustainability and protecting water-dependent environments. Water allocation plans are used to guide individual water licensing decisions and inform how:

- water resources information will be collected
- water management will be adapted to changing circumstances
- water resources can be best used.

Water management plans are currently being updated for Gingin, Jurien and Arrowsmith. Data quoted in this section is largely from 2015–17 publications (Department of Water, 2015a and 2015b; Department of Water, 2017).

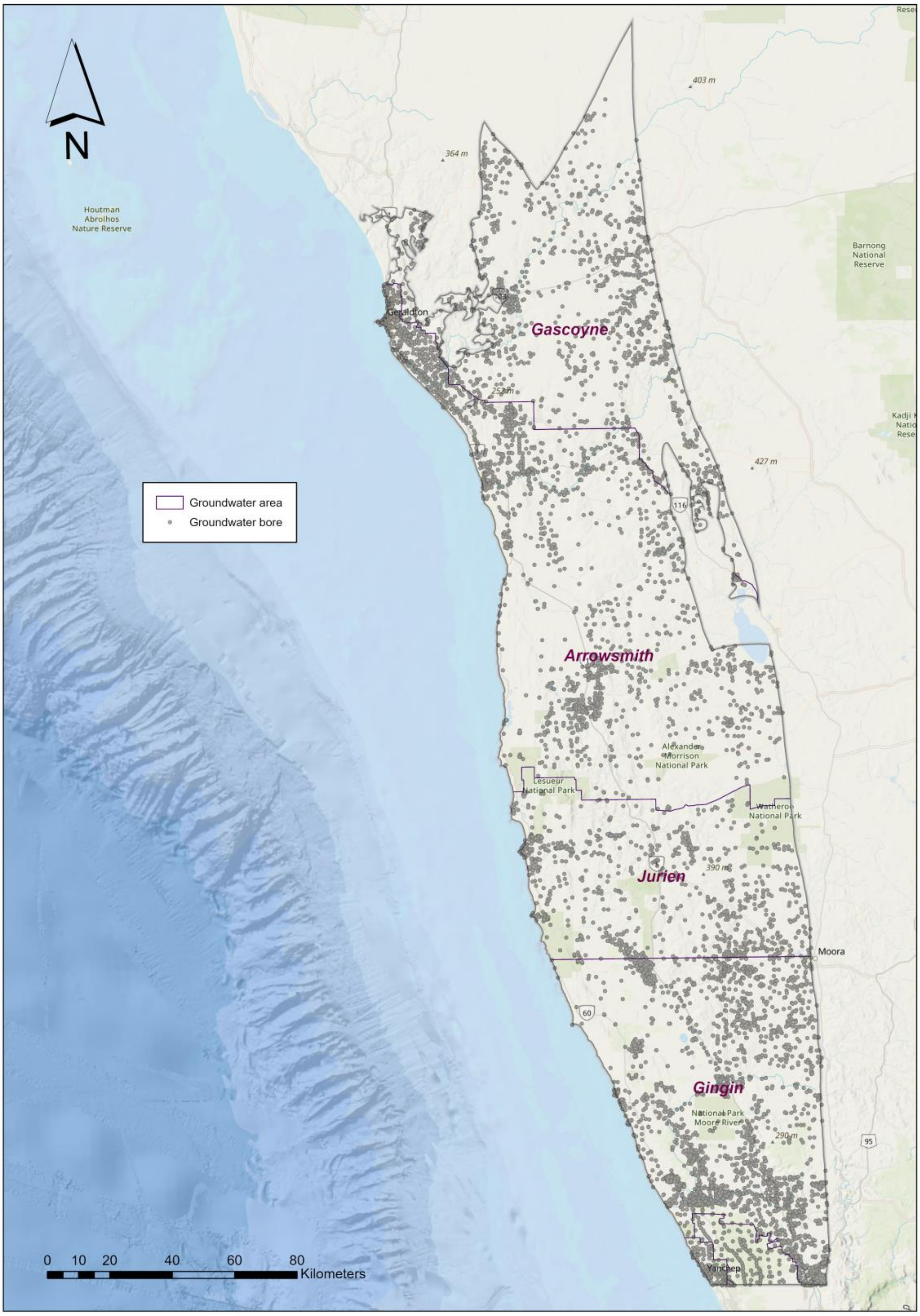


Figure 40. Groundwater management areas in the northern Perth Basin (Rutherford *et al.,* 2005) and distribution of groundwater production wells.

The majority of water wells have been drilled to a depth of less than 100 m (Figure 41). Some deeper water wells (up to 2000 m in depth) were drilled mainly for monitoring purposes or industrial use.

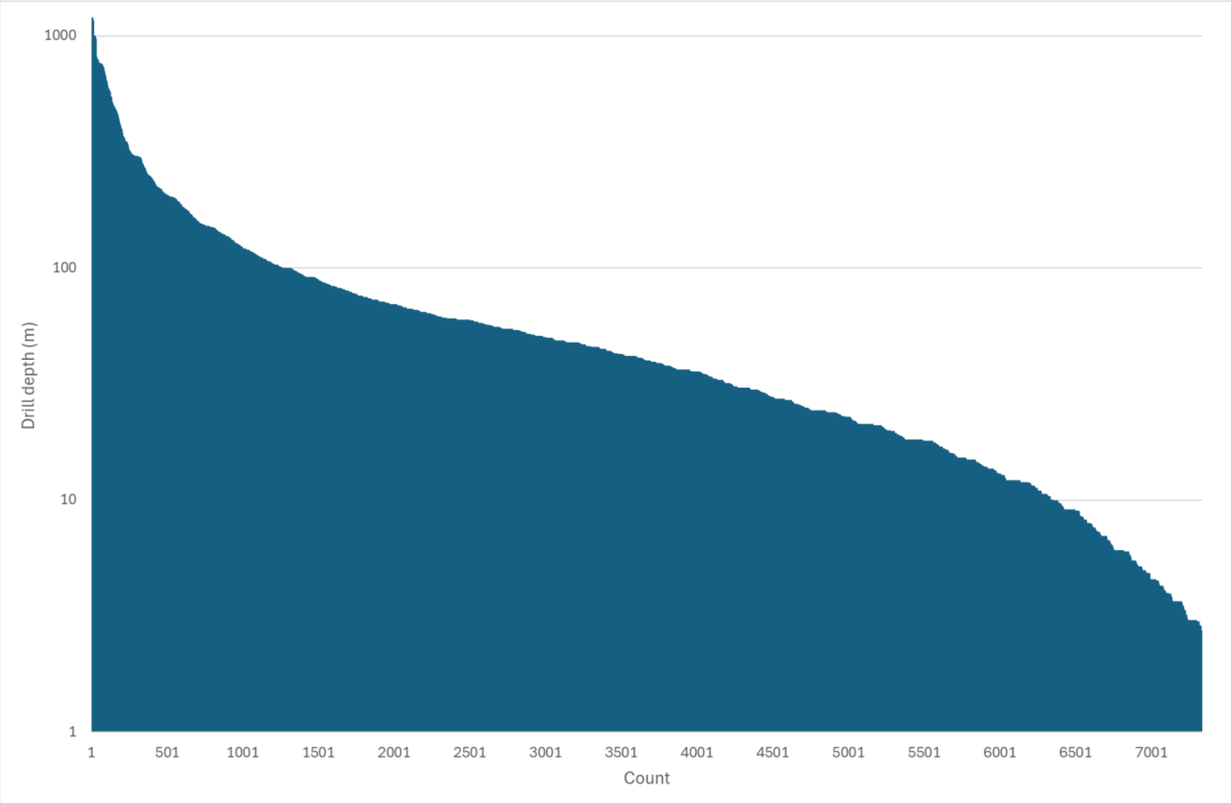


Figure 41. Drilled depth of water wells in the northern Perth Basin. Depth is shown on a logarithmic scale along the y-axis.

Currently, most groundwater withdrawal in the Arrowsmith and Jurien groundwater areas is from the Yarragadee aquifer (Figure 40). Long-term outlooks suggest that water supplies in Geraldton and towns such as Jurien Bay and Morawa are secure until at least 2030, assuming that about 200 GL/year of groundwater will be available to meet anticipated future demands (Department of Water, 2015a). The total volume of water remaining in the region for licensing is greater than the projected demand. However, the proposed water supply options for the port and industrial estate at Oakajee include piping water from the Yarragadee aquifer from outside the Mid West groundwater areas, for example, from north of the Irwin River (in the Allanooka and Casuarinas subareas) or from the Carnarvon Basin, and desalinating seawater onsite (Department of Water, 2015a).

The Midlands groundwater and land assessment is investigating groundwater availability, land capability and crop suitability in the area between Gingin and Dongara as part of the state government's Royalties for Regions Water for Food project. The upper bound of projected demand for irrigated agriculture in the entire Mid West region by 2043 is about 30 GL/year (Department of Water, 2015a).

In the Gingin management area, most groundwater abstraction is from unconfined surficial or superficial aquifers. Future growth is expected, particularly to the north of Gingin, in the western part of the Wheatbelt region. However, there is less than 40 GL/year of groundwater available for further allocation (Department of Water, 2017).

There is scope for increased abstraction from current groundwater sources and for the development of new major sources that are located away from areas of greatest groundwater demand. Potential new sources are mainly within the Superficial aquifer north-east of Lancelin, the unconfined Yarragadee aquifer between the Hill and Irwin rivers and in the coastal Cattamarra and Eneabba-Lesueur aquifers (Department of Water, 2017). Desalination of brackish or saline groundwater could be practical if cheap sources of energy are available.

There are 4 main drivers of future water demand in the northern Perth Basin region, according to the Department of Water (2015a and 2017):

- proposed and planned mining projects
- a potential future port facility and industrial estate at Oakajee (24 km north of Geraldton)
- growth of Geraldton and other rural towns
- northward expansion of irrigated agriculture and horticulture, including the Water for Food Midlands area between Moora and Dongara.

4. Evaluation of resource interactions

As described in the methodology section, the evaluation of resource interaction potential was performed on the basin-scale by investigating the distribution of each subsurface resource in the form of suitability maps, the overlap of resources in a certain geological interval (interaction maps), potential interactions of specific resources (thematic interaction maps) and the cumulative overlap of resources throughout the sedimentary column (cumulative interaction map and integrated cumulative interaction maps) (Figure 19). A more detailed assessment was performed for Dongara, Beharra Springs and Donkey Creek Terraces.

4.1. Basin-scale results

4.1.1. Suitability maps

The suitability maps (Figure 19) provide a foundational assessment of subsurface resource potential across multiple stratigraphic intervals in the northern Perth Basin. The maps define areas where petroleum, CGS, geothermal, UGS, and groundwater resources are most favourable based on geological, structural, and technical factors (Appendix 1: *Suitability*).

Each suitability map highlights high, moderate and low suitability zones for a given resource at a specific interval. The results inform our understanding of resource interactions, forming the primary input for the interaction maps.

Figure 42, Figure 43, Figure 44, and Figure 45 show the suitability maps for the Lower Permian to the Cenozoic intervals.

Figure 46 presents the proportion of each stratigraphic interval that is moderately or highly suitable for specific subsurface resources, based on the suitability maps. The bar charts allow for the direct comparison of resource occurrence across intervals. They illustrate how the availability and distribution of petroleum, CGS, UGS, geothermal, and groundwater change with depth. The distribution of moderate to high suitability across resources reveals distinct patterns of potential use and competition within each stratigraphic interval.

In the Lower and Upper Permian intervals (G1low and G1up, Figure 46), petroleum and CGS both show extensive spatial presence (over 40% of the interval), with geothermal resources also showing significant occurrence (up to 24% of the interval G1up). This co-occurrence increases the likelihood of competition for pore space among these resources. Groundwater is absent in these deeper intervals, therefore no interactions are expected. In the Triassic-Lower Jurassic interval (G2A1), petroleum and CGS show extensive spatial presence, while groundwater appears in around 15% of the interval, suggesting some potential for interactions. However, Figure 44D suggests that the groundwater resource in this interval is geographically isolated from the other resources. In contrast, the younger intervals (A2, abA2 Leederville Parmelia, and abA2 Superficial) are dominated by groundwater, with minimal or no suitability recorded for other subsurface resources. Appendix 2: *Suitability maps description* includes a description of each suitability map.

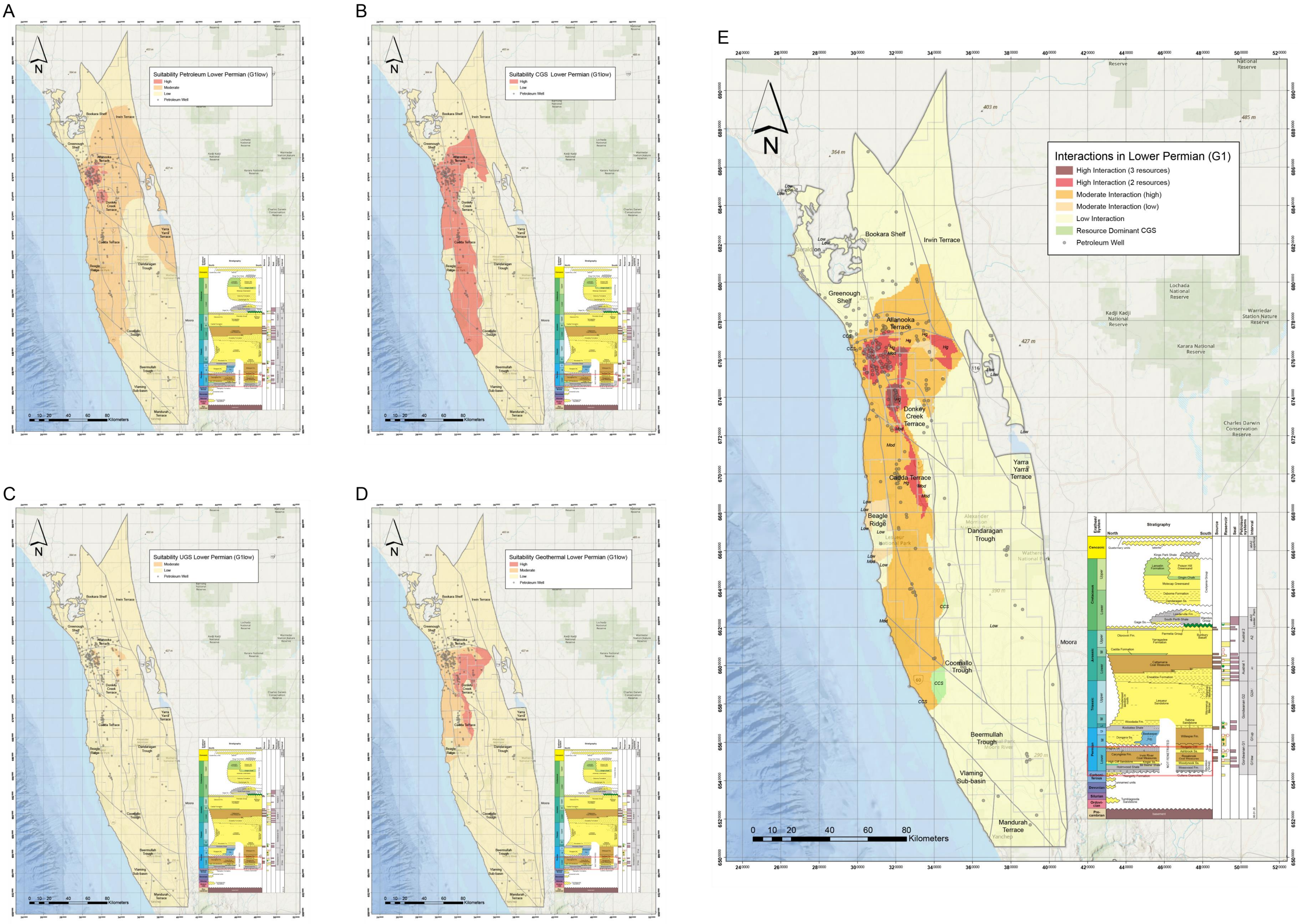


Figure 42. Suitability and interaction maps for the Lower Permian (G1low) interval (descriptions are available in Appendix 2 and Appendix 3): A) petroleum suitability map, B) CGS suitability map, C) UGS suitability map, D) geothermal suitability map, E) interaction map.

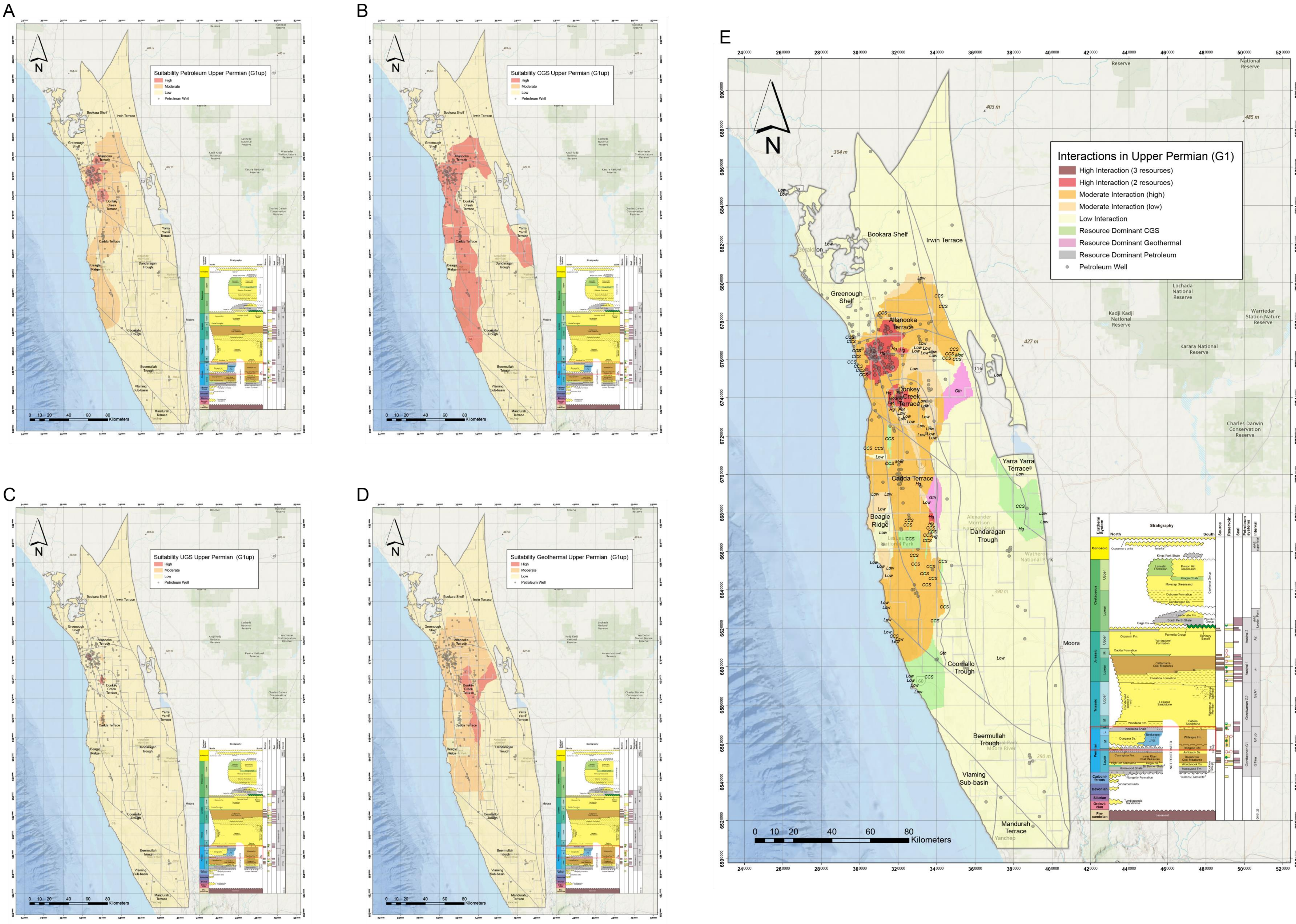


Figure 43. Suitability and interaction maps for the Upper Permian (G1up) interval (description available in Appendix 2 and Appendix 3): A) petroleum suitability map, B) CGS suitability map, C) UGS suitability map, D) geothermal suitability map, E) interaction map.

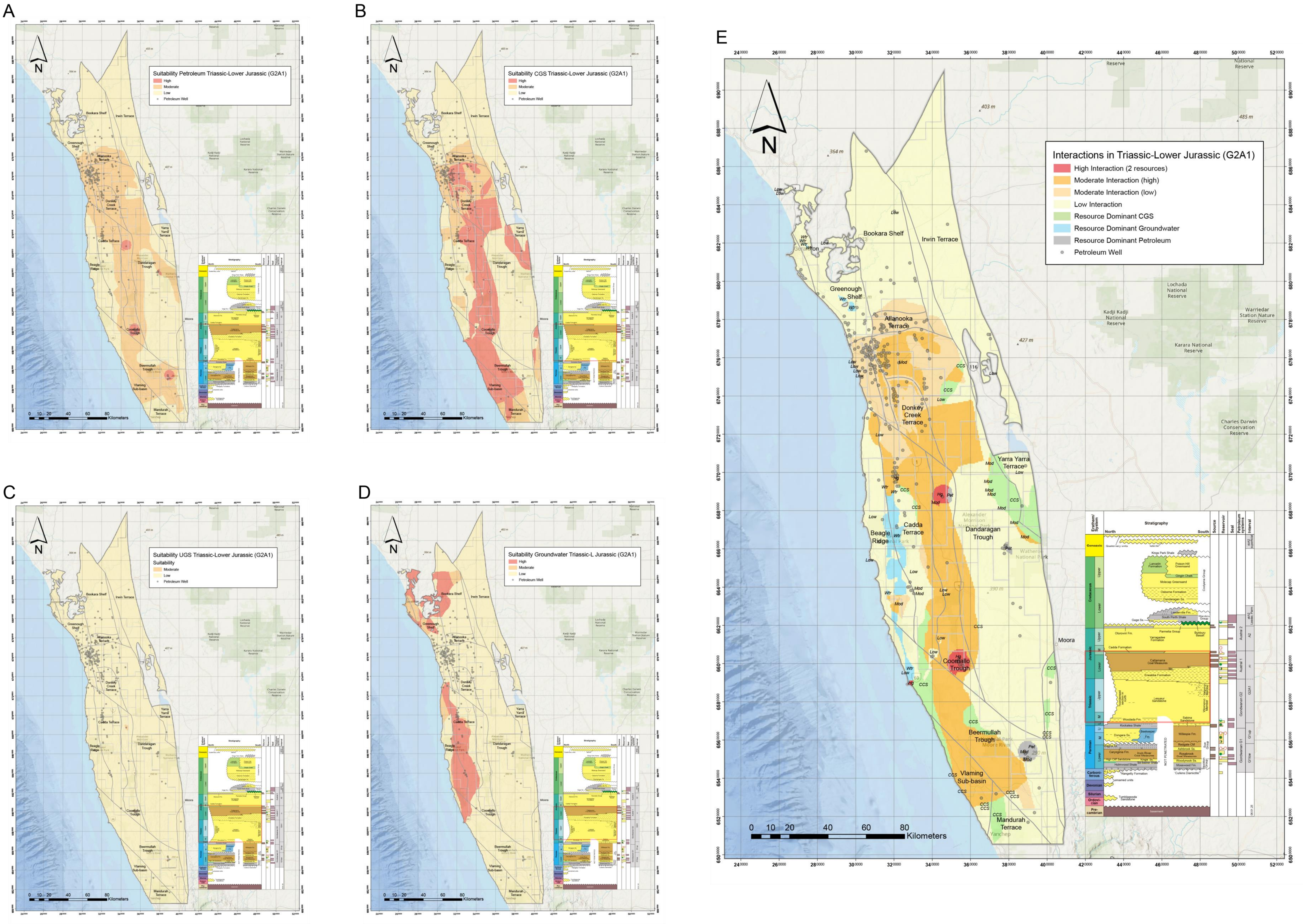
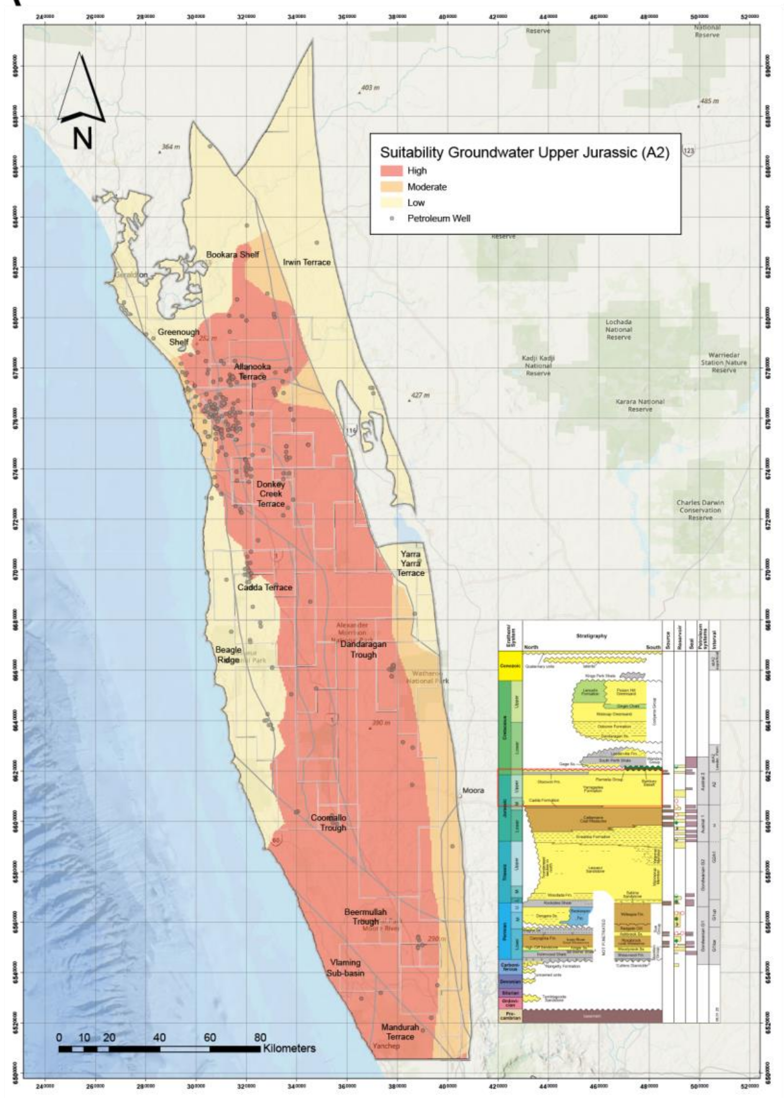
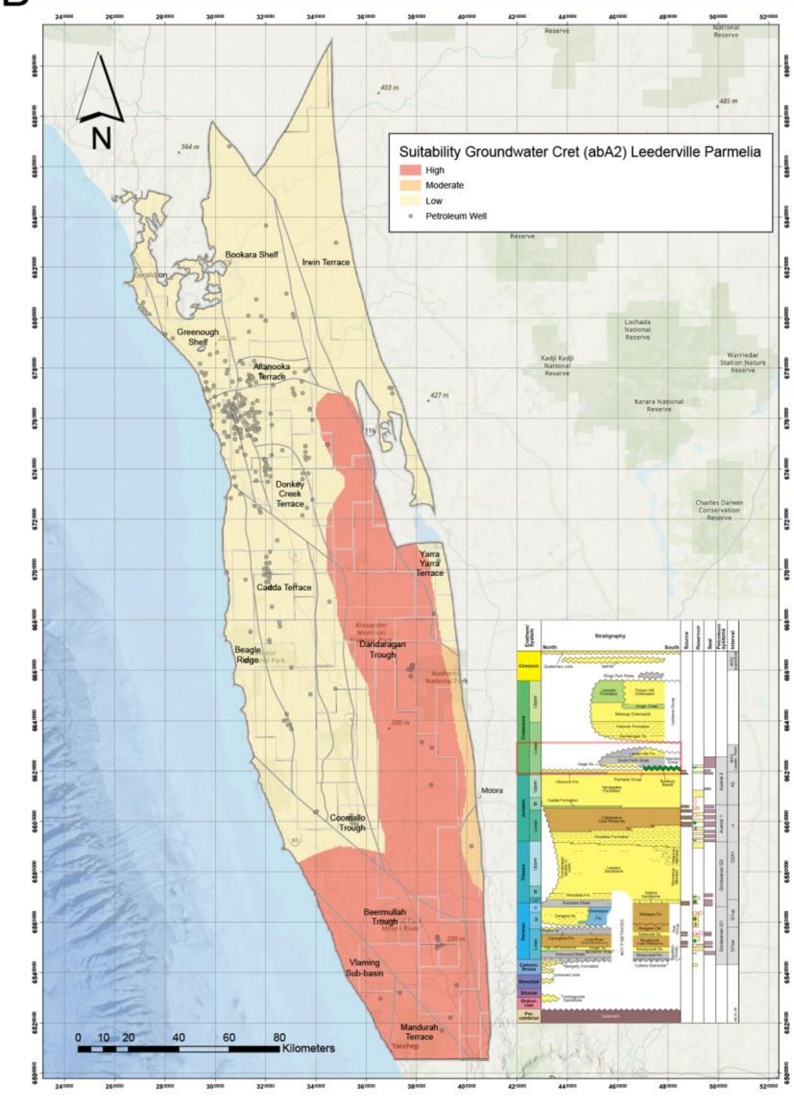


Figure 44. Suitability and interaction maps for the Triassic – Lower Jurassic (G2A1) interval (description in Appendix 2 and Appendix 3): A) petroleum suitability map, B) CGS suitability map, C) UGS suitability map, D) groundwater suitability map, E) interaction map.

A



B



C

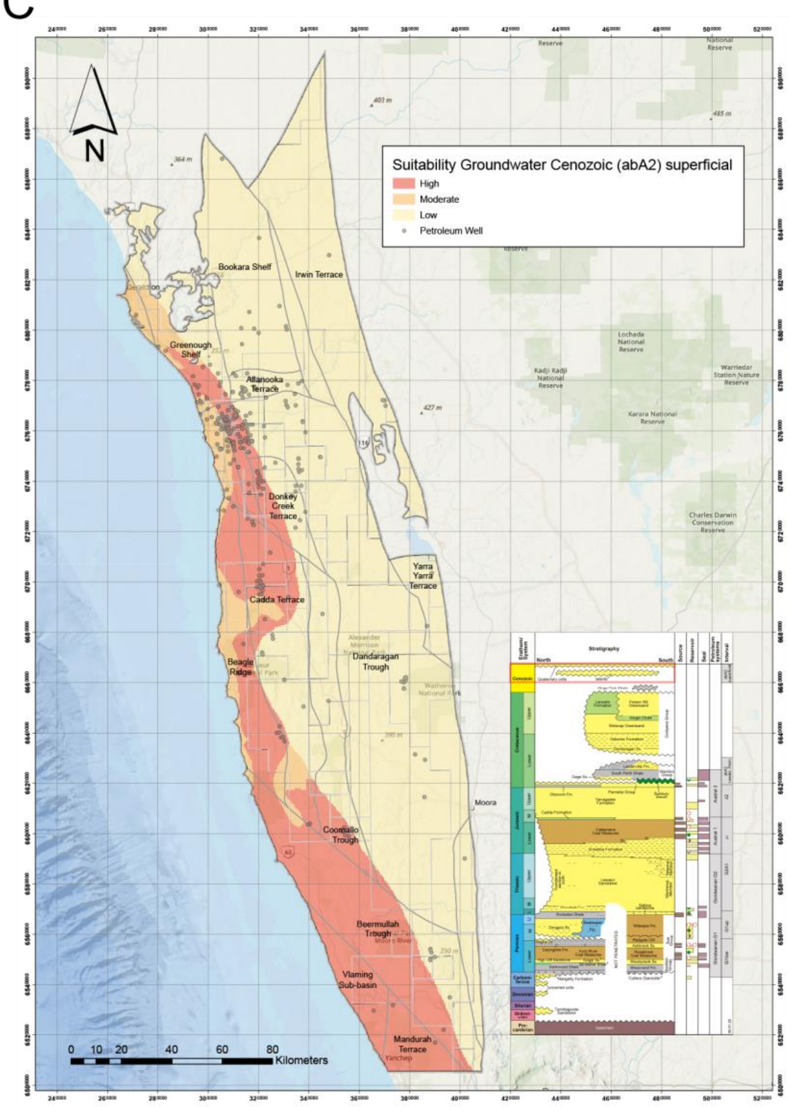


Figure 45. Suitability maps for the groundwater for the Upper Jurassic to Cainozoic intervals (description in Appendix 2): A) Yarragadee aquifer, Upper Jurassic suitability map (A2), B) Leederville-Parmelia aquifer, Lower Cretaceous suitability map (abA2), C) superficial aquifer, Cainozoic suitability map (abA2).

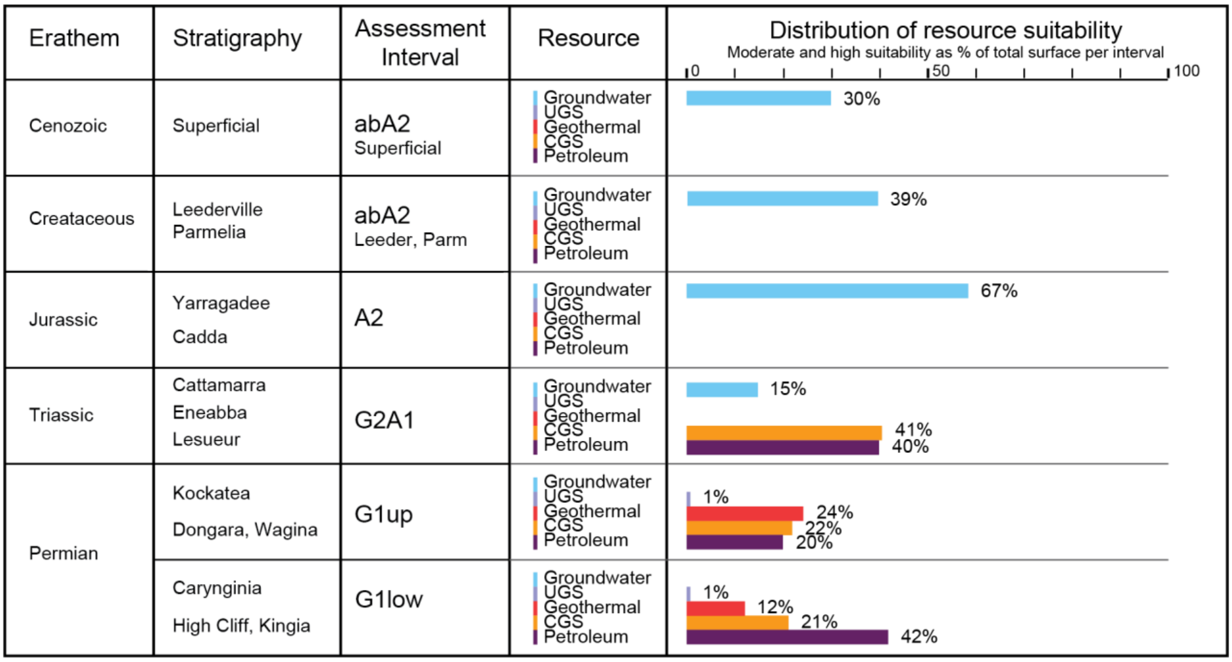


Figure 46. Distribution of resource with moderate to high suitability across assessment intervals.

4.1.2. Interaction maps

The interaction maps (Figure 19) illustrate the spatial relationships between subsurface resources across different stratigraphic intervals. They depict interactions between petroleum, CGS, geothermal, UGS, and groundwater resources to identify areas where resource development may compete or overlap.

Figure 42E, and Figure 43E show the interaction maps from the Lower Permian to the Cenozoic intervals. Appendix 3: *Interaction maps description* includes a detailed description of each suitability map.

The interaction between subsurface resources in the northern Perth Basin varies across stratigraphic intervals, with CGS and petroleum consistently emerging as the most dominant interacting resources. Across all 3 intervals Figure 42E, Figure 43E and Figure 44E), CGS frequently co-occurs with petroleum, reflecting their shared reliance on similar storage formations and sealing units. Geothermal and UGS play a secondary role, appearing more in moderate interaction areas rather than high-interaction zones.

The Lower and Upper Permian intervals (Figure 42E and Figure 43E) exhibit the highest interaction intensities, where CGS and petroleum strongly overlap. This reinforces the potential to repurpose petroleum reservoirs for CO_2 storage. In the Lower Permian interval, CGS is the most dominant interacting resource, while in the Upper Permian interval, petroleum is more prominent.

The Triassic-Lower Jurassic interval (Figure 44E) presents the lowest overall interaction intensity, though CGS and petroleum remain the key interacting resources. Groundwater appears in this interval but has limited overlap with deeper resources, suggesting that interaction risks are generally low. However, local structural features could create pathways that require careful management.

Resource dominance is limited across all intervals, with CGS being the most dominant resource occurring independently of other subsurface uses. This suggests that, in certain locations, CGS suitability is high enough to be considered a primary underground use, independent of petroleum or UGS.

In simple terms, CGS and petroleum are the most significant interacting resources across all intervals, frequently overlapping in shared geological formations. While interaction intensities vary, the overall pattern reinforces the need for integrated resource management to balance petroleum extraction, CO_2 storage and groundwater protection. Understanding these interactions can help minimise conflicts and optimise long-term subsurface resource use.

Description of interactions for the Lower Permian interval (G1low)

The Lower Permian interval (Figure 42E) is characterised by strong interactions between CGS and petroleum, as they frequently share the same underground storage formations. CGS is the most dominant interacting resource in high-interaction cases, appearing in 93% of cases, followed by geothermal resources (64%) and petroleum (52%). This highlights the significant overlap between these energy resources, which could influence future development strategies.

Moderate interactions are far more common than high interactions (24% vs 4%), indicating that indirect resource competition is more prevalent than direct high-intensity overlaps. Petroleum is the dominant resource in moderate interactions, appearing in 100% of cases, followed by CGS (84%) and geothermal resources (43%). The most frequent interaction combination (57%) in this category is petroleum (moderate suitability) and CGS (high suitability), showing that these 2 resources remain closely associated even in lower suitability zones.

Resource dominance is rare, accounting for only 0.5% of all interactions, with CGS as the only dominant resource. This suggests that no single resource overwhelmingly controls the Lower Permian interval, reinforcing the need for integrated subsurface planning.

In summary, CGS and petroleum interact the most in the Lower Permian interval because they depend on the same underground structures for storage and extraction. High-interaction zones are mostly found in Dandaragan Trough, Beharra Springs Terrace, Donkey Creek Terrace and Dongara Terrace, where CGS and petroleum frequently overlap. No groundwater resource is present in the Lower Permian interval. Understanding these interactions can help inform strategies for managing underground space, allowing different energy uses (such as oil extraction and CO_2 storage) to be developed in a coordinated and compatible manner.

Description of interactions for the Upper Permian interval (G1up)

The Upper Permian interval (Figure 43E) is characterised by strong interactions between petroleum and CGS, with petroleum appearing in 97% of all high-interaction cases. CGS (87%) and geothermal resources (11%) also play significant roles, though geothermal has a lesser influence in direct high interactions. These trends suggest that petroleum and CGS continue to share underground space, reinforcing the importance of coordinated planning.

Moderate interactions are more frequent, accounting for 21% of all interactions, and are mostly Petroleum-dominated. The most common moderate interaction combination (42%) is petroleum (moderate suitability), CGS (high suitability), and geothermal (moderate suitability), indicating that geothermal resources play a stronger role in moderate suitability zones compared to high-interaction areas.

Resource dominance is observed in 6% of cases, with CGS being the most dominant resource. This suggests that in certain areas, CGS suitability is high enough to be considered a primary underground use, independent of other resources.

Overall, petroleum and CGS have the strongest interactions in this interval, with geothermal resources playing a more moderate role compared to petroleum and CGS. High-interaction zones align with known oil and gas accumulations, reinforcing the need for integrated management of CO_2 storage and petroleum production. Understanding these interactions can help balance future energy extraction, carbon storage, and potential geothermal development in the Upper Permian interval.

Description of interactions for the Triassic-Lower Jurassic interval (G2A1)

Overall, the Triassic-Lower Jurassic interval (Figure 44E) presents lower interaction intensity compared to the Permian interval, with high-interaction cases accounting for only 0.7% of all interactions. CGS is the dominant resource in high-interaction zones (100%), reinforcing its role as a primary subsurface use. Petroleum (97%) also plays a significant role, while groundwater (3%) has limited direct overlap with other resources.

Moderate interactions are more common (31%), with petroleum and CGS being the most frequently co-occurring resources. The most common moderate interaction combination (68%) is petroleum (moderate suitability) and CGS (high suitability), showing that CGS remains a key factor in defining underground use in this interval.

Resource dominance is present in 6% of cases, with CGS being the most dominant resource. This suggests that while CGS is a major player, it does not completely control subsurface use in this interval.

Simply put, this interval has fewer high-interaction areas than the Lower and Upper Permian intervals, with CGS and petroleum continuing to be the most significant resources. No geothermal resource is present in the Triassic-Lower Jurassic interval. Groundwater has minimal overlap with other subsurface resources, but where it does interact, it requires careful management to ensure resource compatibility. Understanding these interactions can help balance petroleum development, CO_2 storage, and groundwater protection in the Triassic-Lower Jurassic intervals.

4.1.3. Thematic interaction maps

The thematic interaction maps (Figure 19) highlight areas of high and moderate suitability for specific resources, as well as interactions with other resources. These maps provide a more detailed, granular view of resource interaction patterns across different intervals.

Figure 47 shows the thematic interaction maps from the Lower Permian to Lower Jurassic intervals. Appendix 4: Thematic interaction maps description includes a detailed description of each interaction map.

Description of petroleum interactions for the Lower Permian interval (G1low)

Petroleum in the Lower Permian interval (Figure 47A) always interacts with at least one other resource, most frequently CGS (86%), followed by geothermal resources (30%). This strong correlation with CGS suggests that many historical petroleum fields could be viable for future CO_2 storage projects.

Moderate suitability petroleum covers a large portion of the basin (41%), with 48% interacting with CGS and 27% interacting with geothermal resources. However, 18% of moderate suitability petroleum occurs in isolation, indicating the presence of some standalone hydrocarbon zones.

In other words, petroleum in this interval is almost always linked to CGS, reinforcing the potential for repurposing oil and gas fields for CO_2 storage. Understanding these interactions is key to managing the transition between fossil fuel extraction and carbon sequestration, ensuring a balance between resource use and emissions reduction.

Description of CGS Interactions for the Lower Permian interval (G1up)

CGS in the Lower Permian interval (Figure 47B) interacts significantly with petroleum, with 98% overlap of high suitability CGS areas with petroleum zones. This highlights the strong geological link between CGS and petroleum reservoirs, as they often share the same storage formations and sealing units. Geothermal resources play a secondary role, interacting with 41% of high suitability CGS areas.

A small portion (2%) of high suitability CGS areas do not exhibit interactions, mainly in the Cadda Terrace and Beermullah Trough, suggesting some potential for independent storage sites.

Put simply, CGS in the Lower Permian interval is almost always found alongside petroleum, reinforcing the need for careful planning when repurposing former oil and gas fields for CO_2 storage. Understanding these interactions is essential for balancing hydrocarbon extraction with long-term carbon storage goals.

Description of petroleum interactions for the Upper Permian interval (G1up)

Petroleum in the Upper Permian interval (Figure 47C) interacts most frequently with geothermal resources (95%) and CGS (80%), indicating significant overlap between hydrocarbon reservoirs, CO_2 storage potential and geothermal energy sources. These interactions are strongest in Allanooka Terrace, Dongara Terrace, Beharra Springs Terrace, Dandaragan Trough and Donkey Creek Terrace, where known oil and gas accumulations align with high geological suitability for other resources.

Despite these overlaps, 0.4% of high-suitability petroleum areas exist without interactions, indicating that, while rare, some independent hydrocarbon zones remain.

In simple terms, petroleum in this interval is closely linked to both CGS and geothermal resources, meaning future energy projects must consider how oil and gas extraction, CO_2 storage and geothermal development can coexist. Understanding these interactions is critical to optimising subsurface resource use while ensuring sustainable energy development.

Description of CGS interactions for the Upper Permian interval (G1up)

The Upper Permian interval (Figure 47D) shows a strong interaction between CGS, geothermal resources and petroleum, with 61% of high suitability CGS areas overlapping with geothermal resources and 55% with petroleum. The moderate proportion of isolated CGS zones (20%) suggests that some areas remain geologically distinct, offering potential standalone storage opportunities.

Put simply, CGS in the Upper Permian interval is highly connected to both geothermal and petroleum resources, meaning they often coexist in the same geological formations. Any future CGS storage or geothermal development must consider these overlaps to ensure efficient resource management. Understanding these interactions is critical for optimising underground storage while balancing energy production and carbon storage goals.

Description of petroleum interactions for the Triassic-Lower Jurassic interval (G2A1)

The Triassic-Lower Jurassic interval (Figure 47E) exhibits lower interaction intensity than the Permian intervals, with petroleum interacting with CGS in 61% of high suitability cases and 78% in moderate suitability zones. Unlike deeper layers, 37% of high suitability petroleum is found in isolation, indicating more localised accumulation patterns.

In other words, petroleum in this interval has fewer high interactions than in the Permian interval, but still shares significant overlap with CGS. The limited interaction with groundwater suggests lower risk to water resources, though any CGS or oil development in this zone must still be managed carefully. Understanding these interactions is essential for ensuring the sustainable development of petroleum and CGS while protecting groundwater supplies.

Description of CGS interactions for the Triassic-Lower Jurassic interval (G2A1)

CGS in the Triassic-Lower Jurassic interval (Figure 47F) continues to interact predominantly with petroleum (81%), but with minimal interaction with groundwater (1%). The 19% of isolated high suitability CGS areas suggest that there are pockets of potential standalone storage sites that are less likely to be influenced by extraction of other resources.

In simple terms, CGS in this interval shares underground space mostly with petroleum, while its overlap with groundwater is limited. This means that CGS storage sites in this interval may pose less risk of water contamination, making them more favourable for long-term CO_2 storage. Understanding these interactions is crucial for selecting optimal CGS storage locations and ensuring they do not interfere with existing petroleum or water resources.

Description of groundwater interactions for the Triassic-Lower Jurassic interval (G2A1)

Groundwater in the Triassic-Lower Jurassic interval (Figure 47G) is largely independent of other subsurface resources, with 66% of high suitability groundwater areas having no interaction. When interactions do occur, they are mostly with petroleum and CGS (23% each), highlighting the potential for hydrocarbon development and CO_2 storage to impact groundwater systems in specific locations.

The Beagle Ridge, Cadda Terrace and Beermullah Trough contain the largest isolated groundwater zones, where no interaction is observed. These areas may represent important groundwater reserves that should be protected from subsurface development.

In summary, groundwater in this interval is mostly separate from other subsurface resources, but where it overlaps with petroleum and CGS, careful planning is needed to protect water quality. Understanding these interactions is crucial for ensuring safe groundwater management while balancing energy and storage needs.

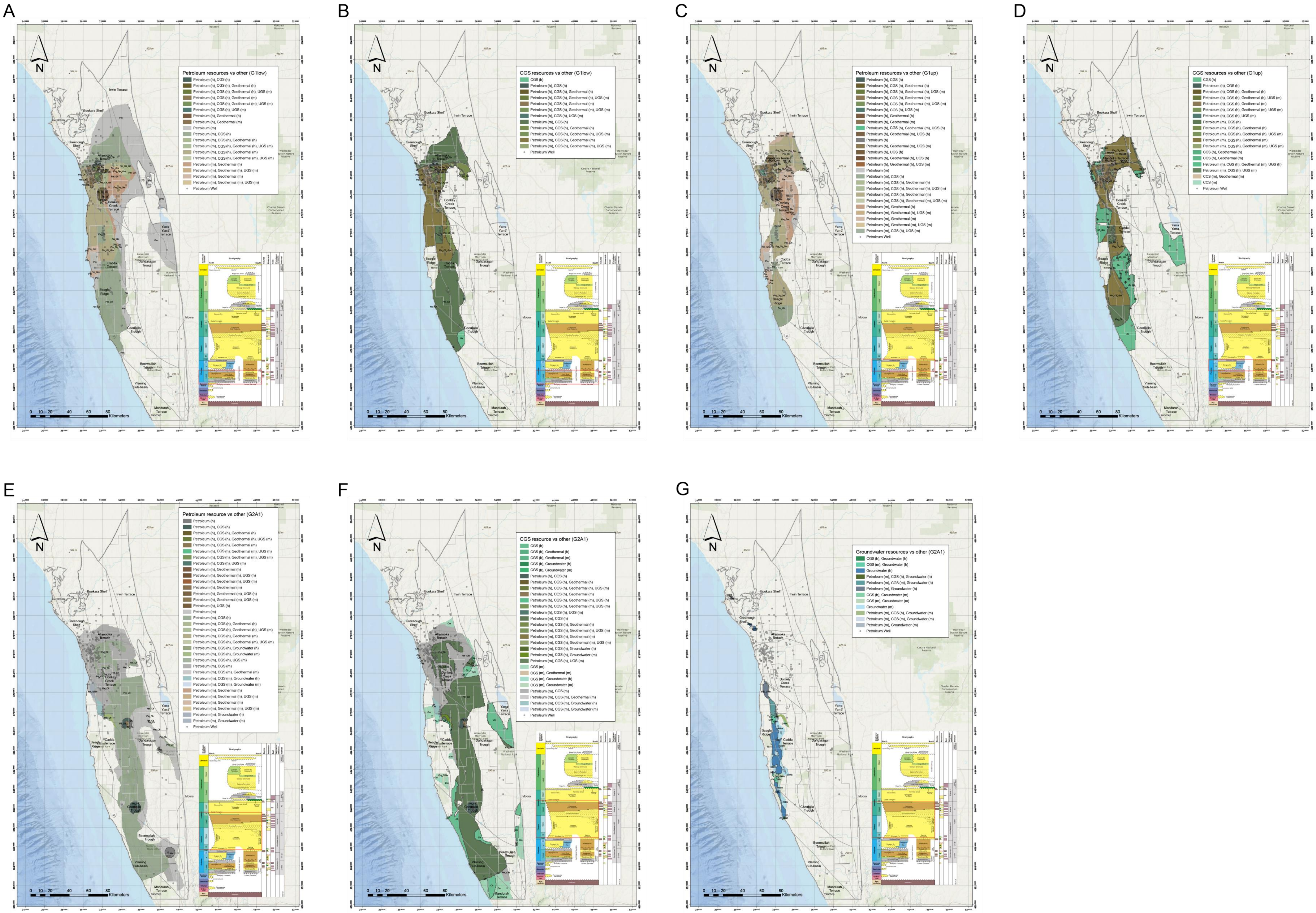


Figure 47. Thematic interaction maps (description available in Appendix 4). On the maps, the resources are labelled P (petroleum), C (CGS), G (geothermal), U (UGS), GW (groundwater), h (high suitability), and m (moderate suitability). A) Interaction with petroleum resources in the Lower Permian interval (G1low), B) interaction with CGS resources in the Lower Permian interval (G1low), C) interaction with petroleum resources in the Upper Permian interval (G1up), D) interaction with CGS resources in the Upper Permian interval (G1up), E) interaction with petroleum resources in the Triassic-Lower Jurassic interval (G2A1), F) interaction with CGS resources in the Triassic-Lower Jurassic interval (G2A1), and G) interaction with groundwater resources in the Triassic-Lower Jurassic interval (G2A1).

4.1.4. Cumulative interaction map

The cumulative interaction map (Figure 48) aggregates interaction data across 3 stratigraphic intervals (Lower Permian (G1low), Upper Permian (G1up), and Triassic-Lower Jurassic (G2A1)). It provides a basin-wide view of potential competition between deep subsurface resources, including petroleum, CGS, UGS, geothermal energy and (to a lesser extent) groundwater. By combining resource suitability across intervals, the map highlights areas where multiple subsurface uses may coexist or conflict.

Overall, high-interaction zones represent approximately 5% of the basin. These areas are dominated by petroleum and CGS suitability, and typically correspond to shared structural traps and reservoir-seal systems. This reinforces the geological connection between hydrocarbon accumulations and future CO_2 storage potential. Moderate interaction zones, representing 20% of the basin, form a buffer around the high-interaction clusters and are more strongly associated with geothermal and UGS suitability. These areas present opportunities for alternative resource development but may still require coordinated planning to avoid indirect competition.

Spatially, the most prominent high-interaction cluster is located east and southeast of Dongara, covering the Allanooka Terrace, Dandaragan Trough, Beharra Springs Terrace, Dongara Terrace, and Donkey Creek Terrace. This area aligns with historical petroleum fields and infrastructure in Permian reservoirs. An elongated high-interaction corridor extends south through the Cadda Terrace, Coomallo Trough and Beermullah Trough, where co-suitability for petroleum and CGS is also high. The moderate interaction belt surrounds these high-stress areas and includes zones such as the Wicherina Terrace, Bookara Shelf, Greenough Shelf, Beagle Ridge and Yarra Yarra Terrace.

These observed patterns suggest that legacy petroleum areas, east and southeast of Dongara, could serve as key locations for future CGS projects. They also highlight the importance of managing overlapping resource claims. The broader moderate interaction belt offers flexibility for alternative resource use, but still warrants case-by-case evaluation. While groundwater plays a limited role in this particular map (Figure 48), the presence of deep resource interactions beneath major aquifers emphasises the importance of considering potential soft interactions, especially in areas where vertical migration pathways may be present.

4.1.5. Integrated maps

To enhance the assessment of subsurface resource interactions, 2 additional factors have been integrated into the cumulative interaction map: groundwater demand and potential migration pathways. The resulting integrated cumulative interaction maps (Figure 49 and Figure 50) offer a more comprehensive view of resource pressure zones, particularly in areas where deep energy resources may have an indirect impact on groundwater systems. This includes both demand-driven stress (where resource development overlaps with intensive groundwater use) and ‘soft’ interactions (see methodology, integrated cumulative interaction maps), where deep and shallow resources may be connected via vertical pathways such as faults or petroleum wells. The 2 integrated map types (groundwater demand and migration pathways) highlight areas where such interactions are more likely.

Groundwater demand

To evaluate where groundwater extraction and deep subsurface resource development may coincide, the cumulative interaction map was combined with bore density data, serving as a proxy for groundwater use intensity. This reveals dual-resource stress zones, where both energy development and water demand may compete (Figure 49).

Key areas of concern include:

- Inland of Dongara (Figure 49C), where regions of high-interaction overlap directly with high bore density (Figure 49A and B).
- East of Leeman (Figure 49C), where groundwater demand intersects with a corridor of high deep resource suitability along the Cadda Terrace.

Migration pathways

To assess the potential for vertical connectivity between deep and shallow systems, a second set of integrated maps incorporates structural features and well infrastructure as possible migration pathways. These include:

- Faults displacing the Cadda and Kockatea seals, which may juxtapose deep reservoirs with overlying aquifers and/or where damage zones with increased structural permeability could facilitate vertical fluid movement (Faulkner *et al.,* 2010) (Figure 50A).
- Petroleum wells penetrating Permian reservoirs, which could act as conduits for vertical fluid movement (Figure 50B).

A major convergence of faults and high well density occurs inland of Dongara, across the Donkey Creek, Beharra Springs and Dongara Terraces (Figure 50A and Figure 50B). A secondary zone of concern lies along the Cadda Terrace, where large faults could compromise seal integrity (Figure 50A and Figure 50B).

No site-specific well integrity or geomechanical assessments were conducted. All wells were treated uniformly, and no fault seal analysis was applied. This reinforces the first-order, basin-scale nature of the analysis. Nonetheless, the map provides a valuable tool for highlighting zones where deep resource development may require additional scrutiny due to potential migration risks.

Soft interaction to aquifers

To evaluate potential soft interactions between deeper resources and shallow groundwater, the pathway-integrated map (Figure 50D) was compared against major aquifer boundaries (Lesueur-Eneabba-Cattamarra, Yarragadee, Leederville-Parmelia and Superficial aquifers) (Figure 51). These aquifers include freshwater and saline or brackish zones, with salinities up to 14,000 mg/l (Department of Water, 2017).

The degree of overlap between migration pathways and aquifer distribution varies across the basin:

- **Lesueur-Eneabba-Cattamarra aquifer** (Figure **51**A)**:** Extends across the western-central portion of the basin, mostly overlapping moderate migration pathway zones and resource interaction zones, suggesting limited deep-shallow connectivity.

- **Yarragadee aquifer** (Figure **51**B)**:** Covers most of the northern Perth Basin, aligning with high and moderate migration pathway zones and resource interaction zones, indicating a greater likelihood of soft interactions if migration pathways exist.
- **Leederville-Parmelia aquifers** (Figure **51**C)**:** Located in the eastern and southern basin margins, primarily overlapping low to moderate migration pathway zones and resource interaction zones, suggesting minimal connectivity to deep resource units.
- **Superficial aquifer** (Figure **51** D)**:** Found along the coastal regions from Greenough Shelf to Mandurah Terrace, exhibiting variable overlap with high to low migration pathway zones, reflecting spatially dependent soft interaction potential.

These integrated analyses do not confirm active fluid migration, but rather, highlight areas where geological and well infrastructure features could facilitate interactions between deep resources and shallower aquifers. Future assessments should incorporate high-resolution structural models, well integrity assessments and site-specific hydrogeological data to refine predictions of potential migration risks and resource coexistence.

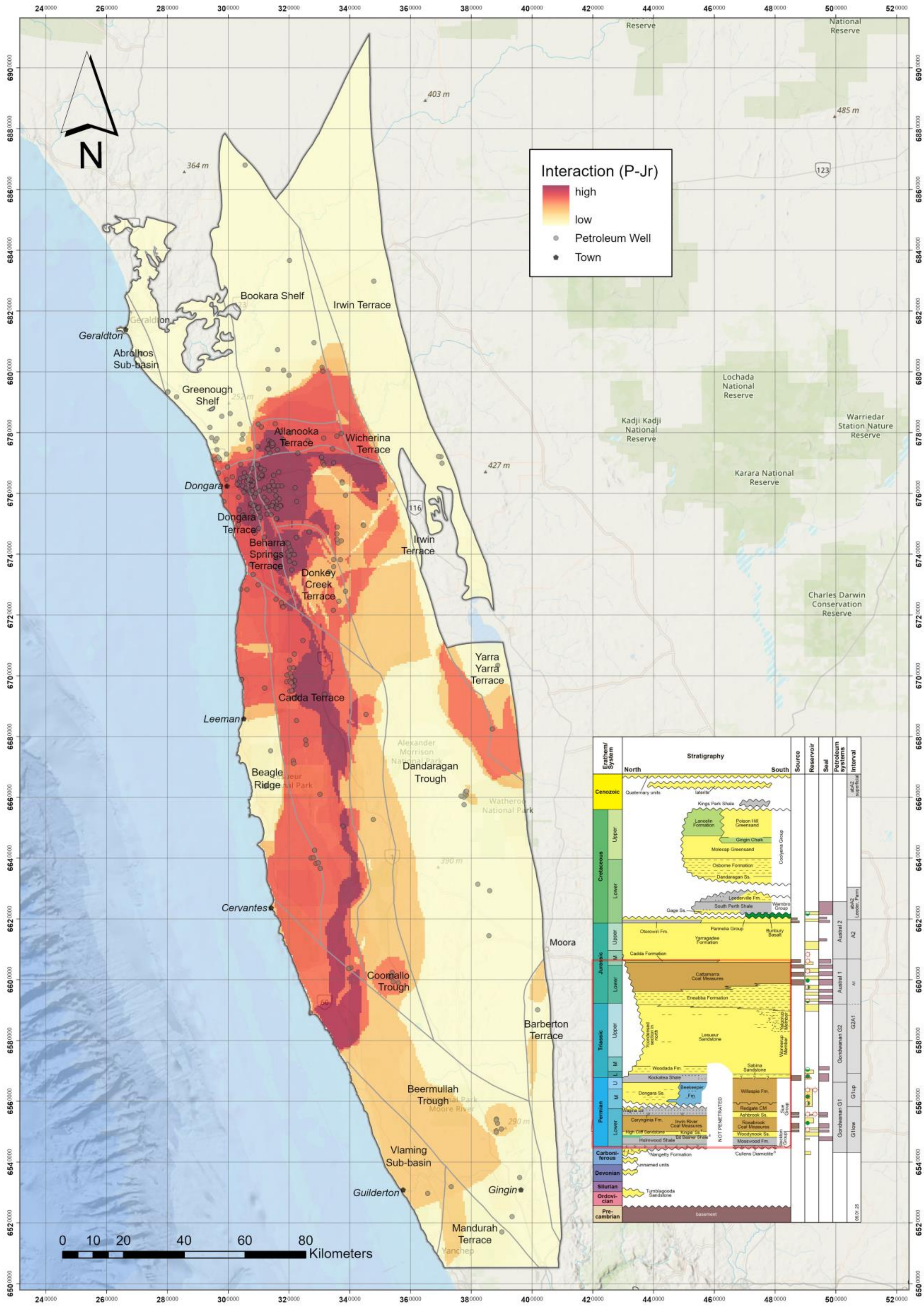


Figure 48. Cumulative interaction map for the Lower Permian-Lower Jurassic intervals (G1low, G1up, G2A1).

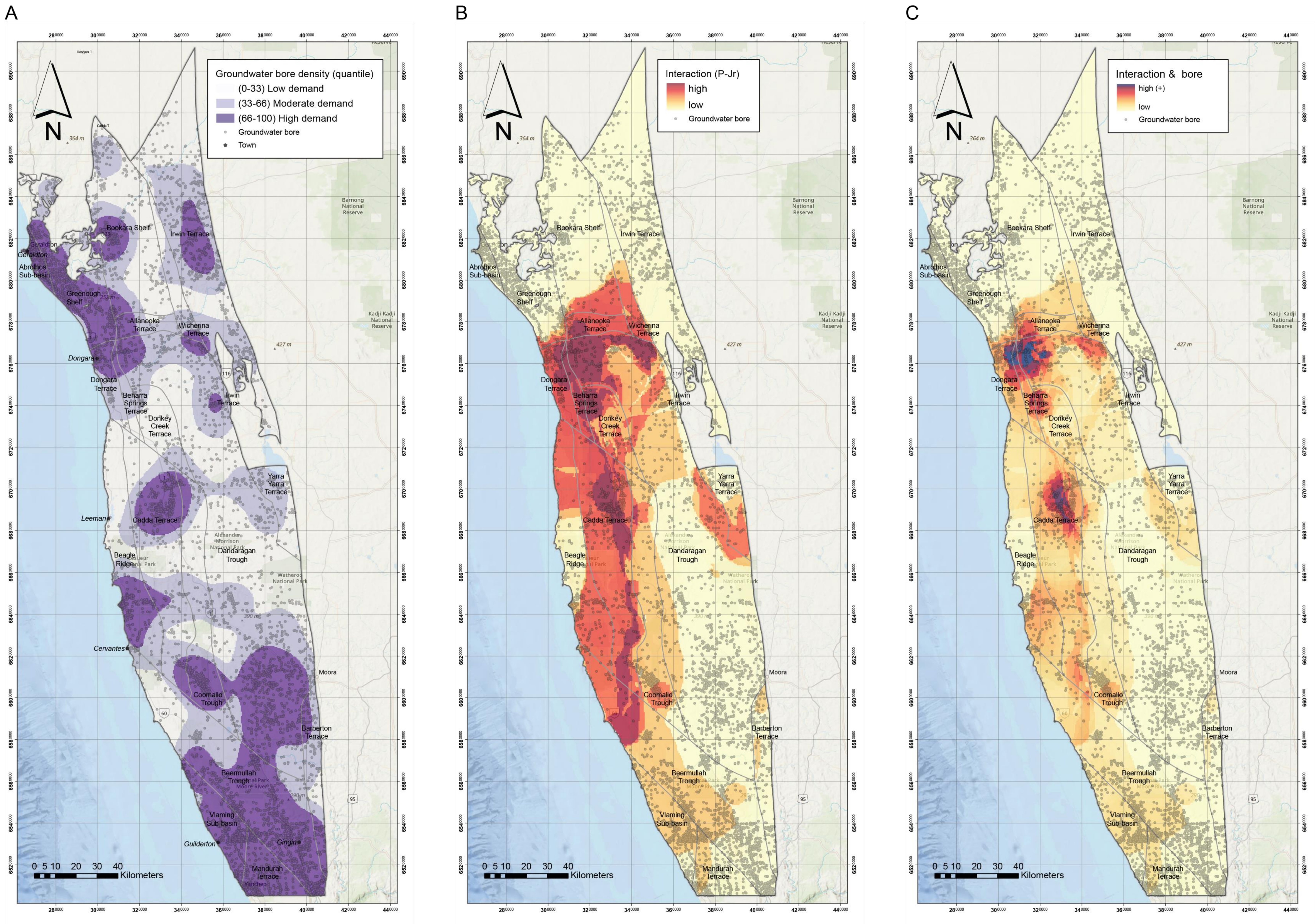


Figure 49. Integration of groundwater demand and resource cumulative interaction. A) Groundwater bore distribution and density (shown as quantiles), used as proxy for water usage, B) cumulative interaction map (Figure 48) and groundwater bores, C) integrated map, interaction and bore; bore density is reclassified and used to adjust the deep resource cumulative interactions for water use intensity. Warmer colours indicate a higher potential for dual-resource stress between deeper resources and shallow aquifers.

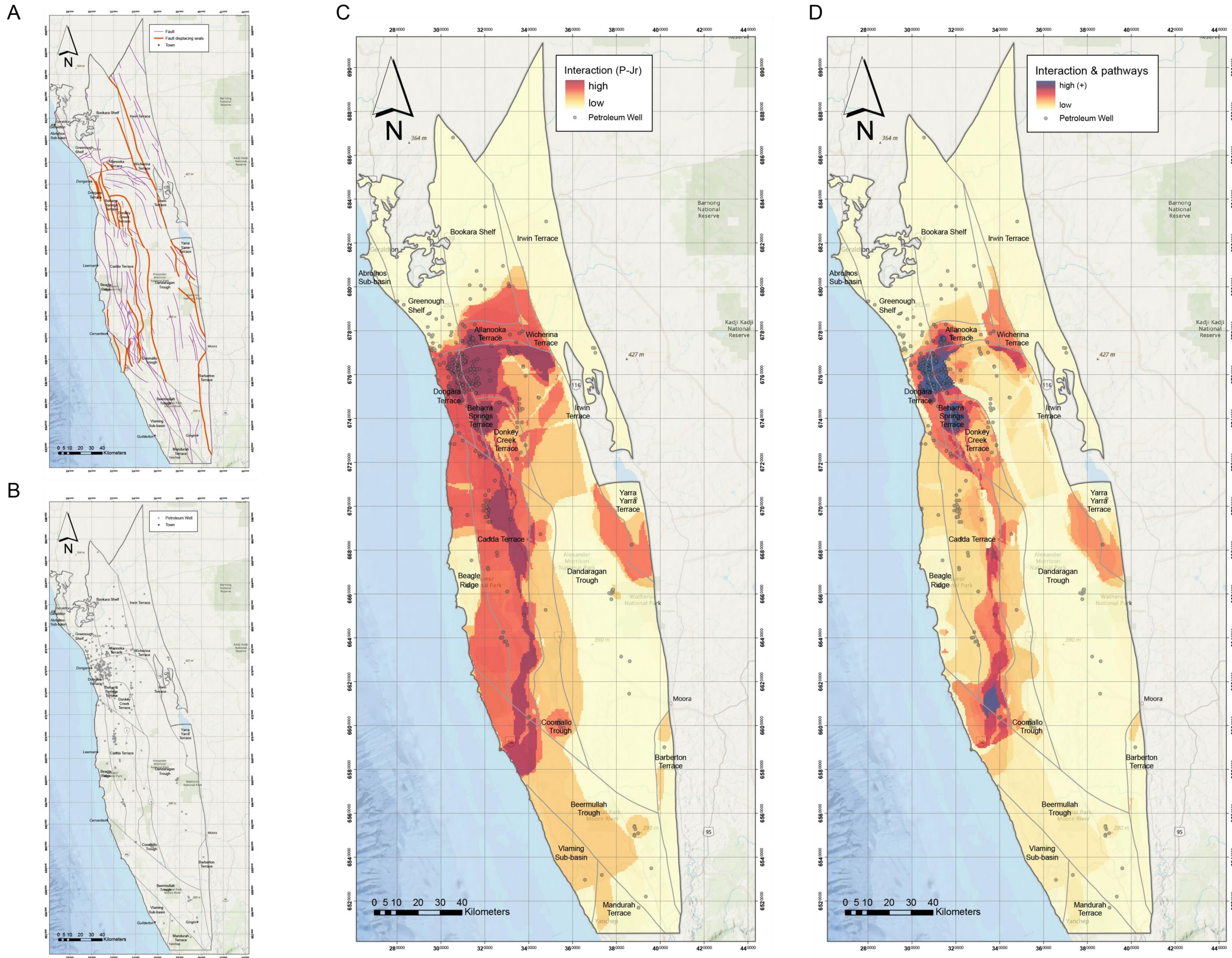


Figure 50. Integration of potential pathways and resource cumulative interaction. A) Distribution of faults potentially acting as migration pathways; regional faults (purple) and fault displacing the Cadda and Kockatea seals (red), B) distribution of petroleum wells potentially acting as migration pathways, C) cumulative interaction map, D) integrated map, interaction and pathways; pathway density is reclassified and used to adjust the deep resource cumulative interactions for pathways intensity. Warmer colours indicate a higher potential for vertical migration of deeper resources.

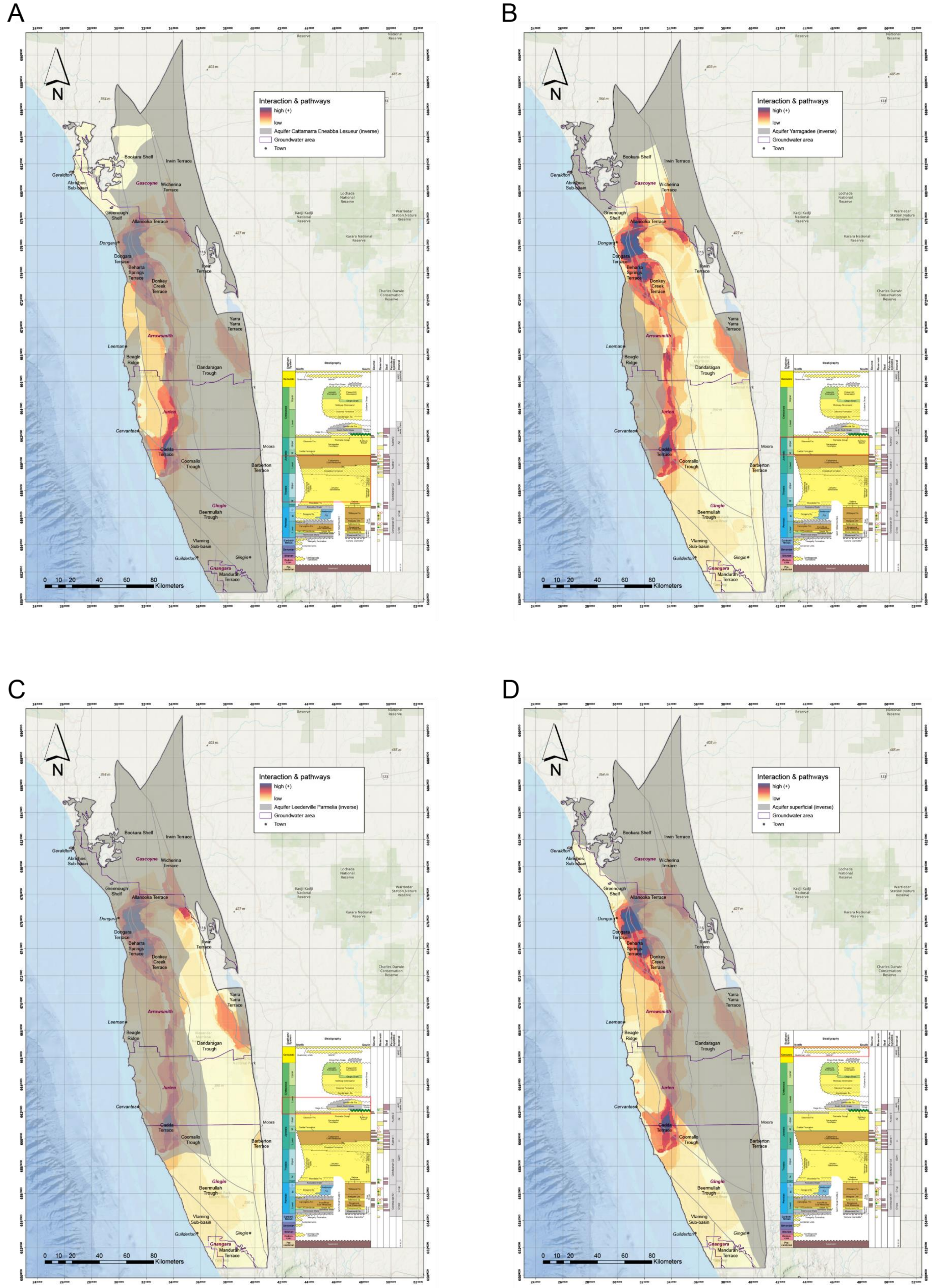


Figure 51. Potential soft interaction between Lower Permian-Lower Jurassic resources and aquifers. A) Cumulative interaction map and outline of Lesueur-Eneabba-Cattamarra aquifers, B) cumulative interaction map and outline of Yarragadee aquifer, C) cumulative interaction map and outline of Leederville-Parmelia aquifers, D) cumulative interaction map and outline of superficial aquifers.

Local evaluation: Dongara-Beharra Springs-Donkey Creek Terraces

The Dongara-Beharra Springs-Donkey Creek Terraces represent one of the most significant areas of resource interaction in the northern Perth Basin, aligning with the highest cumulative interaction anomalies observed in the cumulative interaction map (Figure 49 and Figure 52A). This also aligns with the high migration pathway density observed in the integrated map for migration pathways (Figure 50D, Figure 52B). This area exhibits strong correlations with interaction patterns in the Lower and Upper Permian intervals, where petroleum, CGS and UGS suitability strongly overlap, and geothermal suitability to a lesser extent (Figure 53). Gas production is the only purely extractive operation leading to under-pressures, particularly in fault compartments with no aquifer pressure support. This is the case for the depleted Dongara field, which is still severely under-pressured 10 years after production ceased. In this case, the resource overlap presents an opportunity for CO_2, natural gas or hydrogen storage. The compartmentalisation also provides some confidence that stored fluids remain within the structure and that there is a low risk of pressure impacts beyond the storage complex. However, the maximum storage volume and injection rates are constrained by the original reservoir pressure, which should not be exceeded to avoid fracture creation. Natural gas and hydrogen storage have regular injection-production cycles with no net pressure change, allowing for continuous operations. Contrastingly, CO_2 injection ceases once the pressure limit is reached.

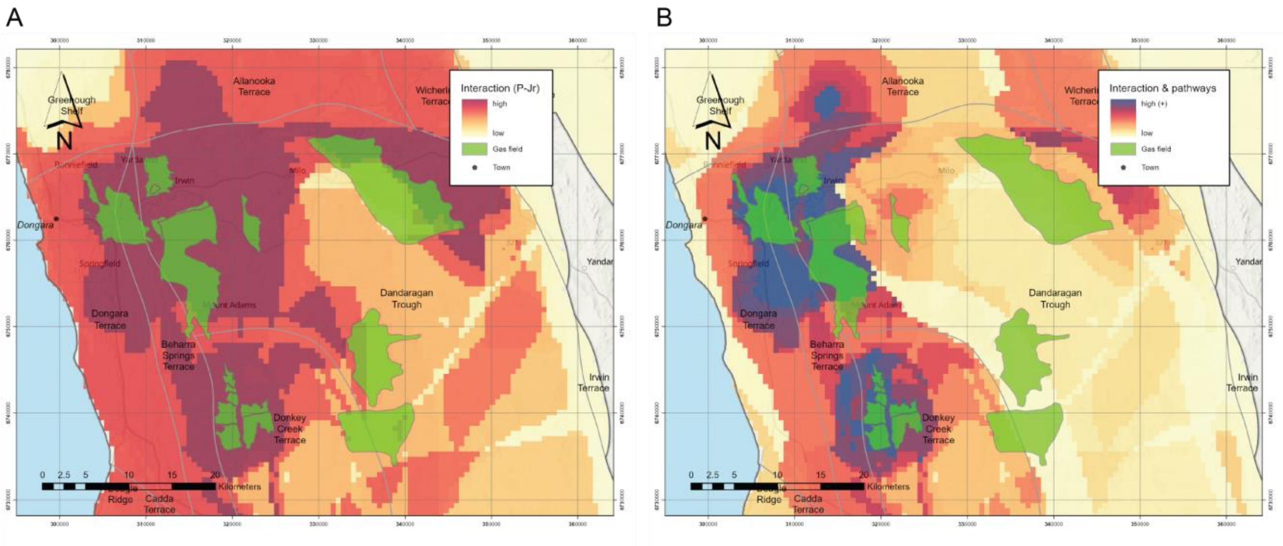


Figure 52. Dongara-Beharra Springs-Donkey Creek Terraces. A) Cumulative interaction map showing aggregated interaction data across Lower Permian-Lower Jurassic intervals, B) integrated map, interaction and pathways showing potential for vertical migration of deeper resources.

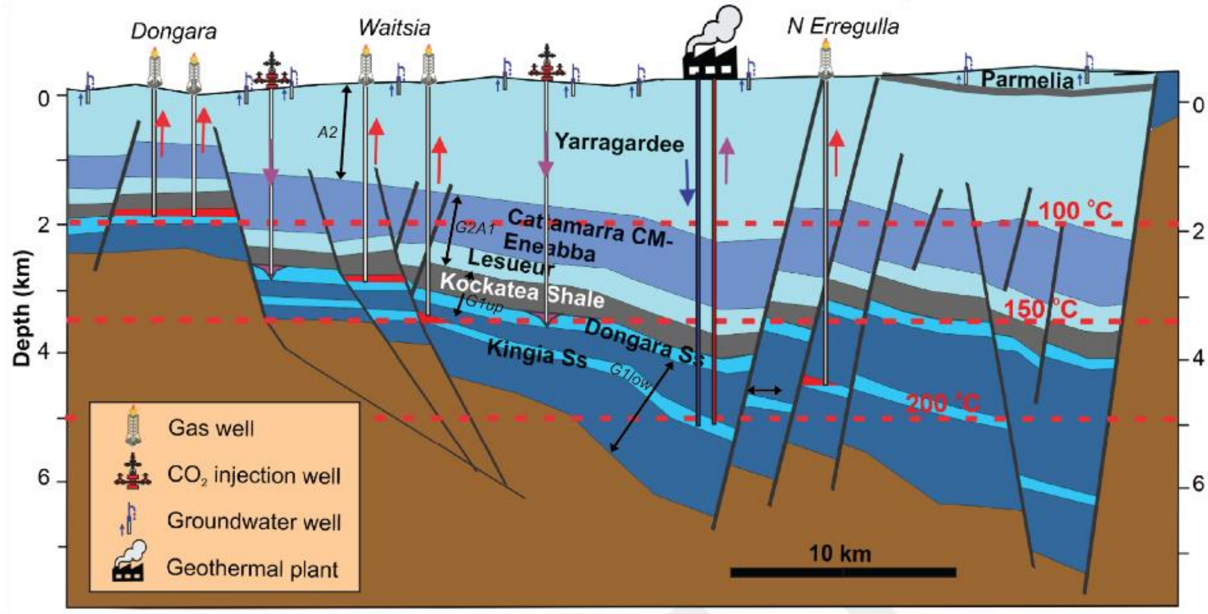


Figure 53. Diagrammatic west-east cross-section showing vertical temperature distribution and potential locations of future geothermal energy production and CO_2 injection in relation to existing gas fields.

4.1.6. Observed interaction patterns on Dongara-Beharra Springs-Donkey Creek Terraces

Lower Permian interactions (G1low)

This area contains some of the highest interaction zones in the Lower Permian interval. Petroleum and CGS suitability strongly coincide across this region, reinforcing its potential for repurposing depleted petroleum fields for CO_2 storage. UGS suitability is also concentrated here, as most of the highest-tier storage sites align with depleted petroleum fields, making this region a prime candidate for underground gas storage development. In contrast, geothermal suitability plays a minor role in the high-interaction areas, as it is primarily located to the east of the petroleum and CGS suitability zones.

Upper Permian interactions (G1up)

Interaction intensity remains high in the Upper Permian, with a continued overlap between petroleum, CGS, and UGS. The same geological structures that favour petroleum and CGS storage in the Lower Permian interval extend into this interval, contributing to the continuity of high-interaction zones. UGS suitability remains strong, further supporting the suitability of this area for gas storage in depleted reservoirs. Geothermal suitability, however, is limited in this part of the basin, indicating lower thermal potential compared to other intervals.

Cumulative interactions

The Dongara–Beharra Springs–Donkey Creek region stands out as one of the main cumulative interaction hotspots in the northern Perth Basin (Figure 52A). This area exhibits a high degree of subsurface resource overlap, making it a critical zone for integrated multi-resource planning and management. Reservoir and seal quality are key factors driving interaction intensity, particularly between CGS and petroleum. Permian reservoirs in this region are both widespread and overlapping, serving as viable storage formations for CO_2 and hydrocarbon accumulations alike. The regional Kockatea Shale provides a robust sealing unit, exceeding 100 metres in thickness, which ensures effective containment for both CO_2 storage and hydrocarbon retention.

Key takeaways

The Dongara-Beharra Springs-Donkey Creek Terraces represent a key area of subsurface resource overlap, where petroleum, CGS and UGS interact most intensely across the Lower and Upper Permian intervals. Reservoir quality is a primary driver of interaction intensity in this area, as both CGS and petroleum rely on the same porous formations for storage and extraction. Similarly, seal quality plays a critical role, with the thick and continuous Kockatea Shale ensuring effective containment of CO_2 and hydrocarbons.

Additionally, this region is overlain by the Yarragadee and Superficial aquifers. Faults and deep wells are highly concentrated where fault networks intersect. While deep and shallow subsurface systems are typically isolated, structural features may act as potential migration pathways. The extent of fluid movement between these intervals is controlled by fault permeability, basin evolution and vertical lithological variations, requiring further localised assessment to determine the likelihood of deep-shallow interactions.

This region is one of the most important zones for subsurface resource management, as it contains overlapping petroleum fields, CGS storage potential and UGS suitability. While its high-quality reservoirs and seals make it an optimal location for hydrocarbon production and gas storage, the presence of shallow aquifers and structural complexity suggests that potential migration pathways, and increasing deep-shallow interaction risk, must be carefully evaluated. These insights highlight that coordinated planning is needed in this region, particularly around Dongara, where petroleum production, CO_2 storage and gas storage are all technically viable and spatially overlap. Future energy projects should prioritise detailed site assessments to evaluate migration risks, manage potential resource competition and identify locations where resource coexistence is feasible without compromising groundwater protection.

5. Summary

Data for subsurface resources, including petroleum, geothermal energy, CGS, UGS and groundwater were compiled and assessed from various sources. This information was integrated into a GIS-based framework to analyse resource distribution and potential interactions. At a regional scale, the overlap of subsurface resources follows 3 key stratigraphically controlled categories (Figure 54):

1. **Within the Permian intervals below the Kockatea Shale**: petroleum, CGS, UGS and geothermal resources show high-interaction potential.
2. **Within the Triassic-Lower Jurassic Cattamarra Coal Measures-Eneabba/Lesueur interval:** groundwater, petroleum and CGS resources show medium to low interaction potential.
3. **Within the Upper Jurassic-Cenozoic interval:** groundwater resources show low interaction potential, but increasing demand for future domestic, agricultural and industrial use.

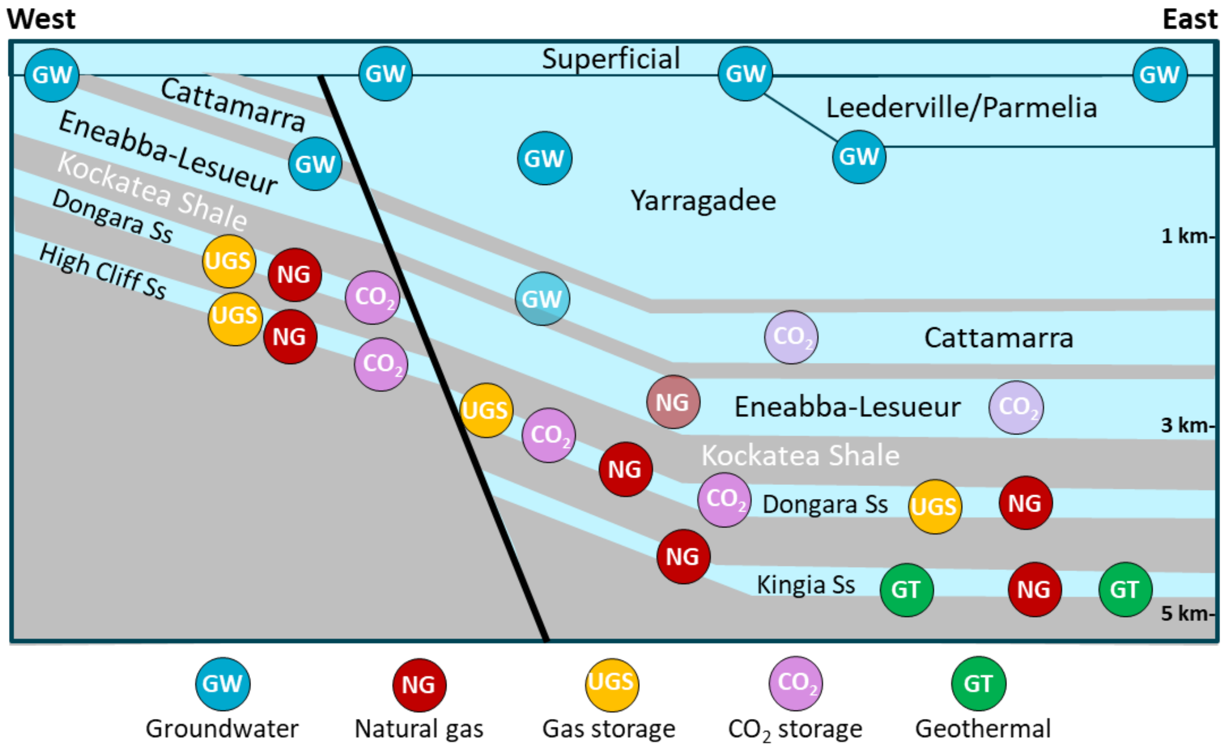


Figure 54. Formations targeted by different subsurface developments in the northern Perth Basin suggesting potential overlap of natural gas, CO_2 storage, UGS and geothermal resources below the Kockatea Shale, and b) limited overlap of groundwater, natural gas and CO_2 storage in the Cattamarra Coal Measures-Eneabba/Lesueur interval. Faded colours imply limited suitability.

The interactions between deep subsurface resources and groundwater in the northern Perth Basin are generally limited, as most petroleum, CGS, UGS and geothermal resources are stratigraphically separated from key aquifers by sealing formations. However, localised interaction pathways could exist where structural permeability is enhanced. In areas with high fault displacement or legacy well networks, there is potential for upward migration of fluids, which requires careful assessment to mitigate risks to groundwater quality and availability. While the primary groundwater sources (Yarragadee, Leederville-Parmelia and Superficial aquifers) remain largely unaffected by deep resource development, industrial water use and future groundwater allocations must be considered alongside subsurface energy projects to ensure sustainable water resources management.

5.1. Petroleum, CGS, UGS and geothermal resources below the Kockatea Shale

The Permian interval below the Kockatea Shale has the highest potential for resource interaction, where petroleum, geothermal, UGS and CGS prospects largely overlap to form a northern interaction hotspot, extending from the Allanooka Terrace and northern Dandaragan Trough, and continuing south, in a narrower corridor, along the Cadda Terrace (Figure 55).

In general, this zone of high resource interaction aligns with the western flank of the northern Perth Basin, where these resources are at the appropriate depths (< ~ 4000 m) for development.

- CGS and petroleum resources exhibit strong spatial overlap in the Permian intervals due to their shared reliance on high-quality reservoir formations and regional sealing units.
- Geothermal and UGS act as secondary interacting resources.
- Currently, no commercial CGS or geothermal projects are operational in the northern Perth Basin, leading to significant uncertainty about the viability, extent and economic feasibility of these resources.
- Groundwater suitability is absent in Permian intervals, as no aquifers under the Kockatea Shale are currently considered viable for groundwater extraction.

Figure 55A and Figure 55B provide conceptual views of overlapping resource interactions in key areas, including:

- the northern hotspot near the Allanooka, Beharra Springs, Donkey Creek and Irwin Terraces (Figure 55A and Figure 55E)
- the north-south corridor, from Donkey Creek Terrace to the Beermullah Trough, where petroleum and CGS suitability remain high on the western flank of the basin (Figure 55B).

While geothermal potential is highest in the northern part of this region, constrained by elevated temperatures in the Kingia Sandstone, petroleum and CGS suitability extend across a wider area within multiple Permian formations, including the Wagina and Dongara formations (Figure 47A–D).

Given the strong overlap of resources below the Kockatea Shale, future resource development in this interval will require coordinated subsurface planning. Petroleum and CGS operations will likely be the dominant users of these formations. The potential for geothermal activities remains uncertain due to current data limitations and the lack of active projects. Further technical assessments and regulatory frameworks will be necessary to resolve resource competition and optimise multi-use subsurface strategies in this highly prospective region.

5.2. Groundwater, petroleum and CGS in the Cattamarra Coal Measures, Eneabba, and Lesueur interval

The Triassic-Lower Jurassic interval, which includes the Cattamarra Coal Measures, Eneabba Formation and Lesueur Sandstone, exhibits moderate to low resource interactions, primarily between CGS and petroleum. These interactions form a north-south corridor extending from the Allanooka Terrace to the Mandurah Terrace (Figure 55).

In general, this zone of resource interaction also aligns with the western flank of the northern Perth Basin.

- CGS is the dominant interacting resource in this interval, overlapping extensively with petroleum prospects.
- Groundwater resources are present in this interval but mainly occur in the shallowest portions of the formation toward the west, where they do not significantly overlap with petroleum or CGS resources.

Figure 55C and Figure 55D illustrate the conceptual distribution of overlapping resources.

- In the Allanooka, Beharra Springs, Donkey Creek and Irwin Terraces area (Figure 55C), CGS exhibits spatial overlap with petroleum resources, while groundwater resources remain distributed in overlying formations. No significant interaction occurs between groundwater and petroleum or CGS within this interval.
- Along the north-south corridor (Figure 55D), CGS overlaps with petroleum in the deeper part of the basin (for example, the Coomallo Trough), while groundwater is present in the shallowest part of the interval closer to the coast.

Development of petroleum and CGS within the Cattamarra-Eneabba/Lesueur interval is relatively limited and mostly located west of the Dandaragan Trough axis (Figure 55D and Figure 55E). Groundwater production from these formations is largely restricted to western areas where they are shallow, minimising the potential for conflicts with deeper resource operations (Figure 55D).

While resource interaction in the Triassic-Lower Jurassic interval is lower than in the Permian interval, CGS and petroleum remain the most relevant interacting subsurface resources. Groundwater production from these formations is minimal and occurs in specific shallow areas, reducing the likelihood of direct resource conflicts. However, broader groundwater management concerns must be addressed, particularly regarding industrial water use and future groundwater allocations. Moving forward, integrating groundwater protection measures with petroleum and CGS development plans will be essential to ensure long-term resource sustainability and regulatory alignment.

5.3. Groundwater resources within the Upper Jurassic-Cenozoic interval

The Upper Jurassic-Cenozoic interval, which includes the Yarragadee Formation, Parmelia Formation, Leederville Formation and superficial deposits, represents the primary groundwater resource in the northern Perth Basin. These aquifers support town water supply, agriculture, mining and petroleum industries, making groundwater a critical economic and environmental asset for the region (Figure 53).

Groundwater resources are widespread across the northern Perth Basin, but are mostly restricted to shallow depths, generally less than 1000 m (Figure 49, Figure 55C and Figure 55D). The distribution of key aquifers varies across the basin:

- In the northern part of the basin (Figure 55C), groundwater suitability is primarily associated with the Yarragadee Formation, where it is shallow and subcropping. Additional groundwater resources are present in the Leederville-Parmelia formations, which is largely confined east of the basin axis, and in the Superficial aquifers, which occur at shallow depths along the western flanks of the basin.
- In the central region of the basin (Figure 55D), groundwater resources follow similar patterns, with the addition of the Triassic and Lower Jurassic aquifers (Lesueur, Eneabba and Cattamarra formations). These subcrop along the western flank of the basin, particularly in areas such as the Cadda Terrace.

The Upper Jurassic-Cenozoic groundwater resources are generally stratigraphically isolated from deeper subsurface resource units. Thick regional seals and aquitards, such as the Kockatea Shale and Cadda Formation, typically prevent hydraulic connectivity between deep petroleum, CGS, UGS, and geothermal formations and the overlying aquifers.

However, localised migration pathways could exist where faults or well networks enhance structural permeability. Areas with high fault displacement may create potential conduits for fluid movement, particularly where faults juxtapose reservoir units against aquifers. Additionally, older or abandoned wells could act as vertical conduits, increasing the potential for interaction between deep and shallow groundwater systems.

Given the importance of groundwater resources for regional water supply, careful management is required to ensure sustainable use while mitigating risks from subsurface resource development. Although direct competition between groundwater and deeper petroleum or CGS operations is unlikely, resource extraction industries (including oil, gas, and CGS projects) could rely on groundwater for operational use. Future assessments should focus on monitoring well integrity, fault-related permeability and groundwater extraction impacts to ensure sustainable groundwater management. Understanding these hydrogeological interactions is necessary for balancing resource development while safeguarding regional water supplies for both industry and local communities.

6. Recommendations

This review of basin resource management methodologies, Western Australian regulations and experience from other jurisdictions helps inform management options for the development of subsurface resources in the northern Perth Basin.

6.1. General considerations

There are different ways of managing the co-development of, and potential conflicts between, various subsurface resources. These are based on different drivers (economic, environmental, societal), which lead to different forms of prioritisation.

- The most straightforward option would be a **clear ban or prioritisation** of one resource over the other, which provides certainty and avoids lengthy and costly arbitration hearings. However, economics and priorities can change, which would require regulations to be updated in the future.
- **Co-development** of resources and avoidance of detrimental impacts is, in most cases, more economical, but requires more detailed regulatory considerations.
    - Generally, direct impacts (such as contamination of one resource by the operations of another) are relatively easy to identify, and compensation can be paid based on lost revenue if impacts are impossible to mitigate.
    - Pressure impacts, on the other hand, are harder to predict and more difficult to attribute to a source. They are not necessarily detrimental, and in some cases, may even be favourable.

Prior to development, hydrodynamic modelling or reservoir simulations are required to predict resource interactions and identify monitoring locations and **trigger values**. Having clear trigger values for acceptable pressure changes in neighbouring reservoirs or storage resources provides certainty and helps parties agree on monitoring and compensation solutions before any conflict arises. This is particularly important in cases where the pressure impact is detrimental (for example, in cases where both parties rely on pressure reduction or increase to develop their respective resources).

6.2. Suggestions for the management of subsurface resource development in the northern Perth Basin

Existing resources and groundwater regulations in Western Australia provide frameworks and guidelines for managing certain resource development interactions (for example, the protection of groundwater resources and co-development of petroleum and geothermal resources). However, the latter case has not yet been tested because there are no geothermal energy projects currently operational in the northern Perth Basin. Also, existing regulations are currently being updated to account for CO_2 geological storage. In the case of expected detrimental impacts, the government, in consultation with industry and community stakeholders, may need to prioritise one resource over another and ensure that adequate compensation provisions are in place. The scale of future CO_2 storage and geothermal resource developments is still uncertain and conflicts may never reach a level of concern. The first new operations will provide important experience and information regarding the adequacy of existing assessment methodologies and regulations.

Additionally, while direct interactions between deep resources and groundwater are unlikely, structural complexities in areas such as the Dongara-Beharra Springs-Donkey Creek Terraces must be closely monitored. High well integrity standards, fault permeability assessments and enhanced groundwater monitoring will be key to ensuring resource coexistence while protecting water supplies.

Based on the interaction maps, thematic interaction maps and cumulative interaction maps, several management challenges and strategies can be identified for balancing resource extraction, CGS, UGS, geothermal energy production and groundwater protection.

Suggested management approaches are provided for various aspects of resource management, some of which are already embedded in current resources and regulations in Western Australia.

6.2.1. Integrated subsurface planning for overlapping resources

CGS and petroleum resources show the highest interaction potential in the northern Perth Basin, particularly in Permian reservoirs, due to their shared reliance on the same geological formations for storage and extraction. UGS (and UHS) sites are primarily aligned with depleted petroleum fields, reinforcing the need for strategic planning to repurpose hydrocarbon reservoirs for gas storage or CO_2 sequestration. Therefore, regulatory coordination is required to ensure that one resource development does not compromise another, particularly where storage operations (CO_2 or UGS) could affect pressure dynamics in petroleum reservoirs.

Suggested management approach:

- Prioritise subsurface resources based on their economic and/or environmental values.
- Provide regulations that either give priority to one resource over the other, or provide a regulatory framework that allows for co- or staggered resource development.
- In the case of co-development, identify the potential for direct impacts like contamination of one resource by the operations of another and require plan for mitigation and/or compensation to be paid based on lost revenue.

6.2.2. Pressure and flow management across resource boundaries

Pressure changes from resource extraction and storage (for example, CGS injection and gas extraction) can affect adjacent resources, particularly in zones of high interaction, and potentially compromise containment integrity.

Suggested management approach:

- Make hydrodynamic modelling or reservoir simulations of resource interactions a requirement before approving injection or withdrawal projects. This is particularly important for high-interaction clusters in the Dandaragan Trough, Beharra Springs Terrace, Dongara Terrace and Donkey Creek Terrace.
- Require a geomechanical assessment of the cumulative pressure impacts on fault stability and seal integrity.
- Agree on pressure monitoring locations and trigger values.

6.2.3. Fault and well integrity considerations for groundwater protection

The deep resources and shallow aquifers are largely stratigraphically separated, minimising the likelihood of direct hydraulic interactions. However, faults and deep wells may serve as potential migration pathways between deeper formations and groundwater systems. For example, the Dongara-Beharra Springs-Donkey Creek region has a high density of structural discontinuities, particularly faults that may displace regional seals like the Kockatea and Cadda formations.

Suggested management approach:

- Conduct an assessment of fault permeability in areas where CGS or petroleum development overlaps with groundwater aquifers.
- Require regular well integrity monitoring and decommissioning for legacy petroleum wells to prevent unintended fluid migration into potable water sources.

6.2.4. Managing soft interactions between deep resources and groundwater

The Yarragadee aquifer, covering much of the northern Perth Basin, overlaps with high and moderate resource interaction zones, suggesting that if migration pathways exist, localised groundwater impacts could occur. The Lesueur-Eneabba-Cattamarra and Leederville-Parmelia aquifers have lower interaction potential, but specific geological structures could still create localised risks.

Suggested management approach:

- Require groundwater monitoring in areas of potential deep resource interaction, particularly where faults could enhance fluid movement.
- Use salinity and pressure data from deep and shallow formations to assess hydraulic connectivity risk.

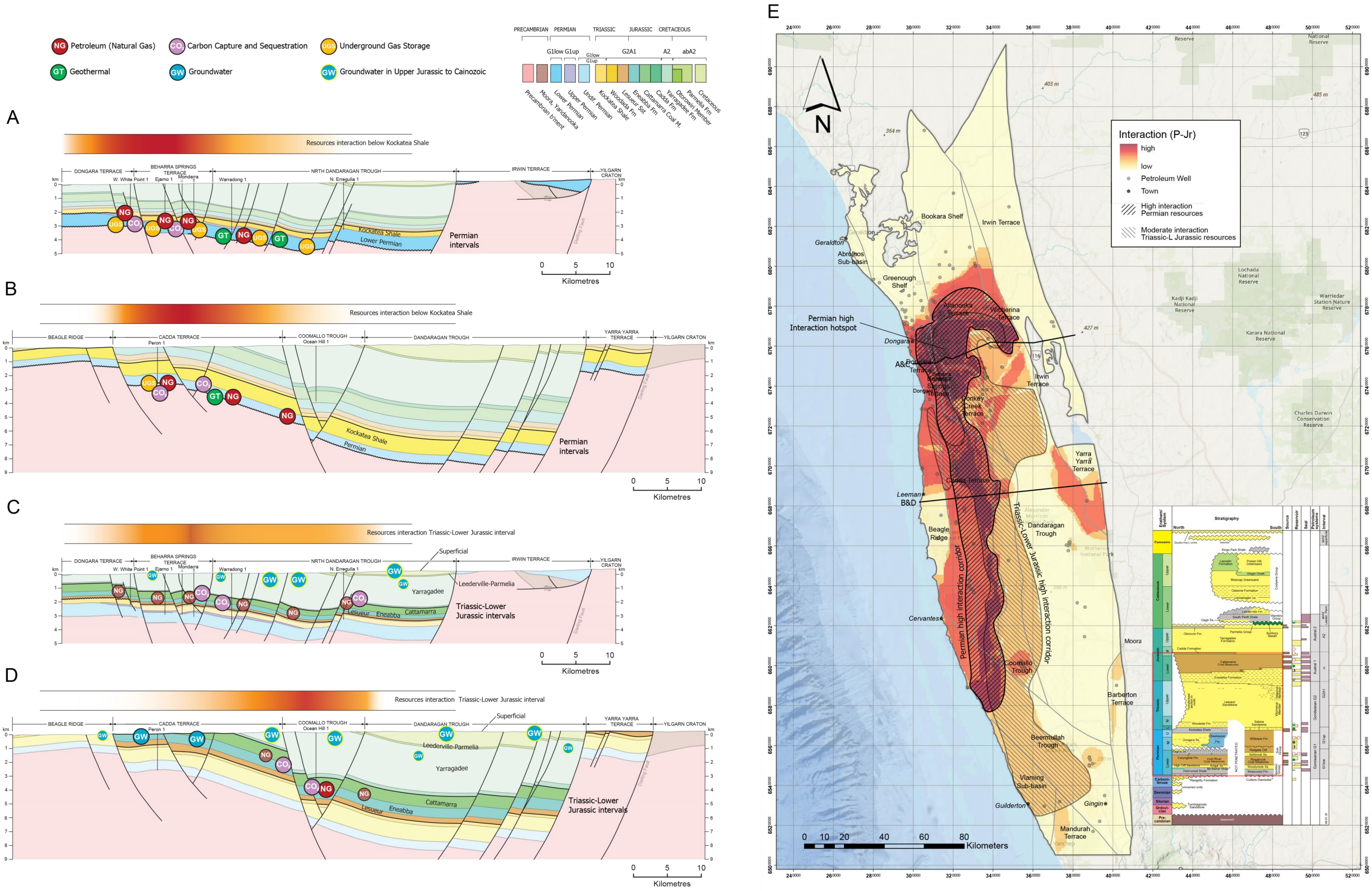


Figure 55. Summary of resource interactions. A) E-W cross-section across the northern interaction hotspot for the Permian intervals; the resources are shown schematically on the intervals; CGS and petroleum are the main interacting resources, geothermal and UGS are secondary resources; high-interaction hotspot aligns with the western flank of the basin, B) E-W cross-section across the N-S interaction corridor for the Permian intervals; the resources are shown schematically on the intervals; CGS and Petroleum are the main interacting resources; high-interaction corridor aligns with the western flank of the basin, C) E-W cross-section across the northern part of the interaction corridor for the Triassic-Lower Jurassic intervals; the resources are shown schematically on the intervals; CGS and petroleum are the main interacting resources; high-interaction corridor aligns with the western flank of the basin; groundwater resources in the Upper Jurassic-Cainozoic intervals are shown with a yellow outline, D) E-W cross-section across the southern part of the interaction corridor for the Triassic-Lower Jurassic intervals; the resources are shown schematically on the intervals; CGS and petroleum are the main interacting resources; groundwater is present to the west where the intervals outcrop; high-interaction corridor aligns with the western flank of the basin; groundwater resources in the Upper Jurassic-Cainozoic intervals are shown with a yellow outline, E) cumulative interaction map showing aggregated interaction data across Lower Permian-Lower Jurassic intervals.

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Appendix

Appendix 1: Suitability factors

The complete set of evaluation factors used for the development of the suitability maps for the Petroleum resources, Geothermal resources, carbon geological storage (CGS), underground gas storage (UGS) and Groundwater resources.

Resource	Interval	Factor	Significance	Source	Weight (AHP)
Petroleum	G1low	Petroleum field (density)	proxy for exploration success	EDIN (S&P)	0.21
Petroleum	G1low	Reservoir (IRCM Kingia) (presence)	presence of reservoir, pore space	WAPIMS (DEMIRS), 3DGEO (2013)	0.21
Petroleum	G1low	Seal (Caryngginia) (presence)	presence of containment	3DGEO (2013)	0.21
Petroleum	G1low	Fault (density)	proxy for presence of structure and closure	WAPIMS (DEMIRS)	0.21
Petroleum	G1low	Petroleum prospect (density)	proxy for prospectivity	EDIN (S&P)	0.09
Petroleum	G1low	Petroleum permit (presence)	presence exploration or production rights	WAPIMS (DEMIRS)	0.05
Petroleum	G1low	Pipeline (distance to)	proxy for commercial viability	WAPIMS (DEMIRS)	0.02
Petroleum	G1up	Petroleum field (density)	proxy for prospectivity	EDIN (S&P)	0.21
Petroleum	G1up	Reservoir (Wagina Beekeeper Dongara) (presence)	presence of reservoir, pore space	Mory and Iasky (1996)	0.21
Petroleum	G1up	Seal (Kockatea) (thickness)	presence of containment	WAPIMS (DEMIRS)	0.21
Petroleum	G1up	Fault (density)	proxy for presence of structure and closure	WAPIMS (DEMIRS)	0.21
Petroleum	G1up	Petroleum prospect (density)	proxy for prospectivity	EDIN (S&P)	0.09
Petroleum	G1up	Petroleum permit (presence)	presence exploration or production rights	WAPIMS (DEMIRS)	0.05
Petroleum	G1up	Pipeline (distance to)	proxy for commercial viability	WAPIMS (DEMIRS)	0.02
Petroleum	G2A1	Petroleum field (density)	proxy for prospectivity	EDIN (S&P)	0.21
Petroleum	G2A1	Reservoir (Cattamarra) (presence)	presence of reservoir, pore space	WAPIMS (DEMIRS), 3DGEO (2013)	0.21
Petroleum	G2A1	Seal (Cadda) (thickness)	effectiveness of containment	Mory and Iasky (1996)	0.21
Petroleum	G2A1	Fault (density)	proxy for presence of structure and closure	WAPIMS (DEMIRS)	0.21
Petroleum	G2A1	Petroleum prospect (density)	proxy for prospectivity	EDIN (S&P)	0.09
Petroleum	G2A1	Petroleum permit (presence)	presence exploration or production rights	WAPIMS (DEMIRS)	0.05
Petroleum	G2A1	Pipeline (distance to)	proxy for commercial viability	WAPIMS (DEMIRS)	0.02
CGS	G1low	Seal (Caryngginia) (presence)	presence of containment	3DGEO (2013)	0.43

CGS	G1low	Reservoir (IRCM) (presence)	presence of reservoir, pore space	WAPIMS (DEMIRS), 3DGEO (2013)	0.43
CGS	G1low	Fault (density)	proxy for compartmentalisation and baffle reducing flow	WAPIMS (DEMIRS)	0.09
CGS	G1low	Fault (at Kockatea level) (distance)	proxy for permeability increase and potential risk near major faults	WAPIMS (DEMIRS)	0.04
CGS	G1up	Seal (Kockatea) (thickness)	effectiveness of containment	WAPIMS (DEMIRS)	0.43
CGS	G1up	Reservoir (Wagina Beekeeper Dongara) (presence)	presence of reservoir, pore space	WAPIMS (DEMIRS), 3DGEO (2013)	0.43
CGS	G1up	Fault (density)	proxy for compartmentalisation and baffle reducing flow	WAPIMS (DEMIRS)	0.09
CGS	G1up	Fault (at Kockatea level) (distance)	proxy for permeability increase and potential risk near major faults	WAPIMS (DEMIRS)	0.04
CGS	G2A1	Seal (Cadda) (thickness)	effectiveness of containment	Mory and Iasky (1996)	0.43
CGS	G2A1	Reservoir (Lesueur Cattamarra) (presence)	presence of reservoir, pore space	WAPIMS (DEMIRS), 3DGEO (2013)	0.43
CGS	G2A1	Fault (density)	proxy for compartmentalisation and baffle reducing flow	WAPIMS (DEMIRS)	0.09
CGS	G2A1	Fault (at Cadda level) (distance)	proxy for permeability increase and potential risk near major faults	WAPIMS (DEMIRS)	0.04
UGS	G1low	Field for storage (presence)	presence of constrained storage site	WAPIMS (DEMIRS), EDIN (S&P), Craig *et al.* (2022)	0.67
UGS	G1low	Seal (Caryngìnia) (presence)	presence of containment	3DGEO (2013)	0.14
UGS	G1low	Reservoir (IRCM Kingia) (presence)	presence of reservoir, pore space	WAPIMS (DEMIRS), 3DGEO (2013)	0.14
UGS	G1low	Fault (density)	proxy for presence of structure and closure	WAPIMS (DEMIRS)	0.05
UGS	G1up	Field for storage (presence)	presence of constrained storage site	WAPIMS (DEMIRS), EDIN (S&P), Craig *et al.* (2022)	0.67
UGS	G1up	Seal (Kockatea) (thickness)	effectiveness of containment	WAPIMS (DEMIRS)	0.14
UGS	G1up	Reservoir (Wagina Beekeeper Dongara) (presence)	presence of reservoir, pore space	WAPIMS (DEMIRS), 3DGEO (2013)	0.14
UGS	G1up	Fault (density)	proxy for presence of structure and closure	WAPIMS (DEMIRS)	0.05
UGS	G2A1	Field for storage (presence)	presence of constrained storage site	WAPIMS (DEMIRS), EDIN (S&P), Craig *et al.* (2022)	0.67
UGS	G2A1	Seal (Cadda) (thickness)	effectiveness of containment	3DGEO (2013)	0.14
UGS	G2A1	Reservoir (Cattamarra) (presence)	presence of reservoir, pore space	WAPIMS (DEMIRS), 3DGEO (2013), Mory and Iasky (1996)	0.14
UGS	G2A1	Fault (density)	proxy for presence of structure and closure	WAPIMS (DEMIRS)	0.05

Geothermal	G1low	Reservoir (Kingia) (presence and temperature)	presence of reservoir, pore space and temperature	WAPIMS (DEMIRS)	0.75
Geothermal	G1low	Geothermal permit (presence)	presence exploration or production rights	WAPIMS (DEMIRS)	0.25
Geothermal	G1up	Reservoir (Wagina Beekeeper Dongara) (presence)	presence of reservoir, pore space and temperature	WAPIMS (DEMIRS), Mory and Iasky (1996)	0.75
Geothermal	G1up	Geothermal permit (presence)	presence exploration or production rights	WAPIMS (DEMIRS)	0.25
Groundwater	G2A1	Aquifer (Cattamarra, Eneabba, Lesueur) (presence and salinity)	proxy for water resource potential	Department of Water (2017)	0.73
Groundwater	G2A1	Fault (density)	proxy for leakage risk	WAPIMS (DEMIRS)	0.17
Groundwater	G2A1	Bore (intersecting Cattamarra, Eneabba, Lesueur) (density)	proxy for stress on water resource	National Groundwater Information System	0.09
Groundwater	A2	Aquifer (Yarragadee) (presence and salinity)	proxy for water resource potential	Department of Water (2017)	0.73
Groundwater	A2	Fault (density)	proxy for leakage risk	WAPIMS (DEMIRS)	0.17
Groundwater	A2	Bore (intersecting Yarragadee) (density)	proxy for stress on water resource	National Groundwater Information System	0.09
Groundwater	AbvoveA2	Aquifer (Parmelia, Leederville) (presence and salinity)	proxy for water resource potential	Department of Water (2017)	0.74
Groundwater	AbvoveA2	Fault (density)	proxy for leakage risk	WAPIMS (DEMIRS)	0.17
Groundwater	AbvoveA2	Bore (intersecting Parmelia, Leederville) (density)	proxy for stress on water resource	National Groundwater Information System	0.09
Groundwater	AbvoveA2 (superficial)	Aquifer (superficial) (presence and salinity)	proxy for water resource potential		0.74
Groundwater	AbvoveA2 (superficial)	Fault (superficial fault) (density)	proxy for leakage risk	WAPIMS (DEMIRS)	0.17
Groundwater	AbvoveA2 (superficial)	Bore (intersecting superficial aquifer) (density)	proxy for stress on water resource	National Groundwater Information System	0.09

Appendix 2: Suitability maps description

Suitability – petroleum, Lower Permian (G1low)

Suitability factors and weight (seeAppendix 1)

- Petroleum field density – Proxy for exploration success (0.21)
- Reservoir (IRCM Kingia) presence – Pore space availability (0.21)
- Seal (Carynginia) presence – Containment capability (0.21)
- Fault density – Indicator of structural closure (0.21)
- Petroleum prospect density – Proxy for prospectivity (0.09)

- Petroleum permit presence – Exploration or production rights (0.05)
- Pipeline distance – Proxy for commercial viability (0.02)

High suitability areas

- Concentrated in the northern Dandaragan Trough, Dongara Terrace, Beharra Springs Terrace and Donkey Creek Terrace.

Geological influence

- High suitability correlates strongly with known Lower Permian petroleum accumulations.
- Controlled by the presence of Lower Permian reservoirs and the Carynginia Formation top seal.

Spatial distribution

- Defined by clusters around Lower Permian fields.

Key controlling factors

- Distribution of petroleum accumulations, reservoirs and top seal integrity.

Moderate suitability areas

- Extends from the Irwin Terrace to the Beermullah Trough.
- Controlled by the distribution of Lower Permian reservoirs.

Suitability – CGS, Lower Permian (G1low)

Suitability factors and weight (seeAppendix 1)

- Seal (Carynginia) presence – Containment effectiveness (0.43)
- Reservoir (IRCM) presence – Pore space availability (0.43)
- Fault density – Indicator of compartmentalisation and baffle reducing flow (0.09)
- Fault at Kockatea level (distance) – Proxy for permeability increase and risk near major faults (0.04)

High suitability areas

- Concentrated in Wicherina Terrace, Allanooka Terrace, Dandaragan Trough, Dongara Terrace, Beharra Springs Terrace, Donkey Creek Terrace, Cadda Terrace, Beagle Ridge, Beermullah Trough.

Geological influence

- CGS suitability is strongly controlled by the presence of Lower Permian reservoirs within the CGS depth window (800 m–3200 m) and the Carynginia Formation top seal.

Spatial distribution

- Widespread, elongated N-S to NNW-SSE corridor (~220 km by 40 km).

Key controlling factors

- Reservoir presence and CGS depth window constraints.

Suitability – UGS, Lower Permian (G1low)

Suitability factors and weight (seeAppendix 1)

- Field for storage presence – Constrained storage site (0.67)
- Seal (Carynginia) presence – Containment effectiveness (0.14)
- Reservoir (IRCM, Kingia) presence – Pore space availability (0.14)
- Fault density – Indicator of structural closure (0.05)

High suitability areas

- No high suitability in Lower Permian.

Moderate suitability areas

- Northern Dandaragan Trough, Beharra Springs Terrace, northern Cadda Terrace.

Geological influence

- Storage suitability is linked to known Lower Permian depleted petroleum fields, reservoir quality and containment effectiveness.

Spatial distribution

- Defined by depleted field outlines, extending up to 20 km.

Key controlling factors

- Field production status and containment structure presence.

Suitability – geothermal, Lower Permian (G1low)

Suitability factors and weight (see Appendix 1)

- Reservoir (Kingia) presence and temperature – Pore space and thermal potential (0.75)
- Geothermal permit presence – Exploration or production rights (0.25)

High suitability areas

- Northern Dandaragan Trough, Donkey Creek Terrace, Beharra Springs Terrace, Cadda Terrace.

Geological influence

- Suitability is based on Kingia Sandstone presence above the 5000 m depth threshold, with reservoir temperature modelling from DEMIRS (2025).

Spatial distribution

- Elongated N-S corridor (~100 km long).

Key controlling factors

- Reservoir presence and thermal gradient.

Moderate suitability areas

- Northern Dandaragan Trough, Dongara Terrace, Beharra Springs Terrace, Beagle Ridge, Cadda Terrace.
- Controlled by temperature of the Kingia Sandstone reservoir.

Suitability – petroleum, Upper Permian (G1up)

Suitability factors and weight (seeAppendix 1)

- Petroleum field density – Proxy for prospectivity (0.21)
- Reservoir (Wagina, Beekeeper, Dongara) presence – Pore space availability (0.21)
- Seal (Kockatea) thickness – Containment capability (0.21)
- Fault density – Indicator of structural closure (0.21)
- Petroleum prospect density – Proxy for prospectivity (0.09)
- Petroleum permit presence – Exploration or production rights (0.05)
- Pipeline distance – Proxy for commercial viability (0.02)

High suitability areas

- Concentrated in northern Dandaragan Trough, Dongara Terrace, Beharra Springs Terrace and Donkey Creek Terrace.

Geological influence

- High suitability aligns with known Upper Permian petroleum accumulations.
- Reservoir presence (Wagina Sandstone, Dongara Sandstone, Beekeeper Formation) and Kockatea Shale as the regional top seal drive suitability.

Spatial distribution

- Clusters around Upper Permian fields.

Key controlling factors

- Presence and distribution of known petroleum accumulations, reservoirs, and top seal integrity.

Moderate suitability areas

- Extends from the Wicherina Terrace to the Beermullah Trough.

- Controlled by the distribution of Upper Permian reservoirs.

Suitability – CGS, Upper Permian (G1up)

Suitability factors and weight (see Appendix 1)

- Seal (Kockatea) thickness – Containment effectiveness (0.43)
- Reservoir (Wagina, Beekeeper, Dongara) presence – Pore space availability (0.43)
- Fault density – Indicator of compartmentalisation and baffle reducing flow (0.09)
- Fault at Kockatea level (distance) – Proxy for permeability increase and risk near major faults (0.04)

High suitability areas

- Wicherina Terrace, Allanooka Terrace, Dandaragan Trough, Dongara Terrace, Beharra Springs Terrace, Donkey Creek Terrace, Cadda Terrace, Beagle Ridge, Beermullah Trough, Yarra Yarra Terrace.

Geological influence

- Suitability is controlled by the presence of Upper Permian reservoirs within the CGS depth window (800 m–3200 m) and the regional Kockatea Shale top seal.

Spatial distribution

- Widespread, elongated N-S to NNW-SSE corridor (~220 km by 40 km).

Key controlling factors

- Presence of Upper Permian reservoirs and top seal integrity.

Suitability – UGS, Upper Permian (G1up)

Suitability factors and weight (seeAppendix 1)

- Field for storage presence – Constrained storage site (0.67)
- Seal (Kockatea) thickness – Containment effectiveness (0.14)
- Reservoir (Wagina, Beekeeper, Dongara) presence – Pore space availability (0.14)
- Fault density – Indicator of structural closure (0.05)

High suitability areas

- Dongara Terrace, Beharra Springs Terrace, Northern Dandaragan Trough, Donkey Creek Terrace.

Geological influence

- Storage suitability is linked to the distribution of known Upper Permian depleted petroleum fields, reservoir properties, and production status.

Spatial distribution

- Defined by field outlines, extending up to 10 km in length.

Key controlling factors

- Reservoir suitability and containment integrity in depleted petroleum fields.

Moderate suitability areas

- Same tectonic elements as high suitability areas.
- Controlled by the production status of Upper Permian depleted fields.

Suitability – geothermal, Upper Permian (G1up)

Suitability factors and weight (seeAppendix 1)

- Reservoir (Wagina, Beekeeper, Dongara) presence and temperature – Pore space and thermal potential (0.75)
- Geothermal permit presence – Exploration or production rights (0.25)

High suitability areas

- Donkey Creek Terrace, northern Dandaragan Trough, Coomallo Trough.

Geological influence

- Suitability is based on the presence of Upper Permian reservoirs at sufficient depths to reach geothermal gradient thresholds.
- Modelled temperature data for the Top Permian (DEMIRS, 2025) confirms areas with viable thermal potential.

Spatial distribution

- Elongated N-S corridor (~80 km long).

Key controlling factors

- Reservoir presence and subsurface thermal gradient determine geothermal suitability.

Moderate suitability areas

- From northern Bookara Shelf to southern Cadda Terrace.
- Controlled by variations in modelled temperature at the top of the Permian reservoirs.

Suitability – petroleum, Triassic-Lower Jurassic (G2A1)

Suitability factors and weight (see Appendix 1)

- Petroleum field density – Proxy for prospectivity (0.21)
- Reservoir (Cattamarra) presence – Pore space availability (0.21)
- Seal (Cadda) thickness – Effectiveness of containment (0.21)
- Fault density – Indicator of structural closure (0.21)
- Petroleum prospect density – Proxy for prospectivity (0.09)
- Petroleum permit presence – Exploration or production rights (0.05)
- Pipeline distance – Proxy for commercial viability (0.02)

High suitability areas

- Coomallo Trough and Beermullah Trough.

Geological influence

- Suitability is controlled by the presence of Triassic-Lower Jurassic reservoirs in Cattamarra Coal Measures and the regional top seal (Cadda Formation).
- High suitability aligns with known Triassic and Lower Jurassic petroleum accumulations.

Spatial distribution

- Clusters around Triassic-Lower Jurassic fields.

Key controlling factors

- Presence and distribution of known petroleum accumulations, reservoirs, and the effectiveness of the top seal.

Moderate suitability areas

- Extends from the Bookara Shelf to the Mandurah Terrace.
- Controlled by the distribution of Cattamarra Coal Measures reservoirs.

Suitability – CGS, Triassic-Lower Jurassic (G2A1)

Suitability factors and weight (see Appendix 1)

- Seal (Cadda) thickness – Containment effectiveness (0.43)
- Reservoir (Lesueur, Cattamarra) presence – Pore space availability (0.43)
- Fault density – Indicator of compartmentalisation and baffle reducing flow (0.09)
- Fault at Cadda level (distance) – Proxy for permeability increase and risk near major faults (0.04)

High suitability areas

- Dandaragan Trough, Beharra Springs Terrace, Donkey Creek Terrace, Cadda Terrace, Coomallo Trough, Beermullah Trough, Mandurah Terrace, Yarra Yarra Terrace, Barberton Terrace.

Geological influence

- Suitability is defined by the presence of Triassic-Lower Jurassic reservoirs within the CGS depth window and the regional Cadda Formation top seal.

Spatial distribution

- Widespread, elongated N-S to NNW-SSE corridor (~270 km by 40 km).

Key controlling factors

- Distribution of Triassic and Lower Jurassic reservoirs and top seal thickness.

Moderate suitability areas

- Pockets between the Bookara Shelf and Beagle Ridge, including Mandurah Terrace and Barberton Terrace.
- Controlled by the distribution and thickness of the Cadda Formation (<20 m = higher risk; 20–100 m = average containment potential; > 100 m = good containment potential).

Suitability – UGS, Triassic-Lower Jurassic (G2A1)

Suitability factors and weight (see Appendix 1)

- Field for storage presence – Constrained storage site (0.67)
- Seal (Cadda) thickness – Containment effectiveness (0.14)
- Reservoir (Cattamarra) presence – Pore space availability (0.14)
- Fault density – Indicator of structural closure (0.05)

High suitability areas

- No high suitability in Triassic-Lower Jurassic.

Moderate suitability areas

- Coomallo Trough, Beermullah Trough.

Geological influence

- Moderate suitability is controlled by the distribution of known Triassic-Lower Jurassic depleted petroleum fields and reservoir quality.

Spatial distribution

- Defined by field outlines, extending up to 10 km.

Key controlling factors

- Presence of depleted petroleum reservoirs with good containment integrity.

Suitability – groundwater, Triassic-Lower Jurassic (G2A1)

Suitability factors and weight (see Appendix 1)

- Aquifer salinity (Cattamarra, Eneabba, Lesueur) – Proxy for water resource potential (0.73)
- Fault density – Proxy for leakage risk (0.17)
- Bore density (intersecting aquifers) – Proxy for stress on water resources (0.09)

High suitability areas

- Northern region: Bookara Shelf, Greenough Shelf.
- Southern region: Beagle Ridge, Cadda Terrace, Beermullah Trough.

Geological influence

- Suitability is controlled by the distribution and reported salinity of the Cattamarra, Eneabba and Lesueur aquifers.

Spatial distribution

- Two distinct high-suitability areas.
- The southern high-suitability region is within a N-S corridor (~150 km by 20 km).

Key controlling factors

- Groundwater salinity variations in the Cattamarra, Eneabba and Lesueur aquifers.

Moderate suitability areas

- Marginal moderate suitability zones exist along the edges of the high suitability regions.

Suitability – groundwater, Upper Jurassic (A2)

Suitability factors and weight (see Appendix 1)

- Aquifer salinity (Yarragadee) – Proxy for water resource potential (0.73)
- Fault density – Proxy for leakage risk (0.17)
- Bore density (intersecting aquifer) – Proxy for stress on water resources (0.09)

High suitability areas

- From Bookara Shelf to Mandurah Terrace, excluding Irwin Terrace, Yarra Yarra Terrace, Beagle Ridge and Barberton Terrace.

Geological influence

- Suitability is controlled by the distribution and reported salinity of the Yarragadee aquifer.

Spatial distribution

- Widespread, elongated N-S corridor (~330 km by 60 km).

Key controlling factors

- Groundwater salinity and aquifer presence define suitability.

Moderate suitability areas

- Marginal moderate suitability zones exist at the east and west edges of the high suitability zone.

Suitability – groundwater, Cretaceous (abA2) – Leederville Parmelia

Suitability factors and weight (see Appendix 1)

- Aquifer (Parmelia, Leederville) presence and salinity – Proxy for water resource potential (0.74)
- Fault density – Proxy for leakage risk (0.17)
- Bore density (intersecting aquifers) – Proxy for stress on water resources (0.09)

High suitability areas

- Dandaragan Trough, Beermullah Trough, Mandurah Terrace.

Geological influence

- Suitability is primarily controlled by the distribution and reported salinity of the Leederville and Parmelia aquifers.

Spatial distribution

- Widespread, elongated N-S corridor (~270 km by <60 km).

Key controlling factors

- Groundwater salinity variations and aquifer presence in the Leederville and Parmelia formations.

Suitability – groundwater, Cenozoic (abA2) – Superficial

Suitability factors and weight (see Appendix 1)

- Aquifer (Superficial) presence and salinity – Proxy for water resource potential (0.74)
- Fault density (superficial faults) – Proxy for leakage risk (0.17)
- Bore density (intersecting superficial aquifer) – Proxy for stress on water resources (0.09)

High suitability areas

- Greenough Shelf, Dongara Terrace, Beharra Springs Terrace, Donkey Creek Terrace, Cadda Terrace, Beagle Ridge, Beermullah Trough, Mandurah Terrace.

Geological influence

- Suitability is controlled by aquifer salinity and distribution of superficial groundwater reservoirs.

Spatial distribution

- Elongated N-S corridor (~300 km by 30 km).

Key controlling factors

- Groundwater salinity and reservoir presence.

Appendix 3: Interaction maps description

Interaction – Lower Permian (G1low)

Resources: Petroleum, CGS, Geothermal, UGS

High interaction

- Spatial distribution
    - High-interaction cases make up 4% of all interactions.
    - Present in Allanooka Terrace, Dandaragan Trough, Beharra Springs Terrace, Dongara Terrace, Donkey Creek Terrace, and Cadda Terrace.
    - Two major clusters are observed:
        - Northern Dandaragan Trough extending across Beharra Springs and Dongara Terraces.
        - Beharra Springs Terrace and northern Donkey Creek Terrace.
    - A north-south high-interaction corridor extends from southern Beharra Springs Terrace to Cadda Terrace.
- Most dominant resource in high-interaction cases
    - CGS (93%) dominates, indicating its dependence on key geological formations.
    - Geothermal (64%) and Petroleum (52%) follow as secondary contributors.
- Resource Pairing Frequency
    - 91% of high-interaction cases involve 2 resources, while 9% involve 3.

- Most common high-interaction combinations
    - Petroleum (m), CGS (h), Geothermal (h) – 47% of high-interaction cases.
    - Petroleum (h), CGS (h), Geothermal (m) – 24% of high-interaction cases.

Moderate interactions

- Spatial distribution
    - Moderate interactions represent 24% of all interactions.
    - Cover Bookara Shelf, Wicherina Terrace, Allanooka Terrace, Dandaragan Trough, Beharra Springs Terrace, Dongara Terrace, Donkey Creek Terrace, Cadda Terrace, Beagle Ridge and Beermullah Trough.
    - Forms a 230 km by 50 km corridor surrounding high-interaction zones.
- Most dominant resource in moderate interaction cases
    - Petroleum (100%) appears in all moderate interaction cases.
    - CGS (84%) and Geothermal (43%) also feature prominently.
- Most common moderate interaction combinations
    - Petroleum (m), CGS (h) – 57% of moderate interaction cases.
    - Petroleum (m), CGS (h), Geothermal (m) – 26% of moderate interaction cases.

Resource dominant cases

- Distribution
    - Resource-dominant cases represent only 0.5% of all interactions.
- Most dominant resource
    - CGS is the only dominant resource in this category.

Interaction – Upper Permian (G1up)

Resources: Petroleum, CGS, Geothermal, UGS

High interaction

- Spatial distribution
    - High-interaction cases make up 2% of all interactions.
    - Observed in Allanooka Terrace, Dandaragan Trough, Beharra Springs Terrace, Dongara Terrace, Donkey Creek Terrace and Cadda Terrace.
    - Two high-interaction clusters align with known petroleum accumulations in Permian reservoirs.
- Most dominant resource in high-interaction cases
    - Petroleum (97%) dominates, followed by CGS (87%) and Geothermal (11%).

- Most common high-interaction combinations
  - Petroleum (h), CGS (h), Geothermal (m) – 69% of all high-interaction cases.
  - Petroleum (h), CGS (h), Geothermal (m), UGS (h) – 7% of all high-interaction cases.

Moderate interaction

- Spatial distribution
  - Moderate interactions represent 21% of all interactions.
  - Cover Bookara Shelf, Wicherina Terrace, Allanooka Terrace, Greenough Shelf, Dongara Terrace, Beharra Springs Terrace, Dandaragan Trough, Donkey Creek Terrace, Beagle Ridge, Cadda Terrace, Beermullah Trough.
  - A 200 km by 50 km corridor surrounds high-interaction zones.
- Most common moderate interaction combinations
  - Petroleum (m), CGS (h), Geothermal (m) – 42% of moderate interaction cases.
  - CGS (h), Geothermal (m) – 19% of moderate interaction cases.

Resource dominant cases

- Distribution
  - Resource-dominant cases represent 6% of all interactions.
- Most dominant resource
  - CGS (h) is the most frequently dominant resource.

Interaction – Triassic-Lower Jurassic (G2A1)

Resources: Petroleum, CGS, UGS, Groundwater

High interaction

- Spatial distribution
  - High-interaction cases account for 0.7% of all interactions.
- Most dominant resource in high-interaction cases
  - CGS (100%) dominates, followed by Petroleum (97%) and Groundwater (3%).
- Most common high-interaction combinations
  - Petroleum (h), CGS (h) – 85% of high-interaction cases.
  - Petroleum (h), CGS (h), Groundwater (m) – 12% of high-interaction cases.

Moderate interaction

- Spatial distribution
  - Moderate interactions account for 31% of all interactions.

- Most common moderate interaction combinations
    - Petroleum (m), CGS (h) – 68% of moderate interaction cases.
    - Petroleum (m), CGS (m) – 28% of moderate interaction cases.

Appendix 4: Thematic interaction maps description

Petroleum interaction – Lower Permian (G1low)

Petroleum with high suitability

- Spatial distribution
  - Covers 2% of the Northern Perth Basin.
  - Located on Allanooka Terrace, Dandaragan Trough, Beharra Springs Terrace, Dongara Terrace, Donkey Creek Terrace.
  - Two main clusters observed:
    - Northern Dandaragan Trough, Beharra Springs Terrace and Dongara Terrace.
    - Beharra Springs Terrace and northern Donkey Creek Terrace.
- Most frequent interactions
  - CGS (86%) is the primary interacting resource.
  - Geothermal (30%) is the secondary interacting resource.
  - No isolated occurrences. Petroleum always interacts with at least one resource.

Petroleum with moderate suitability

- Spatial distribution
  - Covers 41% of the northern Perth Basin.
  - Found on Irwin Terrace, Wicherina Terrace, Bookara Shelf, Allanooka Terrace, Greenough Shelf, Dongara Terrace, Dandaragan Trough, Beharra Springs Terrace, Donkey Creek Terrace, Cadda Terrace, Beagle Ridge, Yarra Yarra Terrace, Coomallo Trough, Beermullah Trough.
- Most frequent interactions
  - CGS (48%) is the primary interacting resource.
  - Geothermal (27%) is the secondary interacting resource.
  - 18% of petroleum with moderate suitability occurs without interactions.

CGS interaction – Lower Permian (G1up)

CGS with high suitability

- Spatial distribution
  - Covers 21% of the northern Perth Basin.
  - Present on Bookara Shelf, Allanooka Terrace, Greenough Shelf, Dongara Terrace, Dandaragan Trough, Beharra Springs Terrace, Donkey Creek Terrace, Cadda Terrace, Beagle Ridge, Beermullah Trough.

- Most frequent interactions
    - Petroleum (98%) is the primary interacting resource.
    - Geothermal (41%) is the secondary interacting resource.
    - 2% of CGS with high suitability occurs without interactions, mostly in Cadda Terrace and Beermullah Shelf.

Petroleum interaction – Upper Permian (G1up)

Petroleum with high suitability

- Spatial distribution
    - Covers 2% of the Northern Perth Basin.
    - Found on Allanooka Terrace, Dongara Terrace, Dandaragan Trough, Beharra Springs Terrace, Donkey Creek Terrace.
    - Two main clusters align with known petroleum accumulations in Permian reservoirs.
- Most frequent interactions
    - Geothermal (95%) is the primary interacting resource.
    - CGS (80%) is the secondary interacting resource.
    - 0.4% of petroleum with high suitability occurs without interactions.

Petroleum with moderate suitability

- Spatial distribution
    - Covers 18% of the Northern Perth Basin.
    - Present on Wicherina Terrace, Bookara Shelf, Allanooka Terrace, Greenough Shelf, Dongara Terrace, Dandaragan Trough, Beharra Springs Terrace, Donkey Creek Terrace, Cadda Terrace, Beagle Ridge, Coomallo Trough, Beermullah Trough.
- Most frequent interactions
    - Geothermal (80%) is the primary interacting resource.
    - CGS (64%) is the secondary interacting resource.
    - 1% of petroleum with moderate suitability occurs without interactions.

CGS interaction – Upper Permian (G1up)

CGS with high suitability

- Spatial distribution
    - Covers 22% of the northern Perth Basin.
    - Present on Bookara Shelf, Allanooka Terrace, Greenough Shelf, Dongara Terrace, Dandaragan Trough, Beharra Springs Terrace, Donkey Creek Terrace, Cadda

Terrace, Beagle Ridge, Yarra Yarra Terrace, Coomallo Trough and Beermullah Trough.

- Most frequent interactions
    - Geothermal (61%) is the primary interacting resource.
    - Petroleum (55%) is the second most frequent interacting resource.
    - 20% of high-suitability CGS areas occur without interactions, mostly in Bookara Shelf, Allanooka Terrace, Greenough Shelf and Beermullah Trough.

Petroleum interaction – Triassic-Lower Jurassic (G2A1)

Petroleum with high suitability

- Spatial distribution
    - Covers 1% of the Northern Perth Basin.
    - Found on Dandaragan Trough, Coomallo Trough and Beermullah Trough.
- Most frequent interactions
    - CGS (61%) is the primary interacting resource.
    - Geothermal (9%) is the secondary interacting resource.
    - 37% of high-suitability Petroleum occurs without interactions, making it more isolated than in deeper intervals.

Petroleum with moderate suitability

- Spatial distribution
    - Covers 39% of the Northern Perth Basin.
    - Present on Bookara Shelf, Allanooka Terrace, Greenough Shelf, Dongara Terrace, Dandaragan Trough, Beharra Springs Terrace, Donkey Creek Terrace, Cadda Terrace, Beagle Ridge, Coomallo Trough, Beermullah Trough and Mandurah Terrace.
- Most frequent interactions
    - CGS (78%) is the primary interacting resource.
    - Groundwater (2%) shows limited interaction with Petroleum.
    - 4% of moderate-suitability Petroleum occurs in isolation.

CGS interaction – Triassic-Lower Jurassic (G2A1)

CGS with high suitability

- Spatial distribution
    - Covers 27% of the northern Perth Basin.

    - Present on Dandaragan Trough, Beharra Springs Terrace, Donkey Creek Terrace, Cadda Terrace, Yarra Yarra Terrace, Coomallo Trough, Beermullah Trough, Barberton Terrace and Mandurah Terrace.
- Most frequent interactions
    - Petroleum (81%) is the primary interacting resource.
    - Groundwater (1%) shows minimal overlap with CGS.
    - 19% of high-suitability CGS areas occur without interactions, primarily in Dandaragan Trough, Cadda Terrace and Beermullah Trough.

Groundwater interaction – Triassic-Lower Jurassic (G2A1)

Groundwater with high suitability

- Spatial distribution
    - Covers 3% of the northern Perth Basin.
    - Found on Greenough Shelf, Beagle Ridge, Cadda Terrace, Beermullah Trough.
- Most frequent interactions
    - Petroleum (23%) and CGS (23%) are the primary interacting resources.
    - 66% of high-suitability groundwater occurs without interactions, mostly in Beagle Ridge, Cadda Terrace and Beermullah Trough.

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