Western Australia's Tight Gas Industry

A review of groundwater and environmental risks

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Acknowledgments

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Executive Summary

Cook et al. (2013) stated in the Australian context that "Shale gas production is no different from any other development of the landscape and like most other land uses, it poses some risks to the condition of the water, soil, vegetation and biodiversity, and has the potential to impact on the capacity of natural resources to supply human, as well as ecological needs into the future." The current study reinforces that premise.

We are working towards a sufficient level of understanding of the geology, hydrogeology, groundwater dependent ecosystems and their links to social values to manage the existing groundwater use in the northern Perth Basin. The increase in water required for a tight gas industry amplifies this issue. There is also the risk of local to regional scale impacts to water quality. The Canning Basin, in particular, is only just starting to be understood in this context.

There is uncertainty around the magnitude of environmental impacts of the tight gas industry. Comprehensive studies are lacking, but this should not be interpreted as tight gas extraction having no potential for impacts. Rather, the tight gas industry does not apply enough resources to the assessment of risk to groundwater and the environment.

There are a number of examples of peer-reviewed literature showing serious unconventional gas impacts on groundwater in the US, regardless of the industry’s insistence that there are no impacts. This should provide a warning to other jurisdictions (such as Western Australia) that impacts do occur and are usually found by third parties. In particular, the typical lack of baseline data collected prior to any unconventional hydrocarbon industrial activity occurring makes impacts difficult to conclusively identify.

Areas where tight gas exploration or production occurs are at risk of impact, the level of risk depending on local factors which are currently difficult to assess due to a lack of data. Hence a precautionary approach should be applied as hydraulic stimulation is irreversible. If there is no significant impact potential, this should be provable. Exploration alone has capacity to impact groundwater resources and the environment, albeit on a local scale near sites that are hydraulically stimulated, including areas hydraulically connected to those sites through faults and other potential conduits. The development of a full production scale tight gas industry in Western Australia has the potential for similar regional-scale impacts to water resources as have been observed in other jurisdictions.

There is no proof that impacts which have occurred elsewhere cannot or will not happen in Western Australia, particularly in areas such as the Canning Basin in the Kimberley and the North Perth Basin in the Mid-West that we are only just starting to understand hydrogeologically. There are exploration leases which cover many parts of the Canning and Northern Perth basins, but also in many other parts of Western Australia including the South West. In areas set aside for conservation or public drinking water source protection, it is advisable to exclude all tight gas activities. Even if economically viable deposits are found in those areas, extracting them would pose an unacceptable risk based on the issues explored herein. There are current exploration leases over Gnangara Mound, Perth’s most important groundwater resource, for example. Public drinking water source protection areas in rural Western Australia are also covered by exploration leases, as are many areas of groundwater supported agriculture.
The Whicher Range in the southern Perth Basin is a poignant Western Australian example of the lack of certainty in methods used by unconventional gas proponents to investigate the risks to aquifers. The Whicher Range seismic data interpretations from 2004 and 2012 draw quite different interpretations of the same data. The 2004 interpretation shows relatively little connectivity between faults and relatively little propagation of faults to the surface, hence the industry’s appraisal of hydraulic stimulation as low risk at this site. The 2012 analysis of the same data shows significantly more fault connectivity at depth in the target zone and fault propagation to nearer the surface. The 2012 interpretation of subsurface structure (faulting) presents a much greater risk that the 600,000 litres of unrecovered diesel injected into the hydraulic stimulation target zone may reach aquifers near the surface.

There is anecdotal evidence that leaks in conventional oil wells have happened already in Western Australia but detailed studies do not exist. Unconventional wells are likely to leak more frequently due to the additional pressure they are subjected to over long production timeframes. There are no detailed monitoring networks set up around the more than a dozen wells hydraulically stimulated thus far in Western Australia. The existing regulatory framework is not giving certainty that impacts are not occurring in the existing conventional and unconventional wells. Hence how can the regulatory framework give the public certainty that the impacts observed in other jurisdictions will not occur here?

The recommendations of this report are as follows:

1. Require that industry proponents fund the investigations necessary to present a robust and defensible understanding of the impact risk (incorporating geology, hydrogeology, environment and Aboriginal cultural heritage, including their linkages) in Western Australia, prior to undertaking tight gas exploration or production activities. This needs to account for project-specific impacts as well as cumulative impacts of a fully-developed tight gas industry.

2. Require that groundwater take be licensed and impact assessed, particularly given the risk of impact from water supply and tight gas wells in the proclaimed Groundwater Areas of the northern Perth and Canning basins. The Department of Mines and Petroleum (DMP) (2015) states that it only may require licensing.

3. Modify the Western Australian regulatory environment to incorporate the issues explored herein, in particular the issues around drilling, monitoring, project approvals and cumulative impacts. The Department of Water (DoW) allocation planning process is an example of a regulatory framework managing cumulative impacts. Given the risk of water and environment related impacts, DoW should have a more significant role in the approval process for the unconventional hydrocarbon industry, not just its water supply.

4. Upgrade groundwater allocation plans for the relevant areas to intensive plans as soon as possible and prior to any additional tight gas exploration or production activities.

5. Augment good oilfield practice (in terms of drilling practice and regulation) with hydrogeological best practice, particularly in the context of unconventional gas wells that pose risks to confined aquifers.

6. Require post well abandonment monitoring across relevant aquifers. Further, in consideration of the long time frames for some impacts to be revealed, a trust fund approach would ensure that resources are available for post abandonment monitoring and well failure remediation.
7. All costs for impact assessment and baseline monitoring should be borne by unconventional hydrocarbon (UCH) proponents, not the tax payer, in line with the recommendations by Cook et al. (2013). The example of Palat et al. (2015), where government bore the costs of a project assessment, is unacceptable.

8. Audit all existing oil and gas wells in Western Australia, in terms of well leakage and well integrity. This will provide an understanding of the impact of existing activities as well as invaluable data on long-term well integrity in a State context.

9. Choose a number of representative existing conventional oil and gas wells, and unconventional wells that will be drilled and stimulated, for detailed hydrogeological investigations. This should include faults and other potential flow conduits, and these sites should be monitored for long term water quantity and quality impacts. The investigations would require the installation of nested piezometers (monitoring wells installed in different depths) across all aquifers (both potable and non-potable) across the full vertical extent of the tight gas wells. Monitoring networks (both local and regional) should be in place for at least 12 months prior to any hydraulic stimulation activity to ensure appropriate baselines are collected.

10. The recommendations in Cook et al. (2013) are comprehensive across all areas of UCH projects in Australia and the reader is suggested to review them also. They recommend that baseline studies are completed before exploration activities are undertaken and that a precautionary approach is applied due to the serious nature of potential impacts.

11. Declare a permanent moratorium on drilling and related exploration or production activities in conservation estate and public drinking water source areas. The risks associated with surface activities alone in the hydraulic stimulation process justify this, let alone the risks of hydraulic stimulation and well failure, which are difficult to currently quantify.

12. Make the Environmental Assessment and Regulatory System (EARS) and EARS2 publically available. The community has the right to know the environmental impact assessment under which tight gas exploration projects are being approved.

A moratorium on further exploration or production experiments is a regulatory option which will ensure protection of the environment and groundwater resources until such time as baseline studies are completed so the impact of all activities (including both exploration and production) can be rigorously assessed. However, a permanent moratorium is recommended over conservation estate and public drinking water source areas, given the considerable risk that even surface activities hold in the context of the biodiversity values or long term water supply security that these areas are created to protect.
## Contents

Introduction ......................................................................................................................... 9

Aim ................................................................................................................................. 9

Unconventional Hydrocarbons: What are they and how do we extract them? ................. 10

- Operational Issues in the Tight Gas Industry ................................................................. 11
- Well Density and Well Integrity ..................................................................................... 14
- Environmental Impacts .................................................................................................. 18

Western Australian Tight Gas ......................................................................................... 25

- Canning Basin ................................................................................................................. 28
  - Ecology and the Natural Environment ....................................................................... 28
  - Aboriginal Cultural Heritage Considerations .............................................................. 29
  - Hydrogeology .............................................................................................................. 30

- Northern Perth Basin ..................................................................................................... 35
  - Ecology and the Natural Environment ....................................................................... 35
  - Aboriginal Cultural Heritage Considerations .............................................................. 38
  - Hydrogeology .............................................................................................................. 38

- Regulation ...................................................................................................................... 43
- Estimate of the Amount of Water Required .................................................................... 48
- Individual Site Impact Assessment .................................................................................. 50

Discussion ......................................................................................................................... 52

Recommendations ............................................................................................................ 58

References .......................................................................................................................... 60
Figures

Figure 1 - Global shale gas resources ........................................................................................................... 9
Figure 2 - Extended petroleum system ........................................................................................................ 11
Figure 3 - Shale gas deposits in Northern America ....................................................................................... 12
Figure 4 - Diagrammatic representation of the stages of the hydraulic stimulation process ......................... 13
Figure 5 - Timeline and summary of activities at a hydraulic stimulation well ................................................ 14
Figure 6 - 31.5 km (east-west) typical aerial view of the Wasson Oil Field in Texas ........................................ 15
Figure 7 - 32 km field (east-west) typical aerial view of the Maverick Basin Oil Field in Texas ...................... 15
Figure 8 - Potential groundwater contamination pathways ............................................................................. 16
Figure 9 - Shallow - deep connectivity scenarios .......................................................................................... 21
Figure 10 - Prospective tight gas areas (shale gas) in Western Australia ......................................................... 26
Figure 11 - "Source" shales in WA that may be prospective for tight gas production with US comparison ......................................................................................................................................... 27
Figure 12 - A typical project timeline for tight gas deposits ............................................................................ 27
Figure 13 - Cross-section of the Fitzroy Trough in the Canning Basin .......................................................... 32
Figure 14 - Faults in the Noonkanbah Formation (left) and fault propagation into the Mesozoic Sediments (right) .................................................................................................................................................. 33
Figure 15 - Groundwater dependent ecosystems of the Canning Basin .......................................................... 35
Figure 16 - Potential GDEs of the northern Perth Basin ..................................................................................... 37
Figure 17 - Deep geology of the northern Perth Basin ....................................................................................... 41
Figure 18 - WNW-ESE oriented seismic profile depicting the subsurface geology of the Whicher Range Field ....................................................................................................................................................... 42
Figure 19 – Visual interpretation of the category/response water allocation planning model including approximate uncertainty at each stage of Management Response .......................................................... 48
Figure 20 - Whicher Range composite seismic section, circa 2004 ................................................................. 51
Figure 21 - Whicher Range composite seismic section, circa 2012 ................................................................. 51
Figure 22 - Map of jurisdictions where hydraulic fracturing is currently banned ............................................. 57
Tables

Table 1 - Review of depth of target formation - aquifer separation in the United States ..................23
Table 2 - Basic and physical data of WA tight gas deposits currently under investigation for production..................................................................................................................25
Table 3 - Category/response water allocation planning model..........................................................47
Table 4 - Work required in allocation plan development.....................................................................47
Table 5 - Estimate of water required..................................................................................................49
Table 6 - Depth of target formations versus the depth of fresh groundwater.................................53
Introduction
Unconventional hydrocarbon (UCH) production, particularly projects involving hydraulic stimulation (or "fracking"), is widely recognised as a highly controversial issue. Over recent years, there has been considerable separation between proponents and opponents of utilising UCH resources. The debate continues, in assessing what the actual and potential impacts are and what they will be.

Substantial UCH deposits, consisting of unconventional oil and unconventional gas, occur in many areas around the world. These provide a considerable increase in available hydrocarbon reserves, important in the context of dwindling hydrocarbon resources and worldwide energy supply (Boyer et al. 2011; International Energy Agency (IEA) 2013). Worldwide occurrence of established and potential unconventional gas deposits are shown in Figure 1. Note that the areas with unknown potential were not included due to scarcity of exploration data or the lack of abundant reserves in conventional natural gas reservoirs. It is likely that UCH deposits do occur in some of these areas (Boyer et al. 2011).

Figure 1 - Global shale gas resources (Boyer et al. 2011).

Aim
The aim of this report is to summarise the potential for impacts to groundwater resources and dependent ecosystems in Western Australia from the extraction of tight and shale gas, an UCH resource. This report represents a review of the main references relevant to this scope, as opposed to an exhaustive review of all literature, which is available elsewhere¹.

¹ For example, US EPA (2016) reviewed over 1200 sources of information for their report into the impacts of hydraulic fracturing for oil and gas.
This report makes recommendations for managing the process of extracting UCH resources with minimum risk to aquifers and ecosystems due to water contamination, in a Western Australian context. Note that air quality issues have not been included, nor have issues relating to infrastructure construction and operation, all of which can create additional impacts.

Unconventional Hydrocarbons: What are they and how do we extract them?

Like unconventional oil, unconventional gas terminology is not rigorously and unanimously defined. The terminology used varies by reference and jurisdiction, but herein unconventional gas is defined as gas which is found in unusual types of reservoirs. These fall into four categories: tight gas; shale gas; coal bed methane; and methane hydrates.

Tight gas is natural gas trapped in extremely low-permeability, typically low-porosity rock, often shale but can also be sandstone or limestone. Tight gas may also contain condensates, a low-density mixture of hydrocarbon liquids present as gaseous components in raw natural gas. Shale gas is natural gas contained in organic-rich sedimentary rocks dominated by shale and, because of the types of reservoir, it is sometimes considered a sub-category of tight gas (IEA 2013).

Coal-bed methane (CBM) is methane trapped within coal seams. Methane hydrates are made up of methane trapped in a solid lattice of water molecules under specific conditions of temperature and pressure typically in deep ocean sediments.

Tight gas and shale gas are the most common forms of UCH deposit but not in all jurisdictions (IEA 2013).

Shale gas and tight gas often occur in areas of conventional hydrocarbon resources (Figure 2), typically deep in the geological profile of sedimentary basins below the point of thermal hydrocarbon maturity (Huc and Vially 2012). The presence of UCH deposits has been identified for some time by the oil and gas industry and was initially seen as a nuisance as these deposits created issues during exploration and extraction of conventional hydrocarbons. There has been a lack of economic drivers (cost of production versus resource value) and technical feasibility to extract these resources until relatively recently (25 years ago), when fracture stimulation and horizontal drilling became technically possible. This occurred as part of exploration, research and development programs in the United States, focussed on the Barnett Shale in Texas (Boyer et al. 2011). Finding and exploring the economic potential of these deposits has since become a global pursuit for many hydrocarbon exploration companies.

The United States has been producing from tight gas deposits (including shale gas) for more than 35 years. Tight and shale gas have become a significant (>50 per cent) and increasing proportion of gas production since the early 2000’s. By 2040, it is predicted than the United States will produce two-thirds of its natural gas from unconventional sources (US Energy Information Administration 2013).
Figure 2 - Extended petroleum system: (1) conventional oil, (2) conventional thermogenic gas, (3) oil shale (immature source rock), (4) coal seams and coal bed methane, (5) primary biogenic gas and methane hydrates, (6) heavy/extra heavy oils, bitumen (7) secondary biogenic gas, (8) tight gas (typically tight sands), (9) tight oil/oil from source rocks and (10) shale gas. Modified after Huc and Vially R. (2012).

Operational Issues in the Tight Gas Industry
Exploration and Production

As the United States has pioneered the tight/shale gas industry, most issues associated with the industry are best explained using their experiences and examples (although every UCH deposit will be different). Since the early work done on the Barnett Shale there has been a rapid expansion of tight gas exploration and production in the United States. Figure 3 shows the location of these deposits (or plays). According to Boyer et al. (2011), the Marcellus Shale has the largest documented reserves followed by the New Albany Shale while the Barnett and Haynesville-Bossier Shales were the greatest gas producers in 2011. From 2000 to 2010 annual production of shale gas in the United States increased from 0.25 to 4.87 billion m$^3$ of dry gas, and is continuing to increase (U S Energy Information Administration, 2016).
There are documented impacts to the environment and water resources which can be attributed to tight gas projects (Vengosh et al. 2014; US EPA 2016). However, prior to describing impacts, it is important to briefly review the hydraulic stimulation process (see Figure 4), as environmental impacts can occur at any stage of this process and the natural resources and receptors impacted vary depending on which stage of the process said impacts occur. According to the United States Environmental Protection Agency (US EPA 2016), there are five stages to a hydraulic stimulation project and the potential areas of impact at each stage are highlighted:

1. water acquisition - the withdrawal of groundwater or surface water to make hydraulic fracturing fluids. Groundwater and surface water resources that provide water for hydraulic fracturing fluids can also provide drinking water for public or non-public water supplies used for agriculture and may also support groundwater dependent ecosystems. This is a key issue in arid areas and areas of limited water resources;

2. chemical mixing - the mixing of a base fluid (typically water), proppant (typically sand to hold open fractures), and additives (which vary company to company) at the well site to create hydraulic fracturing fluids. Spills of additives and hydraulic fracturing fluids can result in large
volumes or high concentrations of chemicals reaching groundwater, impacting groundwater and surface water with the potential to also impact dependent ecosystems;
3. well injection - the injection and movement of hydraulic fracturing fluids through the oil and gas production well and in the targeted rock formation. Belowground pathways, including the production well itself if there is an integrity breach, natural fractures (faults etc.) and newly-created fractures can allow hydraulic fracturing fluids, other fluids and gases to reach underground drinking water resources. Given groundwater can also support surface water resources (Winter et al. 1998), this can potentially impact on surface and groundwater resources and dependent ecosystems (Entrekin et al. 2015);
4. produced water handling - the onsite collection and handling of water that returns to the surface after hydraulic fracturing and the transportation of that water for disposal or reuse. Spills of produced water can impact groundwater and surface water; and
5. wastewater disposal and/or reuse - the disposal and reuse of hydraulic fracturing wastewater. Disposal practices (such as in unlined or poorly lined pits) can release inadequately treated or untreated hydraulic fracturing wastewater to groundwater and surface water resources, impact agricultural water quality and subsequently the wider environment. In some cases, hydraulic fracturing fluids are disposed of directly into groundwater systems.

Figure 4 - Diagrammatic representation of the stages of the hydraulic stimulation process (US EPA 2016).
It is also important to note that hydraulic stimulation of an individual well may occur multiple times over long time periods. Wells may be hydraulically stimulated multiple times to induce continued gas production, or increased gas output. In most cases the lifetime of an individual well is decades (US EPA 2016). A typical timeline of activities is shown in Figure 5 below.

**Figure 5 - Timeline and summary of activities at a hydraulic stimulation well (US EPA 2016).**

**Well Density and Well Integrity**

It is important to note that although conventional oil and gas production can have many of the same types of water resource and environmental impacts (spills, well integrity failure etc.), the well density in an unconventional oil/gas field, when compared to a conventional oil/gas field, is hundreds to thousands of times higher (Figures 6 and 7) depending on when and which commercial operator is developing the particular project, the drilling design and the level of hydraulic stimulation required.

Early in the development of the tight gas industry, hydraulic stimulation was done on vertical wells so a higher well density was required (Figure 6). However, since the development and reduced cost of horizontal drilling techniques, lower well densities are more typical with multiple wells starting from the same drilling site or pad (Figure 7). Although this reduces pad and well density in the landscape, it potentially puts greater pressure on the sites in terms of likelihood of impact due to the increased failure potential in the vertical portion of the well hole. Regardless, there are large increases in well density when compared to conventional oil and gas.

This increased well density increases the risk of impact as greater numbers of wells are present to potentially fail and require increased industrial activity (vehicle movement, spills, pipelines etc.) during construction and operation of these dense well fields. This increases the potential spatial scale and magnitude of impact when compared to conventional oil/gas wells. There are also major issues with the legacy that this well density can leave in the landscape, as even properly constructed wells may lose integrity through time. Well integrity failure rates are difficult to quantify, due to lack of baseline monitoring, and to compare, due to scant during and post stimulation monitoring (Davies et al. 2014).
Figure 6 - 31.5 km (east-west) typical aerial view of the Wasson Oil Field in Texas, some areas have well density as high as 9 wells per square kilometre with a well spacing of 500m (Source: Google Earth accessed 04/01/2017).

Figure 7 - 32 km field (east-west) typical aerial view of the Maverick Basin Oil Field in Texas, note the reduced but still high well density when compared to Figure 6 above (Source: Google Earth accessed 04/01/2017).
Well Integrity Failure Rates

Davies et al. (2014) reviewed only reliable databases of well integrity from around the world and found that failure rates were highly variable from 1.9 to 75 per cent, with the Marcellus Shale well failure rate at 6.3 per cent, for example. They found a greater proportion of failure in injection wells (such as those required for hydraulic stimulation) when compared to production only wells (such as in traditional oil/gas fields). They concluded it is not possible to have zero per cent well integrity failure. They also noted that the amount of information retained by oil and gas companies and regulators was not sufficient for an exhaustive study, hence better records and more post production/abandonment integrity auditing is required to assess the well integrity and impacts of unconventional hydrocarbon projects - but typically much of these data are not released (if they even exist) by the project proponents (Brantley 2015).

Potential groundwater contamination pathways (white arrows in Figure 8) due to failure in well integrity can include: (1) a casing and tubing leak into the surrounding rock, (2) the uncemented space behind the casing (called the annulus), (3) the small space behind the casing (microannulus) between the casing and cement, (4) gaps in cement due to poor cement quality or poor installation, and (5) microannuli between the cement and the surrounding rock (US EPA 2016).

Figure 8 - Potential groundwater contamination pathways (white arrows) due to failure in well integrity (US EPA 2016). Note that this figure is not to scale.
The short and long-term effects of repeated hydraulic fracturing on well components such as cement and casing are not well understood (US EPA 2011; Cohen et al. 2012) but are likely to reduce integrity (Davies et al. 2014). Therefore, increased and ongoing monitoring of well components over the lifetime of projects (and post abandonment) may help understand and subsequently minimise risk of well failure (Cook et al. 2013) as well as allow us to better understand well failure rates generally.

**Well Abandonment**

Once the operations at an oil/gas well (including both conventional and unconventional projects) used for either exploration or production ceases, this well is "abandoned". Well abandonment involves cementing and capping to ensure the well poses as little threat to water and environmental systems as possible or to prevent providing a pathway for gas emissions. As previously noted, it is not possible to have a zero per cent well failure rate during production let alone post abandonment (Davies et al. 2014).

This issue was also highlighted in a 2012 review completed in the United Kingdom (The Royal Society and the Royal Academy of Engineering 2012), which noted that abandonment requirements and an abandonment plan should be considered in the original well design, hence subject to regulation. No subsequent monitoring is required in that jurisdiction. The Royal Society and the Royal Academy of Engineering (2012) also recommended that on-going aquifer monitoring should occur post abandonment. In the United Kingdom, operators maintain responsibility for abandoned wells, with liability to remediate ineffective abandonment. However, without post abandonment monitoring (coupled with effective baseline monitoring) this would be near impossible to pursue in most cases. In the United States, post abandonment monitoring appears rarely, if ever, to be required or undertaken. Much of the information on well integrity and abandonment is held by industry, hence not in the public domain (Lennon and Evans 2016).

**Long-Term Well Integrity**

The very long-term integrity of a cemented and plugged abandoned well (beyond 50 years) is a topic where more information is needed, but it is unlikely that wells will maintain integrity over the long term. The subsurface environment is highly diverse and aggressive in terms of water chemistry (pH and high salinity, for example). Hence, materials used in well construction such as cement, fibreglass and steel are typically not stable in the subsurface for extended periods, particularly in the context of hydraulic stimulation which exposes these materials to pulses of intense pressures over long time frames (Davies et al. 2014; Cook et al. 2013).

In unconventional hydrocarbon well fields there will be a legacy of abandoned wells, which will need to retain integrity if we seek to avoid connections across the subsurface often over thousands of metres. These wells often intersect aquifers used for current and/or future water supply, subsequently well integrity is critical in protecting these vital resources which also support groundwater dependent ecosystems. The hydraulic integrity of strata containing waters from re-injection of flowback and other wastewaters (one common waste disposal method) from the hydraulic stimulation process will also be compromised if well integrity is not maintained (Cook et al. 2013). This is a critical point and is currently broadly not well addressed by the industry or regulators, which will be responsible for monitoring well integrity and remediating wells which have
lost integrity 20-30 years after a hydraulic stimulation project has completed. These issues are also relevant to conventional hydrocarbon wells, however, the increased number and greater spatial extent of wells in an unconventional project increases these risks exponentially.

There is also an issue relating to the effect of hydraulic stimulation on nearby abandoned conventional hydrocarbon wells (US EPA 2016). In most cases, well communication (pressure interaction) during fracturing results in a pressure surge accompanied by a drop in gas production at the hydraulically stimulated well and additional flow of produced water or hydraulic fracturing fluid at a nearby conventional well. However, if the offset well is not capable of withstanding the high pressures of fracturing, more significant damage can occur and subsequently compromise well integrity in the conventional well. An example of this issue occurred in January 2012, when hydraulic stimulation at a horizontal well near Innisfail in Alberta, Canada, caused a surface discharge of fracturing and formation fluids at a nearby operating vertical oil well (Energy Resource Conservation Board (ERCB) 2012).

**Environmental Impacts**

One of the most controversial topics surrounding UCH revolves around environmental impacts. There have been a number of highly publicised documentaries produced examining both sides of this debate. However, this report is concerned with peer reviewed, documented scientific evidence, not popular media. There are numerous studies assessing the environmental impacts of hydraulic stimulation: for example 1200 cited sources were used as part of the US EPA (2016) report which identified a risk of impact to both groundwater and surface water systems and their dependent ecosystems from a variety of aspects of the UCH industry. It is outside the scope of this report to review all of these sources but some of the key studies will now be examined.

A critical review (Vengosh et al. 2014) identified four potential risk areas for water resources (and dependent ecosystems):

1. the contamination of shallow aquifers with stray gas due to well integrity failure, which can also potentially lead to the contamination of shallow groundwater with saline water, hydraulic stimulation fluids etc.;
2. the contamination of surface water and shallow groundwater from spills, leaks, and/or the disposal of inadequately treated wastewater;
3. the accumulation of toxic and radioactive elements in soil or stream sediments near disposal or spill sites; and
4. the over extraction of water resources for high-volume hydraulic fracturing that could induce water shortages or conflicts with other water users, particularly in water-scarce areas.

Analysis of published data (Vengosh et al. 2014) showed evidence of stray gas contamination, surface water impacts in areas of intensive shale gas development, and the accumulation of radium isotopes and other contaminants in some disposal and spill sites. Another recent and significant study (Alawattegama et al. 2015) assessed water quality concerns in an area of hydraulic fracturing in south-western Pennsylvania that started late 2009. Well water samples were collected, analysed and where available pre-drill and post-drill water quality results and legacy operations (e.g. gas and oil wells, coal mining) were incorporated.
In Alawattegama et al. (2015), 56 of the 143 well owners surveyed indicated changes in water quality or quantity while 63 respondents reported no issues. Colour change (brown, black or orange) was the most common (27 households). Chloride, sulfate, nitrate, sodium, calcium, magnesium, iron, manganese and strontium were commonly found, with 25 households exceeding the secondary maximum contaminate level (SMCL) for manganese. Methane was detected in 14 of the 18 houses tested. The 26 wells tested for total coliforms (2 positives) and E. coli (1 positive) indicated that septic contamination was not a factor in the majority of wells. Repeated sampling of two wells revealed temporal variability in contaminants. Since 2009, 65 horizontal wells were drilled within a 4 km (2.5 mile) radius of the community and each well was stimulated on average with 3.5 million gallons of fluids. This study underscores the need for baseline studies of water quality, thorough analyses of data, documentation of legacy activity, pre-drill testing and long term monitoring post hydraulic stimulation.

The Pavilion unconventional gas field in Wyoming is another example of a site in the US where there have been impacts to shallow aquifer water quality due to hydraulic stimulation related activities. In their study, DiGiulio and Jackson (2016) detected organic compounds present in hydraulic stimulation fluids in shallow groundwater in wells installed by the US EPA. Other dissolved water constituents such as salt etc. were also detected. This study took over 10 years to complete, was not funded by industry and suggested that the entire groundwater resource for this area was contaminated with chemicals present in hydraulic stimulation fluids as well as target formation water. DiGiulio and Jackson (2016) suggested that this contamination had primarily come from leakage from surface ponds, however, given the lack of detailed investigation at this site there may be potential for shallow deep connectivity to also be contributing.

The direct contamination of shallow groundwater from hydraulic fracturing fluids in deep formations is an area of intense research interest and debate, which has not been conclusively answered either way. It is likely that the severity of this risk will vary on a site specific basis, but could occur via fluid movement through either induced or natural permeable structural features. Permeable pathways could include wellbores, faults, joints, induced fractures or some combination thereof (Engelder et al. 2009). The debate about the existence and impact of permeable pathways continues (US EPA 2012; Vidic et al. 2013; Lange et al. 2013; Gassiat et al. 2013; Ingraffea et al. 2014; Birdsell et al. 2015; Flewelling and Sharma 2015; Lefebvre et al. 2015; US EPA 2016).

In a recent review of the transport of hydraulic fracturing fluids in the subsurface, Birdsell et al. (2015) identified four drivers for upward migration of hydraulic fracturing and formation fluids: (1) topographically driven flow in a regional groundwater discharge zone, (2) overpressure in a shale gas reservoir, (3) the increase in pressure due to hydraulic fracturing fluid injection, and (4) buoyancy of hydraulic fracturing fluid. They also identified that some of these mechanisms are persistent while others are short lived. Some result directly from hydraulic fracturing while others are pre-existing mechanisms that may be active in conjunction with hydraulic fracturing. Birdsell et al. (2015) concluded that, in the absence of permeable pathways, the travel time for hydraulic fracturing and formation fluids to the surface will be in the order of thousands of years, contradicting and questioning the veracity of the widely criticised Myers (2012) paper which predicted impact in much shorter timeframes. The time for impacts to potentially occur will vary from location to location and will require complex assessments to determine.
Birdsell et al. (2015) also cited a number of examples where this migration has apparently occurred due to the presence of permeable pathways in short (operational) time frames. Llewellyn et al. (2015) concluded in their study of Marcellus Shale gas wells in Pennsylvania that the most likely explanation of the presence of natural gas and organic compounds in initially potable groundwater was stray natural gas and drilling or hydraulic fracturing compounds. These contaminants were driven approximately 1-3 km from the target formation for hydraulic stimulation along shallow to intermediate depth fractures to the aquifer used as a potable water source. Other authors (Warner et al. 2012) identified, through the use of geochemical tracers, the presence of natural and permeable pathways between deep hydraulic stimulation target formations and shallow aquifers in this locality.

With regards to shallow groundwater or environmental impact from deep target formation and shallow aquifer connectivity, Reagan et al. (2015) identified five plausible failure scenarios which are shown diagrammatically in Figure 9:

1. Extensive vertical fracturing of the formations bounding the reservoir because of inadequate design or implementation of the hydraulic stimulation operation, with the resulting fractures reaching shallow aquifers or even permeable formations connected to these formations;

2. Sealed/dormant fractures and faults that can be reactivated by the hydraulic stimulation, creating pathways for upward migration of gas, hydrocarbons and other contaminants;

3. Induced fractures/faults that reach groundwater resources after intercepting conventional hydrocarbon reservoirs, which may create an additional source (not shown in Figure 9 as there are too many variables in this scenario);

4. Hydraulic stimulation creating fractures that intercept older, abandoned unplugged wells (or wells with integrity failure) or their vicinity. This can be caused by lack of information about the location and installation specifics of the abandoned wells, or because of inadequate design or implementation of the stimulation operation resulting in excessively long fractures. These aging wells can intersect and communicate with freshwater aquifers, and inadequate or failing completions/cement can create pathways for contaminants to reach the potable groundwater resources; and

5. Failure of the well completion during stimulation because of inadequate/inappropriate design, installation and/or weak cement. In this case, the well itself is the weak link, and it either includes open voids, or is fractured during the stimulation process, or both. Thus, improper cementing and well completion can result in continuous, high-permeability pathways connecting the reservoir with the shallow aquifer, through which contaminants can be discharged towards the surface. Note that the overlying formations may or may not be fractured in this case.

The likelihood of these impact scenarios manifesting will vary on a site by site and case by case basis, but Reagan et al. (2015) concluded they are all possible.
Figure 9 - Shallow - deep connectivity scenarios. Upper (a) extensive vertical fracturing. Upper (b) sealed/dormant fracture reactivation. Lower (a) older, abandoned wells. Lower (b) well failure (Reagan et al. 2015).
**Induced Earthquakes**

The occurrence of microseismic events (small earthquakes) associated with hydraulic fracturing during and after the hydraulic stimulation process is well documented (US EPA 2016). There has also been increases in seismic activity associated with wastewater disposal through aquifer injection (US EPA 2016). This microseismic activity has the potential to increase the permeability of conduits and extend naturally occurring fractures. Vulgamore et al. (2007) concluded the possibility of fault movement (almost certain to increase conduit permeability) in some settings could extend laterally for thousands of feet away from the area being hydraulically stimulated. Fisher and Warpinski (2012) found the greatest induced hydraulic fracture propagation occurred when the fractures intersected pre-existing faults. It is also important to note that these earthquakes, regardless of their magnitude, have the potential to cause or accelerate well integrity failure as well (Davies et al. 2014).

Most of the earthquakes produced by the hydraulic stimulation and wastewater disposal process are small (between magnitude 2 and 3.6) and too small to cause significant damage. However, there are concerns that some of the largest earthquakes in the United States midcontinent in 2011 and 2012 may have been triggered by nearby hydraulic stimulation fluid wastewater disposal wells. The largest (as at 2013) was a magnitude 5.6 event which damaged hundreds of homes, destroyed 14 homes and injured two people. The mechanism responsible for causing this earthquake appears to be weakening of a pre-existing fault by elevating the fluid pressure causing fault reactivation and slippage (Ellsworth 2013). In September 2016, a 5.8 magnitude earthquake hit the same area and there is now a class action lawsuit against a number of the companies undertaking hydraulic stimulation and waste water disposal by injection in that area (http://www.usatoday.com/story/news/2016/11/07/oklahoma-earthquake-fracking-well/93447830/ accessed 10/1/2017).

**Target Formation - Surface Separation Distance**

It is important to point out that the risk of impact to shallow, typically potable aquifers, surface water systems and the environment increases as the separation between target formations for hydraulic stimulation and freshwater aquifers decreases (US EPA 2016). For context, the depth of the main hydraulic stimulation targets in the United States is given below in Table 1. Note that the examples of impact reviewed above (Vengosh et al. 2014; Llewellyn et al. 2015) are both from the Marcellus Shale, considered a relatively representative, neither shallow nor deep UCH deposit. This statement must be qualified by the fact that all UCH deposits will occur in different geological conditions. Further, these conditions might vary significantly within an individual UCH deposit, not just between them (Table 1).
Table 1 - Review of depth of target formation - aquifer separation in the United States (US EPA 2016).

<table>
<thead>
<tr>
<th>Basin/play/formation</th>
<th>Approx. depth (ft [m] below surface)</th>
<th>Approx. net thickness (ft [m])</th>
<th>Distance between top of production zone and base of treatable water (ft [m])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole plays</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antrim</td>
<td>600 to 2,200 [200 to 670]</td>
<td>70 to 120 [20 to 37]</td>
<td>300 to 1,900 [90 to 590]</td>
</tr>
<tr>
<td>Barnett</td>
<td>6,500 to 8,500 [2,000 to 2,600]</td>
<td>100 to 600 [30 to 200]</td>
<td>5,300 to 7,300 [1,600 to 2,200]</td>
</tr>
<tr>
<td>Eagle Ford</td>
<td>4,000 to 12,000 [1,000 to 3,700]</td>
<td>250 [76]</td>
<td>2,800 to 10,800 [850 to 3,290]</td>
</tr>
<tr>
<td>Fayetteville</td>
<td>1,000 to 7,000 [300 to 2,000]</td>
<td>20 to 200 [6 to 60]</td>
<td>500 to 6,500 [200 to 2,000]</td>
</tr>
<tr>
<td>Haynesville-Bossier</td>
<td>10,500 to 13,500 [5,200 to 4,120]</td>
<td>200 to 300 [80 to 96]</td>
<td>10,100 to 13,100 [3,080 to 3,990]</td>
</tr>
<tr>
<td>Marcellus</td>
<td>4,000 to 8,500 [1,000 to 2,600]</td>
<td>50 to 200 [20 to 60]</td>
<td>2,125 to 7,650 [648 to 2,330]</td>
</tr>
<tr>
<td>New Albany</td>
<td>500 to 2,000 [200 to 600]</td>
<td>50 to 100 [20 to 30]</td>
<td>100 to 1,600 [30 to 490]</td>
</tr>
<tr>
<td>Woodford</td>
<td>6,000 to 11,000 [2,000 to 3,400]</td>
<td>120 to 220 [37 to 67]</td>
<td>5,600 to 10,600 [1,700 to 3,230]</td>
</tr>
</tbody>
</table>

Hydraulic Stimulation Water Requirements and Waste Disposal

Substantial volumes of water are required to be sourced (and waste water disposed of) in hydraulic stimulation projects. The US EPA (2016) quote a median figure per well based on data from 2011 and 2013 in the range of 5.7 million litres, with the 10th and 90th percentiles being 0.28 to 23 million litres respectively. Recent estimates of water required per well in Western Australia are 7 million litres for exploration, 7-17 million litres during evaluation and 21 million litres during production (DMP 2015), which may require multiple hydraulic stimulations to reach ultimate gas recovery targets.

According to the United States EPA (2016), the amount of water required per well can vary significantly between and within an individual UCH deposit. Fresh water is typically desired, but brackish and saline water can be used in some circumstances. Some companies prefer a certain water chemistry, as defined by total dissolved solids and proportions of various chemical constituents such as anions (chloride, sulphate etc.) and cations (sodium, calcium, magnesium and potassium). Wastewater which returns to the surface is a mixture of these hydraulic fracturing fluids and formation water. This wastewater can often be highly saline (up to 7 times sea water) and may contain a large number of toxic chemicals and gases making hydraulic stimulation water reuse difficult (Vengosh et al. 2014). It is outside the scope of this report to review these chemicals and their potential impacts in detail, but the reader is directed to United States EPA (2016), Vengosh et al. (2014) and Cook et al. (2013) for detailed information. Coram et al. (2014) highlighted the large amount of concern and uncertainty over the health impacts of exposure to these chemicals, hence no comprehensive assessment of the fate and impact of the overwhelming majority of these chemicals on flora and fauna (including humans) exists.

The amount of return water, on a well by well basis, available for reuse or requiring disposal varies considerably between and within the various hydraulic fracturing projects. It is difficult to quantify
precisely the amount of injected fluids that return in the wastewater; there is not a clear distinction between hydraulic fracturing fluids and formation water in wastewater. Typical indicators that could be used (salinity and radioactivity, to name two) are not routinely monitored (US EPA 2016).

The amount of produced water as a percentage of the total amount of injected fluid is highly variable (US EPA 2016; Vengosh et al. 2014). The maximum is less than 85 per cent in all but one of the examples given in those compiled in US EPA (2016), and most values are less than 30 per cent. In rare cases, the amount of wastewater is greater than the amount of injected fluid, with the additional water coming from the formation (Nicot et al. 2014) or from a conductive pathway from an adjacent formation (Arkadaksiy and Rostron 2013).

Wastewater reuse (the use of wastewater from a previous well) is typically low with a median of five per cent (range 0 to 20 per cent). Reuse is most common in areas where disposal options are limited, as opposed to areas where water resource availability is limited. Transport costs (i.e. trucking or pipelines) and transport impact considerations are important additional drivers for not transporting contaminated waste water between well sites. Wastewater from other processes (i.e. acid mine drainage or wastewater treatment plant (sewage) effluent, for example) have also been used but there is very little information on how often and how much of these types of water are used (US EPA 2016). In one Western Australian well that was hydraulically fractured, over 600,000 litres of diesel used as stimulation fluid was unable to be recovered (WA:ERA 2012).

**Other Environmental Impacts**

It is outside the scope of this report to comprehensively present the other risk from development of tight gas resources. The reader is directed to Cook et al. (2013), who highlighted the other environmental risks that this anthropogenic activity can cause. Some examples are:

- habitat fragmentation due to land clearing and linear infrastructure (road and pipeline construction);
- hydrological impacts due to linear infrastructure (water excesses or deficits) due to natural surface water (sheet flow) impairment;
- increased road kill or traffic accidents from an increased road network and increased traffic;
- spread of dieback and other pathogens;
- spread of feral animals such as cane toads; and
- seismic impacts on groundwater ecology directly (i.e. stygofauna).
Western Australian Tight Gas

The areas in Western Australia that are prospective for tight gas are shown in Figure 10. Current publicly available estimates of gas present in the most prospective geological units of the two most prospective areas are the northern Perth Basin (29-46 trillion cubic feet of recoverable gas) and the Canning Basin (73-147 trillion cubic feet of recoverable gas) (DMP 2015). Table 2 shows the summary data for the physical extent (of particular note is the depth) of these deposits included the target formations for hydraulic stimulation the northern Perth and Canning basins (Cook et al. 2013). Triche (2012) identified other prospective formations for tight gas deposits in the northern Perth and Canning basins (Figure 11).

It is important to note that, in line with deposits in the United States, the project life for tight gas projects is expected to be in the order of 30+ years (Figure 12). A brief review of the current level of understanding of these landscapes, including hydrogeology, biodiversity, cultural values and groundwater dependence of ecosystems will now be presented. A review of regulations relevant to the tight gas industry will then follow.

Table 2 - Basic and physical data of WA tight gas deposits currently under investigation for production (adapted from Cook et al. 2013).

<table>
<thead>
<tr>
<th>Basin</th>
<th>Northern Perth</th>
<th>Northern Perth</th>
<th>Canning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shale Formation</td>
<td>Carynginia Slate</td>
<td>Kockatea</td>
<td>Goldwyer</td>
</tr>
<tr>
<td>Geologic Age</td>
<td>Upper Permian</td>
<td>Lower Triassic</td>
<td>Middle Ordovician</td>
</tr>
<tr>
<td>Thickness (m)</td>
<td>Interval</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>92-458</td>
<td>92-915</td>
<td>92-736</td>
</tr>
<tr>
<td></td>
<td>Organically Rich</td>
<td>290</td>
<td>702</td>
</tr>
<tr>
<td></td>
<td>Net</td>
<td>76</td>
<td>70</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>Interval</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1220-5032</td>
<td>1007-5032</td>
<td>1007-5032</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>3264</td>
<td>3050</td>
</tr>
</tbody>
</table>
Figure 10 - Prospective tight gas areas (shale gas) in Western Australia (DMP 2015).
Figure 11 - "Source" shales in WA that may be prospective for tight gas production with US comparison (Triche 2012).

Figure 12 - A typical project timeline for tight gas deposits (DMP 2015).
Canning Basin

Ecology and the Natural Environment

The Canning Basin (Figure 10) occurs in the Kimberley region, considered one of the most important biogeographic regions in the world with high endemism and deep ecological divergences (Pepper and Keogh 2014). The area is biogeographically comprised of four bioregions: Dampierland, the Great Sandy Desert, the Ord Victoria Plain and the Tanami (Eco Logical Australia 2013). The following is taken from Cook et al. (2013), who cited Eco Logical Australia (2013) as the original source.

Dampierland is a semi-arid tropical bioregion in Western Australia that intersects part of the Canning Basin. It comprises four distinctive systems (Environment Australia (EA) 2000): (1) Quaternary sandplains overlying Jurassic/Mesozoic sandstones with red soil hummock grasslands on hills; (2) Quaternary marine deposits on coastal plains, with mangroves, samphire – Sporobolus grasslands, Melaleuca acacioides low forests, and Spinifex – Crotalaria strand communities; (3) Quaternary alluvial plains associated with the Permian and Mesozoic sediments of Fitzroy Trough that support tree savannas of Crysopogon – Dichanthium grasses, with scattered Eucalyptus microtheca – Lysiphyllum cunninghamii, interwoven with riparian forests of River Gum (E. camaldulensis) and Cadjeput Melaleuca hummock grasses and vine thicket elements. The main agricultural industries are beef cattle (about 75 per cent of the bioregion is grazed) and horticulture. The region contains Ramsar-listed wetlands and 10 threatened flora and fauna species have been recorded. Dampierland is an under-represented bioregion, with only one per cent of its extent formally reserved (Cook et al. 2013).

The Great Sandy Desert is a vast arid bioregion that covers a large part of the Canning Basin in Western Australia, extending into the Northern Territory. It is characterised by red sand plains, dunefields and remnant rock outcrops. It is intact in terms of contiguous cover, comprising mainly tree steppe grading to shrub steppe in the south (open hummock grassland of T. pungens and Plectrachne schinzii, scattered Desert Walnut (Owenia reticulata) and bloodwoods, Acacia spp., Grevillea wickhamii and G. refracta). Desert Oak (Casuarina decaisneana) occurs in the far east of the region. Calcrete and evaporite surfaces traverse the desert, and include extensive salt lake chains with samphire low shrublands, and Melaleuca glomerata – M. lasiandra shrublands (EA 2000). Tourism, mining and mineral exploration are the main land uses in the Great Sandy Desert. Pastoral leases cover the far western and eastern edges – about seven per cent of the bioregion is grazed. The region contains 30 threatened fauna species, including 10 considered to be extinct (Cook et al. 2013).

The Ord Victoria Plain is a semi-arid bioregion coinciding with the Canning Basin in Western Australia, and includes ridges, plateaus and undulating plains on Cambrian volcanics and Proterozoic sedimentary rocks. The lithological mosaic has three main components: (1) Abrupt ranges and scattered hills mantled by shallow sand and loam soils supporting Triodia hummock grasslands with sparse low trees including Snappy Gum (E. racemosa); (2) Cambrian volcanics and limestones forming extensive plains with short grass (Enneapogon spp.) on dry calcareous soils and medium-height grassland communities (Astrebla and Dichanthium) on cracking clays. Riparian forests of River Gum fringe drainage lines; and (3) in the south-west, lateritised upland sandplains (EA 2000). Extensive grazing is the main industry with at least 80 per cent of the bioregion grazed. Despite this,
the native vegetation mosaic is reasonably intact across the extent of the bioregion. A total of eight threatened species have been recorded (Cook et al. 2013).

The Tanami is a tropical arid bioregion that traverses parts of the Canning and Georgina basins in Western Australia and the Northern Territory. It comprises mainly red Quaternary sandplains overlying Permian and Proterozoic strata which are exposed locally as hills and ranges. The sandplains support mixed shrub steppes of Corkbark Hakea (*Hakea suberea*), desert bloodwoods, acacias and grevilleas over *Triodia pungens* hummock grasslands. Wattle scrub over *T. pungens* hummock grass communities occur on the ranges. Alluvial and lacustrine calcareous deposits occur throughout. In the north they are associated with Sturt Creek drainage, and support *Cryspogon* and *Iseilema* short-grasslands often as savannas with River Red Gum (EA 2000). Over 1500 taxon have been recorded in the Tanami, including 26 threatened flora and fauna. About 25 per cent of the Tanami is suitable for domestic grazing. Feral camels, horses and donkeys are a major management issue, and the declared weed, *Parkinsonia*, is establishing around watering points of pastoral leases in the bioregion. The level of formal reservation is less than 10 per cent. There are also a number of important surface water features with groundwater connectivity, the most important of which is the Fitzroy River, now a target for development of irrigated horticulture industry (Cook et al. 2013).

The Fitzroy River Catchment is in the Dampierland bioregion and is made up of the two distinct habitat types: ranges and plains. The plains portion of the Catchment which occurs on the Canning Basin comprises plains of red sands and alluvials of grey-brown clays with low lying uplands of sandstone and limestone shallow soils (Beard 1990). The Catchment is characterised by acacia thickets with sparse trees, grasslands and savannahs. Spinifex steppes dominate the centre and east of the bioregion with a transition to sparse tree steppe over spinifex and hummock grasses in the north and east (Thackway and Cresswell 1995). Current conservation reserves represent less than five per cent of the Dampierland bioregion and the Fitzroy River has evidence of substantial surface water groundwater interaction, including deep and saline groundwater discharge (CSIRO 2009).

**Aboriginal Cultural Heritage Considerations**

The Canning Basin is a large part of the Kimberley Region, in which Aboriginal people make up 50 per cent of the population and 90 per cent of the people who live outside of major towns (Bergmann 2006). The Aboriginal traditional custodians of the Kimberley are culturally, linguistically, and socio-politically distinct (Toussaint et al. 2001), and this is reflected by the complex relationship that they share with the country they care for.

Aboriginal peoples' traditional knowledge and understanding of terrestrial and aquatic ecosystems is inter-related with their customary use of these landscapes. These ecosystems provide bush foods, art and craft materials, medicines and are culturally significant to the landscape. Water is a sacred and basic source and symbol of life (Langton 2006), and aquatic resources are part of the customary economy and an invaluable component of local experiences. The aquatic species themselves continue to be vital to the livelihoods of the people. Further, traditional fishing, hunting, and gathering activities significantly contribute to financial income and diet (Altman 1987; Jackson and Altman 2009).

The economic and cultural values of the Canning Basin river systems to the Aboriginal traditional custodians are currently poorly understood by environmental managers and water planners (A. Poelina pers. comm. 19 October 2015). Some of these values are difficult to analyse, making water
allocation decisions problematic (Jackson 2008). Few quantitative investigations on the use of resources by Aboriginal people have been conducted, and the values of non-traded goods and services in these societies have not been evaluated (Jackson et al. 2011).

Hydrogeology

Regional Hydrogeology

The hydrogeology of the Canning Basin (Australia’s second largest sedimentary basin) is largely unknown. Detailed studies have been carried out only in: the extreme south west; West Canning Basin (DoW 2010; DoW 2012); around Broome, Dampier Peninsula and LaGrange Subarea (DoW, 2016a) and near Derby (DoW 2008). Elsewhere conditions are inferred from pastoral bores in the Fitzroy Trough and along the coast, and inland from widely spaced hydrocarbon exploration wells. The basin contains some 10 km of sediments ranging in age from Ordovician to Cretaceous, and can be subdivided into the Fitzroy Trough and Gregory Sub-basin (extending south east from Broome and encompassing the Fitzroy River Basin) and the Kidson and Willara Sub-basins, which underlie the Great Sandy Desert.

The Cretaceous Broome sandstone aquifer extends along the entire coast from the De Grey River to Cape Leveque, and inland by up to 150 km. It generally thickens towards the coast, reaching a maximum thickness of around 250m. The Broome Sandstone is an unconfined aquifer, recharged directly from rainfall and conformably overlying the largely impermeable Jarlemai Siltstone. Groundwater is generally fresh, but is brackish to saline towards the De Grey River, with salt water interfaces along the coast and around Samphire Marsh and Roebuck Plains where groundwater discharge supports springs and phreatophytic vegetation. The aquifer is used for Broome town water supply and for agriculture and stock watering (DoW 2010; Laws 1990).

The Jurassic Wallal Sandstone underlies the Jarlemai Siltstone in the west of the basin, and crops out beneath the Great Sandy Desert. It unconformably overlies various formations of Permian age which are not mapped. Together with the overlying Alexander Formation, it forms a 500m thick aquifer, unconfined inland, and confined along the coast where it is overlain by the Jarlemai Siltstone and Broome Sandstone. It is recharged by direct rainfall on the outcrop, and groundwater flow is towards the coast, or locally to King Sound. Groundwater discharge is presumably a considerable distance offshore, as the potentiometric head along the coast is artesian, up to 30m above sea level at Cape Keraudren. Groundwater in the extreme southwest of the basin is low, but salinity increases to brackish north of Samphire Marsh, and is around 2500 mg/L at Broome (Laws, 1990). The aquifer was investigated in the West Canning Basin for supply to Port Hedland, and is now being increasingly used between the De Grey River and Samphire Marsh for irrigation (DoW 2010; DoW 2012).

The Triassic Erskine Sandstone occupies a syncline extending south east of Derby. It is in contact with an overlying outlier of Wallal Sandstone at Derby, and is bounded beneath and around the margin by the underlying Blina Shale. Groundwater is recharged on the outcrop of the aquifer, with groundwater flow towards King Sound. Seawater interfaces occur in the aquifer around the Derby peninsula. The aquifer is used for Derby water supply and small scale horticulture. Shallow groundwater in areas underlain by Blina Shale is generally saline, suggesting some leakage potential (Smith 1992).
The Permian Liveringa Group contains 600m of various sandstone aquifers and fine grained formations, and crops out in the Fitzroy Trough. It overlies the largely impermeable Noonkanbah Formation. Groundwater varies in salinity from marginal to brackish and is used for stock and domestic supply, and was used for irrigation at Camballin (Phil Commander pers. comm. 8/02/2017).

The Permian Poole Sandstone and Grant Group form a major aquifer up to 2100m thick (Laws 1990; Laws 1991). They crop out as inliers in the Fitzroy Trough, in the Grant and St Georges Ranges, and underlie the greater part of the Great Sandy Desert, stratigraphically below the Noonkanbah Formation. In the Great Sandy Desert the Poole Sandstone and Grant Group are in contact with overlying Cretaceous sandstones. There is very little information on the hydrogeology. The water table is generally deep, but comes to the surface to discharge in salt lake chains occupying former drainage lines (palaeodrainages). Groundwater from these aquifers is used for community water supply and along the Canning Stock Route. At the Admiral Bay mineral deposit south-east of Broome, groundwater in the Grant Group is saline, but there is little information on salinity elsewhere (Phil Commander, pers. comm. 8/02/2017).

Very little is known of the aquifers stratigraphically below the Grant Group in the Kidson and Willara Sub-basins. In the eastern Fitzroy Trough there are various sandstones and Devonian limestone reefs which generally contain fresh groundwater and probably represent local flow systems, discharging to the major rivers. The hydrogeological conditions around the Goldwyer Formation are therefore unknown.

An alluvial aquifer, consisting of up to 25m of sands and gravels, stretches some 275 km along the Fitzroy River (Lindsay and Commander 2005). The Fitzroy Alluvium is recharged from the river during the wet season and from discharge of the Canning Basin regional aquifers, generally during the dry season. Groundwater discharge is particularly likely to come from the Liveringa Group that underlies a substantial part of the alluvium. Although exchange with regional aquifers leads to discharge to the river, most of the basin scale discharge is to and beyond the coast (CSIRO 2009). Surface water systems also interact with aquifer systems throughout the Canning Basin, however there is currently not a sufficiently detailed understanding in the context of water allocation planning for even the most studied, the Fitzroy River (Vogwill 2015). What has been shown is that groundwater is an important water supply to surface water systems and their dependent ecosystems (Lindsay and Commander 2005; CSIRO 2009; Harrington et al., 2014).

Salinity in the Fitzroy River is often less 250 mg/L in the wet season and ranges as high as 900 mg/L in the dry season. Dry season salinity is likely related to groundwater salinity as baseflow dominates river input over runoff, and wet season salinity drops in response to dilution from rainfall runoff. The river salinity changes with location and is fresh (< 500 mg/L) between Fitzroy Crossing and Noonkanbah, marginal (500–1000 mg/L total dissolved solids) between Noonkanbah and Myroodah due to groundwater inflow salinity, and fresh again from Myroodah to Willare due to tributary inflows. The variations with location are related to groundwater discharge from the underlying formations such as the Noonkanbah Formation and Blina Shale (Lindsay and Commander 2005).
Geological and Structural Investigations as a Proxy for Hydrogeology

No regional scale study of the hydrostratigraphy (including hydrogeologically relevant faulting) of the Canning Basin exists. For reference, hydrostratigraphy is the structure and distribution of subsurface porous materials in reference to the flow of groundwater, often relating to stratigraphy while stratigraphy is (geology) the study of rock layers and the layering process (stratification). The most recent stratigraphic studies into the deep basin geology identified large gaps in terms of sedimentological and structural assessment due to a lack of data (Parra-Garcia et al. 2014). Consequentially they were only able to map to formation level (based on age) and there is a large amount of uncertainty around sediment type distribution, let alone structural features such as faults and shallow deep connectivity. Studies are underway but are difficult due to the lack of basin scale, detailed data. An example of the level of detail available in Parra-Garcia et al. (2014) is shown in Figure 13. Note the lack of a precise depth scale as there was not enough data to extrapolate the measured depths at drilled locations with the seismic (geophysical) interpretation. The faults as mapped by Parra-Garcia et al. (2014) were also not exhaustive. These were only the most major faults, and their study had no assessment of the permeability (or lack of permeability) of individual fault structures. This will only be possible with detailed hydrogeological studies such as flow mapping and aquifer testing near faults to look for boundary effects (barrier or conduit). More detailed investigations are required to address these considerable data gaps. This is particularly true in the Willara, Kidson and Gregory Sub-basins while the Fitzroy Trough has been the target of a more local scale investigation (Dentith et al. 2014).

Figure 13 - Cross-section of the Fitzroy Trough in the Canning Basin (Parra-Garcia et al. 2014).
In their study of the CO₂ geosequestration potential of the Carboniferous–Permian Grant Group and Permian Poole Sandstone in the Fitzroy Trough, Dentith et al. (2014) had access to more targeted geophysical data. They subsequently were able to provide a more detailed interpretation of faulting and other structural controls over a limited area of the Canning Basin. These features are critical to the sealing potential of various geological layers from a CO₂ sequestration perspective. As part of this study, Dentith et al. (2014) assessed the faults present in the Noonkanbah Formation, Figure 14, an important seal for the Grant-Poole group and also a potential source shale that could become a target of hydraulic stimulation (Triche 2012). Dentith et al. (2014) also observed in some cases the propagation of deep faulting (Figure 14) into the Mesozoic sediments above the break up unconformity, which is typically where the fresh water aquifers occur. Note the much greater number of faults identified as compared to the regional scale interpretation (left hand side of Section 1 on Figure 13).

Figure 14 - Faults in the Noonkanbah Formation (left) and fault propagation into the Mesozoic Sediments (right) (Dentith et al. 2014).

Water Management

At the time of the release of the Kimberley Regional Water Plan working discussion paper (DoW 2009a), there were only 25 active groundwater licenses in the Fitzroy River catchment area. The licenses allowed total abstraction of less than two gigalitres (GL) per year and were granted for Aboriginal community bores, pastoral bores, and limited horticulture. The pastoral bores were for “diversified activities” (other than livestock and domestic use). Abstraction occurs from livestock and domestic bores of the pastoral industry to support tourism and to supplement the Aboriginal community supplies. Due to the historically low usage and demand, allocation limits have not been set across the Basin.
Current surface water management in the catchment appears focussed on collecting additional data and includes gauging stations at Willare, Fitzroy Crossing, Diamond Gorge, Phillips Range and MeNoSavy, with temporary monitoring at Mount Winifred and Mount Krauss. Additional stations to support flood management were set up at Fitzroy barrage, Christmas Creek, Margaret Gorge, Noonkanbah, Looma and Willare but there are still considerable data gaps (DoW 2009a).

Groundwater monitoring is almost non-existent outside of development areas such as the Fitzroy River, regional centres and large-scale mining operations. In the only substantial evaluation of the Fitzroy alluvial aquifer as a water resource, Lindsay and Commander (2005) stated that further field investigations need to be conducted to properly assess the potential for increased abstraction of groundwater.

Ecohydrology

The current state of mapping of groundwater dependent ecosystems (GDEs) in the Canning Basin is shown in Figure 15. Note the variability in type of GDE (dependent on surface expression of groundwater, subsurface availability of groundwater and cave/aquifer systems) and the extensive areas that have not even had a preliminary desktop assessment (cross-hatched areas). Some local scale investigations are underway, focussed on GDEs associated with the Broome Sandstone of the West Canning Basin (Wright et al. 2016), a small portion of the Canning Basin and one study in the Great Sandy Desert. Most of these have not been formally published, so cannot be referenced. Where results are available, high numbers of GDEs have been identified (Wright et al. 2016), with a high number (128) identified in the La Grange Groundwater Area alone.

Although the ecohydrology and groundwater dependence of ecosystems of the area is not well understood, CSIRO (2009) selected four environmental assets from the Kimberley, including two from the Fitzroy River Catchment, for the Directory of Important Wetlands in Australia (Environment Australia 2001), in order to qualitatively assess for changes to their hydrogeological regimes from climate and development effects. These wetlands are important for a variety of ecological reasons and because they have high cultural value, particularly to Aboriginal traditional owners. The following characterisation of these environmental assets is based on the description of the assets given by Environment Australia (2001).

The Camballin Floodplain is in the central reaches of the Fitzroy River and includes the Le Livre Swamp System and numerous other seasonal wetlands (Environment Australia 2001). Halse and Jaensch (1998) reported that the Camballin Floodplain is an important bird habitat and that there are at least 67 recorded species, with bird numbers often exceeding 20,000. The Fitzroy River channel is an important habitat for fish, especially as its large deep pools provide dry season refuges. The river contains a high diversity of fish, including some that are listed as threatened species, for example, the Northern River Shark and the Freshwater Sawfish (Storey et al. 2001; Morgan et al. 2002).

Geikie Gorge National Park is located in the upper Fitzroy catchment approximately 30 km upstream of Fitzroy Crossing. It is a permanent pool on the Fitzroy River about 13 km long and 100m wide. The gorge is an important refuge area for fish and other aquatic fauna during periods of drought (van Dam et al. 2008). The gorge’s permanent water and food resources are valuable to the park’s...
traditional custodians, the Bunuba people, who are involved in sharing its cultural values with visitors.


Northern Perth Basin

Ecology and the Natural Environment

The northern Perth Basin occurs in the Mid-West region, an area which contains important biodiversity (Rutherford et al. 2005; Cook et al. 2013). The Midlands area (a part of the Mid-West region) in particular has been noted to have exceptional flora species richness. Griffin (1994) estimated that this area contains about one-fifth of the floristic diversity of the entire state as understood in 1994. Griffin et al. (1990) found such high floristic diversity in their study, they considered the area has few parallels globally. The area contains three important biogeography regions—Carnarvon, Geraldton Sandplains and Yarloo (Environment Australia 2000). The following is adapted from Cook et al. (2013).

Carnarvon is an arid bioregion in Western Australia that traverses part of the Southern Carnarvon Basin and the northern part of the northern Perth Basin. It comprises Quaternary alluvial, aeolian and marine sediments that overlie Cretaceous strata. It supports a mosaic of saline alluvial plains with samphire and saltbush low shrublands, Bowgada (*A. ramulosa var. linophylla*) low woodland on sandy ridges and plains, Snakewood (*A. xiphophylla*) scrubs on clay flats, and tree to shrub steppe over hummock grasslands on and between red sand dune fields. Limestone strata with *A. startii / bivenosa* shrublands outcrop in the north, where extensive tidal flats in sheltered embayments support mangrove communities (Environment Australia 2000). The often sparse vegetation is largely contiguous. The bioregion supports extensive cattle and sheep grazing. About 85 per cent of the bioregion is grazed, with unmanaged goats contributing to total grazing pressure (Cook et al. 2013).
Located over part of the Southern Carnarvon Basin and the northern part of the northern Perth Basin, the semi-arid Geraldton Sandplains bioregion supports mainly proteaceous scrub-heaths on the sandy earths of an extensive, undulating, lateritic sandplain mantling Permian to Cretaceous strata (Environment Australia 2000). It supports extensive York Gum (E. loxophleba) and Jam (A. acuminata) woodlands that occur on outwash plains associated with drainage. It is a centre of high endemism, particularly for flora and reptiles, and various vegetation communities are identified as being 'at risk' in the absence of reservation. The bioregion also comprises nationally important wetlands. Grazing is practiced across at least 80 per cent of the bioregion, and dryland cultivation and cropping and associated vegetation clearing is also prevalent (Cook et al. 2013).

Yalgoo Bioregion in Western Australia is an arid to semi-arid bioregion in the Perth Basin. It is characterised by low woodlands to open woodlands of Eucalyptus, Acacia and Callitris on red sandy plains of the Western Yilgarn Craton and southern Carnarvon Basin. It includes the Toolonga Plateau of the southern Carnarvon Basin. It is rich in ephemeral species (Environment Australia 2000). Tenure is predominantly pastoral leasehold and sheep grazing is the main enterprise type. The region supports a rich diversity of flora and fauna, including 23 listed taxa (Cook et al. 2013).

Groundwater dependence of ecosystems of the northern Perth Basin have only been assessed at a preliminary level (Rutherford et al. 2005). Numerous river systems and wetlands exist as well as vegetation and caves in areas of shallow depth to groundwater (Figure 16). Most groundwater dependence is inferred due to a lack of site specific investigations. The environmental water requirements of these ecosystems, hence the level of groundwater dependence (i.e. total, partial etc.), is unknown (Rutherford et al. 2005; DoW 2009) - let alone an assessment of the impact of declining groundwater levels or water quality changes. Some preliminary studies of the area’s major river systems (the Murchison, Chapman, Greenough, Irwin, Arrowsmith, Coonderoo, Hill, Moore Rivers and Gingin Brook) have shown variable groundwater interaction (i.e. groundwater recharge or groundwater discharge) along the reach of most rivers.

Initially it was thought that groundwater, which supported these ecosystems, was from the shallow aquifers. But in recent years, studies have shown an increased importance of discharge from the deeper semi-confined and confined aquifers as an important support mechanism for many groundwater dependent ecosystems (DoW 2016b). Development pressures are increasing in the northern Perth Basin, particularly in the Jurien and Arrowsmith groundwater areas, where previously there were only low levels of groundwater use and little need for concern over impacts to groundwater dependent ecosystems. It is now necessary to raise the level of management response to correspond with the increasing level of risk to ecosystem values (DoW 2009).
Figure 16 - Potential GDEs of the northern Perth Basin (Rutherford et al. 2005).
Aboriginal Cultural Heritage Considerations
The Aboriginal cultural heritage value and significance of the northern Perth Basin is difficult to determine as no publications are available. In 2009, DoW mapped the location of sites that were in the Department of Aboriginal Affairs Aboriginal Sites Register in the northern Perth Basin, but this may not be representative of the actual sites of Aboriginal cultural significance (DoW 2009). More generally, Dreamtime stories have long been and continue to be considered sacred to Aboriginal people (Jones 2015). Many of these Dreamtime stories relate to water features in the landscape, so their protection will contribute to the preservation of cultural values in the northern Perth Basin.

Like other parts of the south-west of Western Australia, cultural heritage protection has been eroded due to the institutional cultural heritage management. In 2012, for example, the definition of "sacred" was reinterpreted to only include sites "devoted to a religious use rather than a place subject to mythological story, song or belief" Jones, (2015). Large numbers of previously registered Aboriginal heritage sites in the Department of Aboriginal Affairs Aboriginal Sites Register have been removed and large number of sites have been blocked from being added to due to changes to the definitions (including extensive technical term re-interpretation) (Jones 2015). This was found in 2015 to be a "misconstruction" by Justice John Chaney in the Supreme Court of Western Australia Jones, (2015).

Hydrogeology
The northern Perth Basin (defined as the area of the Perth Basin north of Gingin Brook) contains a sequence of variably interconnected sedimentary units (Figure 17). The hydrogeology of the northern Perth Basin is complex (DoW 2010a; DoW 2016b). Numerous authors have completed studies in the area, but these have all been compiled by the recent review (DoW 2016b). DoW (2016b) presented the current reconnaissance level of understanding.

The hydrogeology of the northern Perth Basin is known from a network of widely spaced government exploratory bores, from private bores and hydrocarbon exploration wells. The basin contains as much as 15 km thickness of sediments close to the eastern margin along the Darling Fault, and thins to around 2 km at the coast near Jurien. Sedimentary rocks are relatively flat lying and undeformed close to the Darling Fault, but are increasingly faulted and tilted in the Hill River area, east of Jurien (DoW 2016b). The basin contains two major aquifers, the Parmelia Aquifer and the Yarragadee Aquifer, in which low salinity groundwater extends to depths of around 3000m (Commander 1974).

There are seven main regional aquifer systems within the northern Perth Basin sedimentary sequence: the Superficial, Mirrabooka, Leederville, Leederville–Parmelia, Yarragadee, Cattamarra and Eneabba–Lesueur Aquifers. There are three minor local scale aquifers within Permian age sediments being the Wagina, Irwin–High Cliff and Nangetty Aquifers. The Tumblagooda Sandstone is another minor aquifer which appears to have both intergranular and fracture porosity. Local, small supplies of groundwater can be sourced from the Proterozoic metasediments and basement, with the fissured Noondine Chert being a significant aquifer (DoW 2016b).

Superficial sands and limestone underlie the coastal plain and form the Superficial Aquifer, which is up to 25m thick. Groundwater is recharged by rainfall, by ephemeral streams and there is also upward discharge in places from the underlying confined aquifers. The Tamala Limestone exhibits karst features, with caves and groundwater conduits. The water table is typically in the Superficial
Aquifer and is generally shallow, supporting wetlands and phreatophytic vegetation (Rutherford et al. 2005), but some areas are unsaturated, with the water table in the Mesozoic aquifers below, but some of the ephemeral wetlands are perched. Groundwater generally becomes increasingly brackish to saline northwards, and saline groundwater occurs near the coast associated with salt lakes. Fresh groundwater resources are limited, but have been used for Jurien and Cervantes water supply (DoW 2016b).

The Cretaceous Parmelia Aquifer occurs below the Dandaragan Plateau, between the Dandaragan Scarp and the Darling and Urella Faults. It is up to 400m thick and is bounded below by the Otorowiri Siltstone, and in the south is overlain by the Leederville Aquifer and the Kardinya Shale aquiclude. It contains low salinity groundwater, except in places along the eastern margin, especially along the chain of salt lakes along the Coonderoo River where groundwater discharge is inferred to take place. Groundwater recharge takes place directly from rainfall infiltrating the sandy soils. Groundwater flows south from a groundwater divide west of Coorow, and north of this discharge occurs to the Arrowsmith River and springs along the Dandaragan Scarp. The aquifer is used for town supply to Mingenew, Three Springs, Carnamah/Coorow, Dandaragan and Moora, for stock and domestic water on farms, and for irrigation (DoW 2016b).

The Jurassic Yarragadee Formation is the most important and widespread aquifer in the northern Perth Basin extending from the metropolitan area almost as far north as the Greenough River. It is up to 3000m thick, outcrops between the coastal plain and the Dandaragan Scarp (except in the Hill River area where older formations occur), and extends below the coastal plain and to the Darling and Urella faults in the east below the Otorowiri aquiclude. Groundwater is recharged by rainfall and local runoff where this aquifer outcrops. Groundwater flows north from a groundwater divide near the Hill River to eventually discharge offshore south of Dongara, and south to discharge to the ocean south of Ledge Point. Locally, north of the Irwin River, groundwater flow is south-westward towards the coast. Around Badgingarra and to the east of Eneabba, and on the Victoria Plateau north of the Irwin River, the water table is deep, as much as 150m below surface (DoW 2016b).

Low salinity groundwater extends to the base of the Yarragadee Aquifer, suggesting the meteoric flow reaches depths of at least 3000m in some areas. Groundwater in the upper part of the aquifer is generally fresh to marginal, but locally saline close to the Arrowsmith and Irwin Rivers. Groundwater from the Yarragadee Aquifer is used for town water supply to Geraldton, Eneabba and Badgingarra, by the mineral sand industry at Cooljarloo and Eneabba, and for stock and domestic supply, and irrigated agriculture (DoW 2016b).

The early Jurassic Cattamarra and Eneabba Formations and the underling Lesueur Sandstone outcrop at the surface in the Hill River area where they are intensely faulted. In the Hill River area, groundwater in the Lesueur and Eneabba is generally fresh, but the Cattamarra Aquifer contains mainly brackish to saline groundwater. In the Dandaragan Trough, below the Yarragadee Aquifer, electric logs from oil wells indicate high salinity, suggesting that the groundwater is stagnant, and less connected to a meteoric groundwater flow system. Groundwater from the Lesueur Aquifer is used for Jurien and Greenhead-Leeman town water supply, irrigation, and stock and domestic supply, though on farms south-west of Eneabba, groundwater in the Cattamarra Aquifer is brackish to saline (DoW 2016b).
The Triassic Kockatea Shale occurs directly below the 25m thick Superficial Aquifer at Jurien, and was reported to contain saline groundwater. East of the Beagle Fault, it is directly overlain by the fresh water bearing Lesueur Sandstone and Woodada Formation. Progressively eastwards, where the Yarragadee occurs at the surface, the Kockatea Shale underlies saline groundwater in the Cattamarra, Eneabba and Lesueur aquifers. The Permian Highcliff Sandstone and Irwin River Coal Measures reach the surface north of the Greenough River, where they are local sources of low salinity groundwater. To the south, in the Dandaragan Trough, where they are confined by the Kockatea Shale, groundwater is saline (DoW, 2016b).

Hydraulic connection between aquifers can be restricted across faults, but in some cases faults appear to be groundwater conduits. Low permeability clay/shale beds within the aquifer units can also restrict groundwater flow but the precise nature of flow restrictions is unknown at most localities. Low permeability units (aquitards) can restrict connectivity between the aquifers, with the main regional aquitards (the Kardinya Shale and South Perth Shale) hydraulically isolating parts of the unconfined Superficial and Mirrabooka Aquifers from the underlying confined Leederville and Leederville-Parmelia Aquifers. Groundwater in the Leederville-Parmelia Aquifer is regionally isolated from the deeper Yarragadee Aquifer by the intervening Otorowiri aquitard. The Carnac Formation in the lower part of the aquifer contains substantial clay. The Leederville Aquifer is separated from the underlying Yarragadee Aquifer by the South Perth Shale over most of its extent. The Kockatea Shale is a widespread aquitard separating the Eneabba–Lesueur Aquifer from deeper Permian aquifers, but is present at a great depth in the basin except over the Beagle Ridge, an area over the southern Yarra Yarra Terrace in the east, and along the northern margins of the basin (DoW 2016b).

Extensive faulting is present in those sediments which occur beneath the Gondwana break up unconformity, a major stratigraphic feature which represents the period when Gondwana started to break up as a function of rifting and sea floor spreading about 155-120 million years ago in the north west and south west parts of the Perth Basin respectively (Falvey and Mutter 1981). As previously noted, the status of these faults as conduits or barriers to groundwater flow is highly variable and has not been widely investigated. There has also been little assessment of how much continued movement on these faults has resulted in fault propagation into the Mesozoic sediments above the break up unconformity, as in the Canning Basin. The location of only major faults has been mapped, using regional scale geophysics. It is likely that significant numbers of other smaller fault systems, typically structurally related to major fault systems, will exist but will require more detailed local studies to map in any detail including their propagation above the Gondwana break up unconformity. In the Southern Perth Basin, a local scale investigation identified a large number of faults propagating to near the surface (Figure 18) (WA: ERA 2012). Leyland (2012) also noted the importance of faulting for structural control and groundwater flow in the Leederville Aquifer in the central Perth Basin.
Figure 17 - Deep geology of the northern Perth Basin (Mory and Iasky 1996).
Figure 18 - WNW-ESE oriented seismic profile depicting the subsurface geology of the Whicher Range Field. Note the large number of faults propagating to near the surface in proximity to wells (WA: ERA, 2012).

Water Management

Groundwater use in the northern Perth Basin is higher than in the Canning Basin, but is still relatively low. The Gingin, Jurien and Arrowsmith Groundwater Areas are all being actively managed (DoW 2015; DoW 2010a; DoW 2010b). The Gingin Groundwater Area has the greatest level of use with an allocation limit of 187 GL across all of the aquifers, of which 140 GL was already licensed and 30 GL were being assessed in 2015 (DoW, 2015). The Jurien Groundwater Area has an allocation limit of 94.6 GL, with 64.4 GL available across all aquifer for allocation to new users as at 2010 (DoW 2010a). The Arrowsmith Area has an allocation limit of 184.9 GL, with approximately half of that (97.9 GL) available across all aquifer for allocation to new users as at 2010 (DoW 2010b).

Water that is abstracted from the aquifers of the area support a number of town water supplies, as well as agriculture and mining. Freshwater (defined as water less than 1000 mg/L total dissolved solids) occurs in the aquifers often to depths of over 1000m, presumably becoming more brackish and saline at greater depth however data is limited below 1000m (DoW 2015; DoW 2010a; DoW 2010b). Groundwater is also used by the environment with approximately 17 per cent of the landscape containing potential GDEs (Rutherford et al. 2005). Groundwater monitoring across all Groundwater Areas is modest and is mostly focussed on the shallower parts of the aquifers (DoW 2015; DoW 2010a; DoW 2010b) with very little quantitative understanding of the reliance of GDEs
on regional groundwater (Rutherford et al. 2005). The allocation plans (DoW 2015; DoW 2010a; DoW 2010b) primarily use a simple percentage of recharge method to determine the amount of water reserved to maintain the environment, but it is unknown how well this has worked as detailed studies of GDEs are not available. A number of the preliminary investigations in Rutherford et al. (2005) identified faults potentially discharging deep groundwater in proximity to GDEs.

**Regulation**

Currently the unconventional gas industry in Western Australia is under the same regulations as the conventional oil and gas industry with the Department of Mines and Petroleum (DMP) as the lead agency. Projects are assessed on a site by site and project by project basis, hence do not account for cumulative impacts. Other state agencies have various roles including conducting environmental impact assessments when tight gas activities may result in significant impacts. Native title holders are not required to approve or reject activities until the production phase. There is currently no requirement for post well abandonment monitoring (DMP 2015).

The legislation relevant to the onshore oil and gas industry in Western Australia, as well as the agencies responsible and their roles, are given in detail in DMP (2015). This is a complicated regulatory environment with multiple agencies having at times somewhat overlapping jurisdiction without clear boundaries, particularly in the water and environmental aspects. Given the report herein is focused on impacts to the environment and water resources, the relevant regulations for those aspects will now be briefly presented. Note that these are mostly State Government agencies except for the Commonwealth Department of Environment. Also note that with the exception of the Allocation Planning Process under the Rights in Water and Irrigation (RIWI) Act 1914, there is no capacity for these regulations to manage cumulative impacts of multiple projects/issues. All other regulations are typically focused on the impact of a single specific project/activity.

- **Department of Mines and Petroleum (DMP)** administers the following legislation in this context: Petroleum and Geothermal Energy Resources Act 1967; Petroleum Pipelines Act 1969; Petroleum (Submerged Lands) Act 1982; Occupational Safety and Health Act 1984; Environmental Protection Act 1986 (delegated Authority for native vegetation clearing); Dangerous Goods Safety Act 2004. These acts cover safety regulation, environmental regulation, native vegetation clearing and resource management and administration.

- **Department of Environment Regulation (DER)** administers the following legislation in this context: Environmental Protection Act 1986; Contaminated Sites Act 2003; Waste Avoidance and Resource Recovery Act 2007. These acts cover regulating activities with potential impacts on the environment, developing and implementing policies and strategies that promote environmental outcomes and reducing the environmental impact of waste.

- **Department of Parks and Wildlife (DPaW)** administers the following legislation in this context: Conservation and Land Management Act 1984; Wildlife Conservation Act 1950; Biodiversity Conservation Act 2016. DPaW has primary responsibility for managing the State’s national parks, marine parks, State forests and other reserves, which cover more than 27 million hectares, for conserving and protecting native animals and plants, and for managing many aspects of the access to and use of the State’s wildlife and natural areas.

- **Department of Water (DoW)** administers the following legislation in this context: Rights in Water and Irrigation Act 1914; Metropolitan Water Supply, Sewerage and Drainage Act 1909; Country Areas Water Supply Act 1947; Water Agencies (Powers) Act 1984; Waterways
Conservation Act 1976. These acts cover licensing of systems to take water, and regulate public drinking water protection in both groundwater and surface water systems. DoW also provides expertise and advice, and prepares policies, plans and guidelines about protecting and managing water resources.

- Environmental Protection Authority (EPA) enforces the Environmental Protection Act 1986 which covers: conducting environmental impact assessments; preparing statutory policies for environmental protection; preparing and publishing guidelines for managing environmental impacts; and providing strategic advice to the Minister for Environment.

Drilling Water Bores, Conventional/Unconventional Hydrocarbon and Mineral Exploration Wells

In Australia, anyone who drills a bore to access groundwater from confined aquifers for water supply for agriculture, irrigation, stock/domestic use and dewatering bores must be licensed, and the type of licence depends on the type of aquifer and drilling method used (Australian Drilling Industry Training Committee (ADITC) 2010). There are three classes of drilling licenses: Class 1 – restricted to drilling operations in single non-flowing aquifer systems such as water table aquifers; Class 2 – in addition to operating in Class 1 conditions, permits drilling operations in multiple on-flowing aquifer systems such as confined aquifers; and Class 3 – in addition to operating in Class 1 & 2 conditions, permits drilling operations in flowing aquifer systems such as artesian aquifers. In Western Australia, DoW, under the RiWI Act 1914, issues groundwater licences in all proclaimed groundwater areas and for all artesian water bores in the State. Water from sub-artesian bores can be taken without a licence in unproclaimed areas, so do not necessarily meet the minimum construction requirements. DoW sometimes includes the 'Minimum Construction Requirements for Water Bores in Australia' as a condition in the 26D permit to construct, but this does not make it legally enforceable. Drillers are required to 'perform all work' in confined aquifer under the 'Minimum Construction Requirements for Water Bores in Australia' (National Uniform Drillers Licensing Committee (NUDLC) 2012).

A driller who drills for exploration or production purposes in the oil, gas and mining industries does not have to be licensed by the same scheme as water production, but does need to be qualified. This qualification, the Australian Qualifications Framework (AQF) is a Federal framework which comprises a series of qualifications formally named "Certificate I, II, III and IV, Diploma and Advanced Diploma" (ADITC 2011). The unconventional gas industry is governed by the Petroleum and Geothermal Energy Resources Acts 1967 which requires all petroleum exploration and production to be carried out in a proper and workmanlike manner and in accordance with 'good oilfield practice'.

'Good oilfield practice' is a long held industry concept that is stated as 'all those things that are generally accepted as good and safe in carrying out exploration or recovery operations' Manifold (2010). The obvious flexibility in this allows for innovation or optimisation during operations (Manifold 2010). However, this also allows different interpretations of regulations and standards, so the concept of 'good oilfield practice' and the subsequent application and engineering will vary from site to site and between operators. The concept of 'good oilfield practice' also appears to be focused on safety and minimising gas explosions and the extent to which 'good oilfield practice' protects the groundwater resources or environment is not well understood. Unconventional wells are also subjected to pressure much greater than are conventional wells or water supply wells, increasing the
risk of well integrity failure. The large number of exploration and production wells required for tight gas projects further amplifies this risk.

The Australian Drilling Industry Association (ADIA) recommends that all drillers should be certified/licensed and that this would help ensure aquifers are protected across the different industries (ADITC 2011), and this has occurred in other Australian jurisdictions such as New South Wales. With mining and oil/gas wells this lack of licensing, particularly with respect to well abandonment, has the potential to leave a legacy of inappropriately decommissioned wells. Wells that may meet 'good oilfield practice' may have a low risk of blow outs etc., but it is uncertain if their well design will provide sufficient safeguards in the context of groundwater and environmental protection. Based on water and environmental impacts observed in oil fields (conventional and unconventional) around the world (US EPA 2016), this appears to not be the case in many examples.

**Water Allocation Planning Process**

Of particular interest in the context of an issue like unconventional hydrocarbon projects, which as previously discussed have been shown overseas to have a risk of impacting water resources and the environment at both a local and regional scale, is the *Rights in Water and Irrigation (RIWI) Act 1914*. The *RIWI* Act was updated post the National Water Initiative (NWI) to provide guidance on Federal expectations in the context of the allocation planning process DoW (2011). The Western Australian allocation planning process is an important part of meeting the State Government's statutory responsibility to manage water. There are five clauses of the NWI that are specific to allocation planning. These are:

- Clause 36 – allocation decision making,
- Clause 37 – meeting ecological and resource security outcomes,
- Clause 38 – deciding when to plan,
- Clause 39 – the content of a plan as per Schedule E; and
- Clause 40 – implementing the plan.

It must be noted that, in general, the inclusion of these clauses by the NWI were not intended to be particularly prescriptive, therefore requiring state and territory governments to determine the timing and rigor of their own impact assessment used in allocation planning.

The Western Australian DoW administers surface and groundwater allocation by issuing licences under clauses 5C and 26D of the *RIWI* Act. Water allocation plans themselves, however, are not statutory documents but are the Department’s statement of how they will support licence assessment, and how much water has (and can) be allocated in a proclaimed Groundwater Area (DoW 2011).

DoW (2011) expanded on the purpose and process by which this is undertaken.

The purpose is to:

- maximise the amount of water available to allocate,
- maintain the integrity of the resource and the environment; and
- establish the required licence conditions for a local area, to protect other water users and the environment.
Their process is further clarified to:

- apply a transparent and consistent process to develop water allocation plans,
- seek advice from stakeholders throughout the planning process,
- put the necessary effort and funding into an area, depending on the current level of allocation and the risk to the resource and its users,
- use the best-available information; and
- provide for ongoing plan review and, if required, adapt our management to meet plan objectives.

The allocation planning process is an iterative one in that the required level of understanding of a water resource (including impacts on the environment) increases as the level of use or threat to the environment increases.

Knowledge and Impact Assessment Needs

The allocation planning process assesses risk to the environment and the water resource use sustainability in order to determine allocation limits. However, different levels of scientific rigor are applied depending on the amount of use as a proportion of the allocation limit. The Category/Response Model is used to assess the required level of management response (assessment) (R1-R4) as function of level of use (C1-C4), as shown in Table 3. Table 4 further summarises the level of investigation required as a Management Response (DoW 2011) and is shown conceptually in Figure 19.

The level of uncertainty during the early parts (C1-R1) of this iterative allocation planning process is high (Figure 19). Consequently there is considerable uncertainty over the allocation limit, and no plan is produced, only an allocation limit. The level of uncertainty then becomes reduced as the level of scientific rigor is increased. For other areas (C2–C4 and R2-R4), DoW produces two types of water allocation plans (DoW 2011):

(1) Standard plans, which are developed for medium-demand areas (C2); these require a low level of planning investment. C2 plans are based on the use of existing information, applying simple, local management rules, and existing State-wide policies.

(2) Intensive plans are developed where demand is high (C3 and C4), during which new studies are commissioned to reduce uncertainty in the allocation limit. These will include water resource and ecohydrological modelling and broad stakeholder consultation. An important part of C3 level planning is to establish environmental water regimes or environmental water requirements (EWRs). Over one-half of the proclaimed water areas in the State are at, or approaching, full allocation (C3) (DoW 2011).

Although this process is considered to be generally sound, the level of scientific investigation and subsequent rigor in the allocation limit can create issues in areas where there are rapid changes in water demand/licences. Figure 19 shows a problematic (A) and ideal (B) water use versus allocation limit trajectory. Under trajectory A, the level of allocation rises rapidly during the initial period where the links between cause and effect are poorly understood. This has the potential to jeopardise the sustainability of the resource, risking loss of human value associated with impacts to dependent biota and water. Under this trajectory there may be a need for an urgent correction accompanied by
environmental, social and economic consequences. Trajectory B is the desired course where the level of use stays within not only the allocation limit but the uncertainty of it at every level of management response. There will always be some level of uncertainty and risk but this process is about minimising this risk and making the process as transparent as possible.

Table 3 - Category/response water allocation planning model (DoW 2011).

<table>
<thead>
<tr>
<th>Category (C)</th>
<th>Licensed % of allocation limit</th>
<th>Impact from further licences</th>
<th>Risk to in-situ values</th>
<th>Licences required</th>
<th>Plan type</th>
<th>Maximum availability from resource</th>
<th>New information developed for plan</th>
<th>Allocation limits protect in-situ values</th>
<th>Specific rules protect values</th>
<th>Specific regimes protect values</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 Low</td>
<td>0 &lt; 30</td>
<td>Low</td>
<td>Low</td>
<td>R1 ✓</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>✓</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>C2 Medium</td>
<td>30 &lt; 70</td>
<td>Med</td>
<td>Med</td>
<td>R2 ✓</td>
<td>Standard</td>
<td>x</td>
<td>x</td>
<td>✓</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>C3 High</td>
<td>70 &lt; 100</td>
<td>High</td>
<td>High</td>
<td>R3 ✓</td>
<td>Intensive</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>C4 Over</td>
<td>&gt; 100</td>
<td>V high</td>
<td>V high</td>
<td>R4 ✓</td>
<td>Intensive</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Table 4 - Work required in allocation plan development (DoW 2011).

<table>
<thead>
<tr>
<th>Response</th>
<th>Aim</th>
<th>Resource assessment</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1 Limits only no plan</td>
<td>Basic approach to avoid potential impact</td>
<td>Flow estimate from gauge data or regional model</td>
<td>Basic rainfall recharge, throughflow or discharge estimate</td>
</tr>
<tr>
<td>R2 Standard plan</td>
<td>Standard approach to avoid impacts and prepare for C3</td>
<td>Flow estimate from gauge data or regional model</td>
<td>Detailed recharge, throughflow or discharge or regional model</td>
</tr>
<tr>
<td>R3 Intensive plan</td>
<td>Detailed approach to maintain C3 status and begin impact management</td>
<td>Flow estimate from gauge data or calibrated, localised model</td>
<td>Regional model and/or local models</td>
</tr>
<tr>
<td>R4 Intensive plan</td>
<td>Detailed approach to return resource to C3</td>
<td>Flow estimate from gauge data or calibrated, localised model</td>
<td>Regional model and/or local models</td>
</tr>
</tbody>
</table>

47 | Page
Figure 19 – Visual interpretation of the category/response water allocation planning model including approximate uncertainty at each stage of Management Response.

Undertaking the Resource Assessment in the allocation planning process requires application of a number of scientific techniques of increasing complexity (Tables 3 and 4). Basic desktop style evaluations at low levels of resource evaluation give way to detailed flow gauging, assessments of surface water/groundwater interaction, numerical modelling, ecohydrological assessment and precise determination of groundwater dependence of ecosystems, including EWR’s. The methodology for determining the level of assessment required is given in DoW (2009b). H3 (highest level) assessments are resource intensive and challenging projects that require long-term data sets but in brief require detailed hydrogeological assessment including installation and testing of investigation bores and modelling. A detailed explanation of the requirements of a H1-H3 level of investigation is given in Appendices A1-A3 in DoW (2009b). In brief, H3 level activities require surface water groundwater interaction and regional scale numerical modelling, including an understanding of GDE environmental water requirements.

Estimate of the Amount of Water Required

An important context for the water resource and environmental impact of tight gas is the amount of water required and the amount of effluent disposal required. Cook et al. (2013) stated that "Because shale gas production in Australia is in its infancy, the average volume of water needed to hydraulically fracture Australian shales is not yet known". It is a difficult question to answer as it depends on required water quality, the size of the gas field in terms of recoverable gas, amount of gas produced per well, lifetime of project wells, amount of reused water from previous wells amongst many other factors which are not available in the public domain. However, to put together an estimate of the water required for the northern Perth and Canning basins a simple indicative analysis has been completed.
To produce this analysis the order of magnitude of water required a number of assumptions must be made. O’Sullivan and Paltsev (2012) presented data of ultimate recovery of gas (or UR) per well in Pennsylvania as $100 \times 10^6$ or $10^8 \text{m}^3/\text{day}$ for a 30 year well with the variability from 50 to $150 \times 10^6 \text{m}^3/\text{day}$. One thousand cubic feet (1 Mcf) = 28.26 m$^3$ so 1 m$^3$ = 0.03538 Mcf, therefore UR per well is $10^6 \times 0.03538 = 3.538 \times 10^6$ in Mcf. One trillion cubic feet (Tcf) = $1 \times 10^9$ Mcf, so the number of wells per Tcf is $1 \times 10^9$ divided by $3.538 \times 10^6 = 282.6$ wells per Tcf for the $100 \times 10^6 \text{UR}$ case. Fifty $\times 10^6$ gives 565.3 wells per Tcf and $150 \times 10^6$ gives 188.4 wells per Tcf.

Each well needs 0.04 GL (40 million litres) over the life of the well (DMP 2015), so 1 Tcf requires $282.6 \times 0.04 = 11.3 \text{ GL over the life of the project}$. If we assume well life of 30 years (to match with O’Sullivan and Paltsev (2012)), 1 Tcf requires $11.3/30 = 0.3769 \text{ GL/year}$. This number is 0.7537 for the $50 \times 10^6 \text{m}^3/\text{day UR}$ case and 0.2512 for the $150 \times 10^6 \text{m}^3/\text{day UR}$ case. In terms of waste requiring disposal, we can assume 30 per cent return of hydraulic fracturing fluids to the surface (Engelder et al. 2014). Table 5 shows the water required in GL/year under the lower ($150 \times 10^6 \text{m}^3/\text{day UR}$), middle ($100 \times 10^6 \text{m}^3/\text{day UR}$) and upper ($50 \times 10^6 \text{m}^3/\text{day UR}$) scenarios.

The estimates of water required under even this simple analysis (Table 5) are variable but are also significant quantities of water which would significantly increase groundwater use in the northern Perth Basin and a more significant increase of groundwater use in the Canning Basin. Neither does this estimate include water required for work camp potable requirements, treatment facilities, pipeline construction, civil construction, dust suppression etc., so should be seen as a very low estimate, in the context of the full range of anthropogenic activities required for an unconventional gas project. Based on the figures from Cook et al. (2013) and DMP (2015), the total gas resource estimates are for the Goldwyer Formation only in the Canning Basin and the Carynginia Shale and Kockatea Formation in the northern Perth Basin. However, many other prospective tight gas reservoirs exist in these basins (Triche 2012). Once the tight gas industry has started in these areas (including constructing large amounts of infrastructure) it is likely that other sources will be developed so more water for hydraulic stimulation will be required and more waste will require disposal.

Table 5 - Estimate of water required.

<table>
<thead>
<tr>
<th>Basin</th>
<th>Gas Resource Estimate (Tcf)</th>
<th>Water per year (GL)</th>
<th>Waste per year (GL)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low₁</td>
<td>High₁</td>
<td>Highest</td>
</tr>
<tr>
<td>Northern Perth</td>
<td>29</td>
<td>46</td>
<td>59</td>
</tr>
<tr>
<td>Canning</td>
<td>73</td>
<td>147</td>
<td>229</td>
</tr>
<tr>
<td>Middle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas Resource Estimate</td>
<td>Low₁</td>
<td>High₁</td>
<td>Highest</td>
</tr>
<tr>
<td>Northern Perth</td>
<td>29</td>
<td>46</td>
<td>59</td>
</tr>
<tr>
<td>Canning</td>
<td>73</td>
<td>147</td>
<td>229</td>
</tr>
<tr>
<td>Upper</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas Resource Estimate</td>
<td>Low₁</td>
<td>High₁</td>
<td>Highest</td>
</tr>
<tr>
<td>Northern Perth</td>
<td>29</td>
<td>46</td>
<td>59</td>
</tr>
<tr>
<td>Canning</td>
<td>73</td>
<td>147</td>
<td>229</td>
</tr>
</tbody>
</table>

Note that 1, 2 and 3 refer to references for gas resource estimate. 1 is (DMP 2015), 2 is (Cook et al. 2013) and 3 is (Triche 2012).
Individual Site Impact Assessment

This section highlights issues with the level of publically available hydrogeological impact assessment at sites in Western Australia that have been hydraulically stimulated. In general it appears as though sites did not undergo detailed impact assessment as they were assumed to be at low to no risk of impact. Originally it was intended to work on a site in the northern Perth Basin or Canning Basin, however the data publically available on the DMP’s Petroleum and Geothermal Information System (WAPIS) contains nothing which can be effectively assessed as to its rigor from a hydrogeological impact assessment perspective. The DMP’s Environmental Assessment and Regulatory System (EARS) can only be accessed by a registered company, and will only display applications lodged by that company (http://www.dmp.wa.gov.au/Environmental-Assessment-and-1471.aspx). Environmental impact assessments should be publically available. Given the larger amount of material publically available for the Whicher Range site in the Southern Perth Basin, it was chosen for assessment.

In Calenergyu Resources Australia (2013), a Whicher project Environment Plan Summary, the only mention of risk to aquifers come in their hydrogeology section which stated: "The Yaragadee is a mostly confined regional aquifer. In EP408 (one of the unconventional gas wells) the Yaragadee Aquifer was intersected from 186m to 932m, and was subsequently isolated behind 3 permanently cemented barriers." There is no reference to risk to any aquifers (potable or not) in their Table 6.2, Risk Identification and Assessment.

During drilling of Whicher 5 (the well which was hydraulically stimulated), substantial amounts of free water entered the hole at approximately 3900m, in Sue Group sediments - the target for hydraulic stimulation. This water came from a groundwater bearing "open fracture", which presumably is a fault, and the water was strongly red coloured, believed due to the presence of iron oxide (Amity Oil 2004). The oil and gas industry has often suggested that faults/fractures at this depth should not allow water flow due to pressure from the overlying sediments and water. Deep faults in the Perth Basin typically propagate to at least the top of the pre-break up unconformity sediments, potentially higher. The Yarragadee Formation is a pre-breakup unconformity unit.

Geophysical seismic data in the main tool used by the oil and gas industry to map faults in the subsurface. Interpretations of these data in 2004 did not include any reference to this permeable fault encountered during drilling, nor did faults mapped typically propagate from the Sue Group up to close to the surface (Figure 20). A 2012 reinterpretation of faulting over a very similar cross section is shown in Figure 21. In particular, note the much greater vertical extent and continuity of faults mapped in 2012, with faults now intersecting the target zone for hydraulic stimulation. This potentially connects the target zones for hydraulic stimulation to shallow freshwater aquifers such as the Yarragadee and Leederville.

In efforts to produce gas from this well, diesel was used as a hydraulic stimulation fluid as water was not considered suitable (WA: ERA 2012). The total diesel injected during the hydraulic stimulation experiment was 7450 bbl (1184550 litres assuming 1 bbl = 159 litres), from which a total of 3546 bbl (563814 litres) were recovered after 36 days of production (Department of Industry and Resources (DIR), 2008). This leaves 620736 litres of diesel in the ground. No pre-hydraulic stimulation monitoring is stated to have been put in place in any of the aquifers, hence no monitoring was completed during stimulation and no post well abandonment monitoring has been completed. The
Whicher Range occurs in proximity to the Margaret River (Ten Mile Brook Dam) Priority 1 (highest level of protection) Drinking Water Protection Area. It is currently unknown what has happened to this more than 600,000 litres of diesel and, given the issues raised in this document, the author suggests a follow up study.

Figure 20 - Whicher Range composite seismic section, circa 2004 (Amity Oil 2004).

Figure 21 - Whicher Range composite seismic section, circa 2012 (WA: ERA 2012).
Discussion

Cook et al. (2013) stated in the Australian context that "Shale gas production is no different from any other development of the landscape and like most other land uses, it poses some risks to the condition of the water, soil, vegetation and biodiversity, and has the potential to impact on the capacity of natural resources to supply human, as well as ecological needs into the future." The current review reinforces that premise.

There is uncertainty about the magnitude of environmental impacts from the tight gas industry. While comprehensive studies are few and far between, this should not be interpreted as tight gas extraction having no potential for impacts. It should be interpreted as the tight gas industry not applying enough resources to its assessment of risk to groundwater and the environment. If there is no significant impact potential, this should be provable. Based on the primarily peer reviewed scientific literature assessed as part of this report, exploration alone has capacity to impact groundwater resources and the environment (albeit on a local scale) near sites that are hydraulically stimulated. Note that this includes areas hydraulically connected to hydraulic stimulation sites through fault and other potential conduits. The development of a full production scale tight gas industry in Western Australia has the potential for regional scale impacts, as have been seen in other jurisdictions.

The conventional oil and gas industry has caused impacts, but these are not well documented. In 1992, 200,000 of the 1.2 million abandoned oil and gas wells in the United States were leaking (Davies et al. 2014). No Australian comparable study exists to the best of the author's knowledge; however, there are some local examples of well failure. Hovea 8, a well in the northern Perth Basin, was shut in 2011 due to casing corrosion during production, only eight years into its operational life (http://www.originenergy.com.au/files/Quarterly_Report_30_June_2011.pdf). In the Robe River oilfield of the Carnarvon Basin during the 1980's, some old wells were bleeding gas and saline water (Phil Commander pers. comm. 8/02/2017) but no specific study or data are available. It is assumed that all of these wells followed 'good oilfield practice'.

Given that conventional oil and gas wells are not exposed to the same level of repeated structural stress as unconventional wells, it would follow that unconventional wells would fail at least as much as conventional wells. The much higher number of wells required for tight gas projects further amplifies this risk. Cook et al. (2013) identified well integrity and abandonment as issues where the current regulations are not sufficient to mitigate the risk to water resources and the environment to an acceptable level in the context of the unconventional gas industry. This is complicated due to the well density and duration of production inherent in these projects.

In terms of geological understanding, there are significant gaps in how well we understand the geology (particularly the structural geology) of the northern Perth and Canning Basins. In particular, our understanding of the Canning Basin is in its infancy with regional scale studies unable to map the geology below formation level to determine the distribution of lithologies within these formations (Parra-Garcia et al. 2014). The distribution of mapped faults across the Canning Basin in Parra-Garcia et al. (2014) is likely to be a significant under-estimate of the faults present, as when more local scale studies are available, like Dentith et al. (2014), Leyland (2012) and WA:ERA (2012), the number of mapped faults is very likely to increase.
Given our understanding of the hydrogeology is inherently based on our geological understanding, it follows that there are even more significant gaps in terms of how well we understand the hydrogeology of these prospective areas. This is particularly true in the context of the distribution of faults and fractures both through natural and potentially induced/reactivated features. Their status as conduits or barriers to groundwater flow will likely require some aquifer testing in proximity to faults to determine their hydraulic barrier or conduit effects. Selley (1992) noted there are natural, high permeability geological pathways for the migration of buoyant fluids, which are typically associated with structural features such as faults and folds. Gassiat et al. (2013) concluded that diffuse contamination with hydraulic stimulation fluids over long timeframes is possible and that the important implications are that hydraulic fracturing should not be carried out near potentially conductive faults, and impacts should be monitored for long timespans. Cook et al. (2013) further commented that there is a high degree of uncertainty about groundwater impacts due to a lack of detailed understanding of deep stratigraphy, faults and discontinuities, stress distribution and deep hydrogeological processes generally, and that a medium to high risk of aquifer impacts exists and that sensitive areas (such as National Parks and other conservation estates) should not be hydraulically fractured.

Our level of understanding of groundwater dependent ecosystems is even more limited. Many relevant areas have not been assessed or assessed at only a reconnaissance level. There is limited understanding of the implication of altered water regimes to these ecosystems, let alone linking them to Aboriginal and other cultural values, which are also not well documented in these areas.

The following data (Table 6) have been compiled to provide perspective on the depth of target formations versus the depth of fresh groundwater. The depth to fresh groundwater (defined as less than 1000 mg/L) comes from figures in DoW (2016b) and Commander (1981) for the northern Perth Basin, and from Ghassemi et al. (1990) for the Canning Basin. There may be fresh groundwater below this depth level in both Basins but hydrogeological investigations of deep aquifers are limited. This is due to the current modest level of use in these areas which means that generally the shallowest of sources have been utilised. When comparing these numbers to Table 1, there are United States tight gas projects with similar separation between target formations and fresh groundwater to those being proposed in Western Australia.

Table 6 - Depth of target formations versus the depth of fresh groundwater.

<table>
<thead>
<tr>
<th>Basin</th>
<th>Northern Perth</th>
<th>Northern Perth</th>
<th>Canning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Formation</td>
<td>Caryngina Shale</td>
<td>Kockatea Fm</td>
<td>Goldwyer</td>
</tr>
<tr>
<td>Depth Range (Cook et al. 2013) in m</td>
<td>1220 – 5032</td>
<td>1007 – 5032</td>
<td>1007 – 5032</td>
</tr>
<tr>
<td>Depth Average (Cook et al. 2013) in m</td>
<td>3,264</td>
<td>3,050</td>
<td>3,660</td>
</tr>
<tr>
<td>Depth to base of fresh known groundwater (approx in m)</td>
<td>1000</td>
<td>1000-3000</td>
<td>1500</td>
</tr>
<tr>
<td>Distance between production zone and groundwater (range in m)</td>
<td>220 – 4032</td>
<td>7 – 4032</td>
<td>0 - 4032</td>
</tr>
<tr>
<td>Distance between production zone and groundwater (avg. in m)</td>
<td>2,264</td>
<td>2,050</td>
<td>2,160</td>
</tr>
<tr>
<td>Aquifer</td>
<td>Yarragadee</td>
<td>Yaragadee</td>
<td>Grant-Poole</td>
</tr>
</tbody>
</table>

In terms of current level of water use versus water required for hydraulic stimulation of the tight gas resource currently identified, this report’s estimates of the water required suggests an
unconventional gas industry will require a significant increase in water use in the northern Perth Basin and a dramatic increase in the Canning Basin. There are also risks of surface and subsurface contamination over broad areas as a result of the full range of activities involved in a production scale tight gas industry.

The current level of water allocation planning in the northern Perth Basin is low, at R1 to R2 level of management. Three Groundwater Areas have been proclaimed with interim allocation limits determined based on simple percentage of recharge methodology. The Canning Basin is essentially unmanaged with the exception of the proclaimed groundwater areas that are at R1 to R2 level of management, but lower than the northern Perth Basin. In the context of increased groundwater use, these areas will be pushed towards requiring an R3 level of management, let alone in the context of tight gas exploration and production which has potential for water quality contamination. An R3 level of management is commensurate with H3 level of investigation. An H3 level of investigation is a resource intensive and challenging project that requires long-term data sets and detailed hydrogeological assessment including installation and testing of investigation bores and modelling. In the context of this report, surface water-groundwater interaction and regional scale numerical modelling would be required, including an understanding of GDE environmental water requirements and their links to cultural values. A detailed explanation of the requirements of a H1-H3 level of investigation are given in Appendices A1-A3 in DoW (2009b) but some important aspects of these investigations will now be discussed in the context of the current level of understanding.

Surface water-groundwater interaction in the northern Perth and Canning basins is an important knowledge gap that should be filled before water allocation/management can increase to an R3 level of use. As detailed in previous sections, the northern Perth Basin has a reconnaissance level investigation identifying GDEs while extensive areas of the Canning Basin remain unassessed. The water management issues surrounding surface and groundwater interaction were first comprehensively summarised by Winter et al. (1998). In this discussion paper (a United States Geological Survey circular), the impact of surface and groundwater use on surface water-groundwater interaction in the United States was summarised, including water quality impacts from land use and impacts to the environment.

There have also been major issues in wider Australia, particularly in the Murray-Darling Basin, relating to the over allocation of groundwater and surface water separately without adequate identification of their interaction. During the last five to ten years there has been a considerable effort in the Murray-Darling Basin to protect the water resource and environment, at a substantial cost to the Australian tax payer (Murray-Darling Basin Authority (MDBA) 2010). This has primarily come in the form of recouping water entitlements from irrigators of the Murray-Darling Basin, with a cost of $1.5 billion from 2008-09 to 2010-11 alone (Connell and Grafton 2011). Numerical modelling, including surface water-groundwater interaction, is an important part of being able to responsibly allocate water resources. Once correctly parameterised and calibrated, numerical models are the best tools we have to assess future impacts of water use, but this analysis should include uncertainty.

Surface water and groundwater modelling are widely accepted techniques for assessing hydrological impacts, and the best practice guideline for the application of groundwater modelling in Australia is Barnett et al. (2012). Although these are not formal guidelines or standards, they are a point of
reference for what is considered to be good practice in this field. Groundwater modelling is frequently applied to assess the impact of regional scale groundwater development and changes in surface water – groundwater interaction, including subsequent impacts to dependent ecosystems.

Although it is outside the scope of this report to summarise the contents of Barnett et al. (2012), their statements on two particularly pertinent issues are highlighted. The first one is the length of data available for calibration versus the length of model predictions. "Transient water resource management models will be run for the duration of the planning period. Where long-term sustainability is a management objective, the model should be run over a longer time frame than the immediate planning period, limiting the duration of predictive model runs to less than five times the duration of the calibration is recommended wherever possible" (Barnett et al. 2012). It is important to note at this point that the duration of proposed tight gas projects is longer than any of the current planning horizons in any of the allocation plans for the relevant areas.

No comprehensive data set exists that covers surface water - groundwater interaction within the context of the associated ecohydrology and the impacts on the system's biota and other culturally significant assets. Hence, it is difficult to see how a robust allocation limit can be determined across all relevant areas at even at R2, let alone an R3 level of management response in the next several years. Effectively, Barnett et al. (2012) advised that to make 50+ year predictions requires at least 10 years' worth of detailed data to for calibrating detailed models. Given that the Western Australian Government is collecting new information in these areas, there is a suggestion that the Department of Water considers the current investigations are working towards an H3 level of investigation.

The second issue to be discussed from Barnett et al. (2012) is the use of coupled surface water - groundwater flow models. "Guiding Principle 11.6: A modelling approach based on linking or coupling surface water models to groundwater flow models should be used when surface water dynamics are significantly affected by exchange flows" (Barnett et al. 2012). This suggests that a high level of impact assessment, R3 (or H3 in the context of an individual project) including coupled surface water groundwater interaction modelling, is required if the potential of impacts exists with increased allocation and potential contamination both on resource sustainability and dependent ecosystems.

Groundwater and surface water dependent ecosystems of high conservation value have the potential to be impacted by the proposed tight gas industry. There are considerable gaps in our understanding of the distribution of biota and other culturally important assets, let alone their vulnerability to impacts due to altered hydrological regimes. Richardson et al. (2011) described the process of assessing impacts, including determining Environmental Water Requirements (EWRs), the intrinsic water quantity and the quality needs of individual biodiversity assets. It also described the transition from EWRs to Environmental Water Provisions (EWP), which are a water quantity and quality regime that will protect a subset of the dependent biodiversity assets. EWP are determined through an extensive stakeholder consultation covering Aboriginal cultural heritage and western values including trade-offs between social and economic implications of resource use, an important part of the allocation planning process. This requires long-term ecohydrological data sets, robust EWRs and deterministic tools based on distributed models or expert opinion to document and predict the cause and effect. Recent work by Warfe et al. (2013) highlighted the linkages between a system's biota, social values and flow regime. The current low level of EWR data in the public...
domain suggests it will be difficult to determine broad EWPs with any level of scientific rigor as trade-offs between economic, social and environmental values are not clear.

In a regulatory context, DMP (2015) stated that water licenses required for water supply to support hydraulic stimulation may be required to adhere to the guidelines for impact assessment from Operational Policy 5.12, “Hydrogeological reporting associated with a groundwater well licence” (DoW 2009b). It would seem prudent that all water supply approvals do follow that guideline and the approval process for an individual well to be hydraulically stimulated should include the same level of rigor, not just its water supply. There should also be detailed monitoring of groundwater heads and chemistry at multiple depths near hydraulically stimulated wells pre, during and post tight gas well installation, hydraulic stimulation and production, to ensure well integrity is maintained. It is counter-intuitive that a driller for a water well requires a higher level of licensing than a tight gas well, which is much deeper and often will intersect multiple aquifers across a greater range in depths than water well drilling. It is also difficult to see how the current Western Australian regulatory environment can cope with cumulative impacts of the tight gas industry. There are also issues in terms of a lack of suitable monitoring network across groundwater, surface water and environmental systems to pick up impacts let alone understanding the links and risks to social values which can only happen at R3 level of management.

Cumulative impacts of poorly understood anthropogenic activities have been an issue in many other contexts in Western Australia. Secondary salinity in the Wheatbelt, as a result of land clearing and agriculture, is a suitable example of broadly distributed water resource and environmental impacts caused by an anthropogenic activity. Land clearing had unpredicted consequences and is very difficult and expensive to remediate. Each act of land clearing likely only has a small impact, but combined they have caused some of the worst water resource and environmental impacts in the State. The environmental consequences of the hydrological impact of secondary salinity have been magnified by the other issues inherent in land clearing specifically: habitat fragmentation and linear infrastructure (road and pipeline construction); hydrological impacts from this linear infrastructure (water excesses or deficits) due to natural surface water (sheet flow) impairment; increased road kill or traffic accidents from an increased road network and increased traffic; spread of dieback and other pathogens; and spread of feral animals. This will also likely be the case with a tight gas industry.

Cumulative impacts in the east Pilbara’s Weeli Wolli Creek Catchment due to surface water diversion, groundwater dewatering and water disposal are another suitable example of anthropogenic activity which has created unforeseen impacts. The substantial number of mines, operated by various mining companies, creates a regulatory situation in which individual mine approvals went ahead, but the lack of incorporation of cumulative impacts during the individual project approval process is making post mortem regulation of this situation difficult. Management of the groundwater related impacts on Gnangara Mound is another Western Australian regulatory situation which has taken 20 or more years to achieve a high level of rigor. This is an area where an initially insufficient understanding of cause and effect in terms of land and water use versus environmental impacts has required a substantial and expensive effort to manage.

The difficulties we collectively have in terms of understanding the risks of the tight gas industry as expressed herein are considerable. There is a modest current level of understanding, but there is risk
of impacts, a medium to high risk according to Cook et al. (2013). This is also the case in other jurisdictions in Australia and globally. This has led some of these other jurisdictions (Figure 22) to declare a moratorium on tight gas activities (including exploration) while additional data is collected and subsequent assessment is completed.

Figure 22 - Map of jurisdictions where hydraulic fracturing is currently banned (FracTracker Alliance 2017).

There is potential for economic benefit to Western Australia from tight gas, however, it is not currently possible to comprehensively understand if the risks outweigh the benefits, or vice versa. To robustly and defensibly understand the risk of impact of a fully developed tight gas industry in Western Australia could also increase our understanding of the potential economic and other benefits. It would require large numbers of scientists across multiple fields in government, academia and industry working for long time frames to collect the data required across the geology, hydrogeology, biodiversity and social values of these areas so environmental impacts of the proposed activities can be balanced across social, environmental and economic values as is required in much of the relevant legislation. Not only would this provide a rigorous and defensible impact assessment in the context of tight gas, it would help with many other areas such as water resource and environmental management generally including the risk posed by existing activities such as dryland and irrigated agriculture, pastoral activity, mining and existing oil and gas projects etc. It would also help us adapt our water resources to climate variability.

Cook et al. (2013) suggested tight gas impacts would be worse here than in the United States. Data being collected by unconventional hydrocarbon companies could also be analysed in more detail in this context. For example, thermogenetic gas is measured during well drilling and water quality...
(salinity) estimates are possible from down hole geophysical logs, but these are rarely analysed or reported in this context (Fiona Mullen pers. comm. 07/02/2017).

Although it is outside the scope of this report to provide precise detail on what would be required, this would be an expensive and long term proposition, funding of which Cook et al. (2013) says should come from proponents. Given the fact that a tight gas industry is still some time away from being economic (DMP 2015), we need to act quickly to get the monitoring networks in place to collect appropriate long term baseline datasets against which future impacts can be measured, if this industry is going to proceed.

**Recommendations**

The US EPA (2016) stated that "In places where we know activities in the hydraulic fracturing water cycle have occurred or are occurring, data that could be used to characterize the presence, migration, or transformation of hydraulic fracturing-related chemicals in the environment before, during, and after hydraulic fracturing were scarce. Specifically, local water quality data needed to compare pre- and post-hydraulic fracturing conditions are not usually collected or readily available. The limited amount of data collected before, during, and after activities in the hydraulic fracturing water cycle reduces the ability to determine whether these activities affected drinking water resources".

The following recommendations will help prevent Western Australia from making the same mistakes.

1. Require that industry proponents fund the investigations necessary to present a robust and defensible understanding of the impact risk (incorporating geology, hydrogeology, environment and Aboriginal cultural heritage, including their linkages) in Western Australia, prior to undertaking tight gas exploration or production activities. This needs to account for project-specific impacts as well as cumulative impacts of a fully-developed tight gas industry.
2. Require that groundwater take be licensed and impact assessed, particularly given the risk of impact from water supply and tight gas wells in the proclaimed Groundwater Areas of the northern Perth and Canning basins. DMP (2015) stated that it only may require licensing.
3. Modify the Western Australian regulatory environment to incorporate the issues explored herein, in particular the issues around drilling, monitoring, project approvals and cumulative impacts. The DoW allocation planning process is an example of a regulatory framework managing cumulative impacts. Given the risk of water and environment related impacts, DoW should have a more significant role in the approval process for the unconventional hydrocarbon industry, not just its water supply.
4. Upgrade groundwater allocation plans for the relevant areas to intensive plans as soon as possible and prior to any additional tight gas exploration or production activities.
5. Augment good oilfield practice (in terms of drilling practice and regulation) with hydrogeological best practice, particularly in the context of unconventional gas wells that pose risks to confined aquifers.
6. Require post well abandonment monitoring across relevant aquifers. Further, in consideration of the long time frames for some impacts to be revealed, a trust fund
approach would ensure that resources are available for post abandonment monitoring and well failure remediation.

7. All costs for impact assessment and baseline monitoring should be borne by UCH proponents, not the tax payer, in line with the recommendations by Cook et al. (2013). The example of Palat et al. (2015), where government bore the costs of a project assessment, is unacceptable.

8. Audit all existing oil and gas wells in the State, in terms of well leakage and well integrity. This will provide an understanding of the impact of existing activities as well as invaluable data on long-term well integrity in a Western Australian context.

9. Choose a number of representative existing conventional oil and gas wells, and unconventional wells that will be drilled and stimulated, for detailed hydrogeological investigations. This should include faults and other potential flow conduits, and these sites should be monitored for long term water quantity and quality impacts. The investigations would require the installation of nested piezometers (monitoring wells installed in different depths) across all aquifers (both potable and non-potable) across the full vertical extent of the tight gas wells. Monitoring networks (both local and regional) should be in place for at least 12 months prior to any hydraulic stimulation activity to ensure appropriate baselines are collected.

10. The recommendations in Cook et al. (2013) are comprehensive across all areas of UCH projects in Australia and the reader is suggested to review them also. They recommended that baseline studies are completed before exploration activities are undertaken and that a precautionary approach is applied due to the serious nature of potential impacts.

11. Declare a permanent moratorium on drilling and related exploration or production activities in conservation estate and public drinking water source areas. The risks associated with surface activities alone in the hydraulic stimulation process justify this, let alone the risks of hydraulic stimulation and well failure, which are difficult to currently quantify.

12. Make the Environmental Assessment and Regulatory System (EARS) and EARS2 publically available. The community has the right to know the environmental impact assessment under which tight gas exploration projects are being approved.

A moratorium on further exploration or production experiments is a regulatory option which will ensure protection of the environment and groundwater resources until such time as baseline studies are completed so the impact of all activities (including both exploration and production) can be rigorously assessed. However, a permanent moratorium is recommend over conservation estate and public drinking water source areas, given the considerable risk that even surface activities hold in the context of the biodiversity values or long term water supply security that these areas are created to protect.
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