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Literature review of dissolved hydrocarbons in groundwater with emphasis on the Australian Surat and Bowen basins

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Copyright and disclaimer

Important disclaimer

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Executive summary

The increased exploitation of coal seam gas (CSG) has raised concerns over the possible presence of dissolved hydrocarbons in produced groundwater, as well as the release of these compounds into groundwater systems hosting coal formations. An extensive literature search has been conducted to gather information on the occurrence of hydrocarbons such as partially water-soluble organic compounds (e.g. benzene, toluene, ethylbenzene and xylenes (BTEX), phenols, polyaromatic hydrocarbons) and total petroleum hydrocarbons (TPHs) in coals and associated coal seam formation groundwater. Queensland coals have been a particular target for CSG in Australia. This review incorporates peer-reviewed literature and text books identified through scientific literature databases, information from state and federal geological surveys, and open file reports identified through internet searches or available in archives and websites. It is also an update of Volk et al. (2011), where the occurrence of TPH and partially water-soluble organic compounds in Permian coals and associated coal seam groundwater was reviewed.

The majority of organic matter in coal is derived from lignin, a predominantly aromatic biopolymer. Water soluble constituents of coal are largely aromatic hydrocarbons and heterocyclics, and they may be produced by the cleavage of the aromatic structures within the coal matrix. Water-soluble compounds from coals and petroleum may include a wide variety of oxygen-bearing aromatic compounds (e.g. phenols, aldehydes, ketones, and various carboxy-, hydroxyl- and methoxy- bearing compounds), nitrogen-bearing compounds (pyridines and amines), and monoaromatic hydrocarbons such as BTEX, and to some extent polycyclic aromatic hydrocarbons (PAHs) and low molecular weight aliphatic hydrocarbons. Many of these organics have potential to cause adverse health effects and some of them are known carcinogens.

Despite the aromatic nature of coals, reports on BTEX and other organics associated with CSG production are sparse. Some reports of organics in groundwater were linked to underground coal gasification (UCG) operations in Queensland, which is a fundamentally different process to CSG production. In March 2005, Sydney Gas reported BTEX below the laboratory limit of reporting (LOR) in their gas exploration well, Jilliby 1 at Wyong which intersected the Newcastle Coal Measures. AGL reported that BTEX concentrations were below the LOR in their gas exploration well HB01 penetrating the Wittingham Coal Measures in the Hunter Coalfield. In November 2010, Arrow Energy announced on its website that traces of benzene (1 to 3 ppb) were detected in three wells during developments in the northern Bowen Basin. Investigations were undertaken to determine whether benzene is naturally occurring at this site or if it is elevated due to resource development activities. In 2015, AGL suspended its Waukivory CSG Pilot Project near Gloucester in northern NSW after traces of BTEX chemicals were found in water samples. AGL stated on its website that the chemicals were detected in five samples of which four were within the range of 12-70 ppb while another was 555 ppb. AGL believes that these BTEX chemicals are naturally occurring.

Data for BTEX, TPH, PAHs and phenols are available for seams from a range of different basins and include waters associated with the Permian Wittingham and Newcastle Coal Measures in the Yarramalong valley and Hunter valley regions (AGL and Sydney Gas), the Bowen and Surat Basins, the Talinga water treatment facility in Queensland as well as the Camden Gas Field in NSW. Often, reported hydrocarbons concentrations were below the LOR.

Although it is recognised that dissolved organic compounds may be present in some CSG produced waters, an extensive study issued by the Committee on Management and Effects of Coalbed Methane Development and Produced Water in the Western United States (2010) highlights that in the USA these compounds and their origin are neither well documented nor well researched. Through the course of this review it became apparent that organics in water associated with coals in Australia have also not been researched in a comprehensive manner. Where organic compounds have been found, it was often difficult to identify their origin. Some of the detected compounds such as halogenated phenols clearly have no natural origin from coal. Others such as BTEX and PAH may be derived from coal.

Additional baseline data, together with periodic assessment of organic compound concentrations throughout the production life of a gas well, would assist in building a suitable database and understanding the occurrence and distribution of these compounds in deep groundwater systems. Fingerprinting of aromatic compounds in coals and how these translate into fingerprints leached into groundwater may offer a way to better trace the origin of these organics in future studies.

PART 1

Introduction and scope

Approach and methods

Organic hydrogeochemistry of coals

1 Introduction and scope

1.1 Australian coal-related resources and associated groundwater in sedimentary basins

Australia possesses significant quantities of discovered coal and coal-associated gas and many of these resources are currently undeveloped. The country ranks fifth (behind the United States, Russia, China and India) in terms of recoverable economic coal resources (Britt et al. 2014). In 2013, national gas production from coal seams was reported to be 232.9 million cubic feet (mmcf) (APPEA 2014).

The state of Queensland, in particular, plays an important role as it hosts significant coal reserves in areas such as the Bowen and Surat sedimentary basins, which are the focus of this review. The Bowen Basin is a prolific coal-bearing basin extending from central east Queensland to northern New South Wales (NSW), covering an area of approximately 60,000km^2 (Figure 1). The Permian units contain numerous coal-bearing sequences, where most of Queensland's economic coal as well as significant gas resources are contained. These units are overlain by Triassic sediments. The geology of the basin has been extensively documented and detailed information can be found in Mallett et al. (1995). Overlying the Bowen Basin are the mainly Jurassic and Cretaceous sediments of the Surat Basin, which extends across an area of approximately 270,000km^2 from southern Queensland into northern NSW (Figure 1). The Walloon Coal Measures host the most significant coal and coal seam gas (CSG) resources in the Surat Basin. See Goscombe and Coxhead (1995) for more information on the geology of that basin.

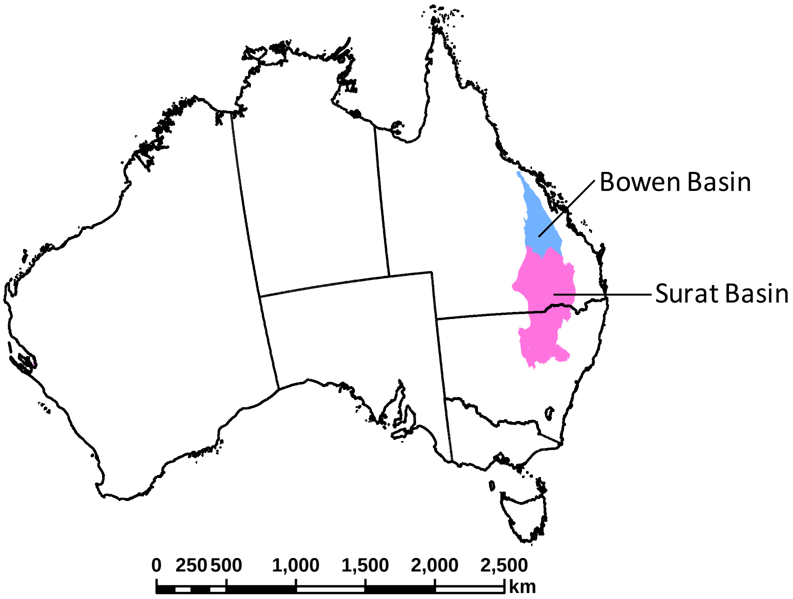


Figure 1: Location of the Bowen and Surat basins (Data source: Geoscience Australia)

Australian coal-bearing sedimentary basins are also host to local and regional sources of groundwater that are of significant importance to environmental, community, agricultural and industrial interests (e.g. Clifton et al., 2007; Tomlinson and Boulton, 2008). In Queensland, for example, the Surat Basin hosts aquifers that form part of the Great Artesian Basin, one of the largest freshwater artesian basins in the world (e.g. Habermehl 1980). As with any exploration and exploitation activities of natural resources, those involving the coal seams in Australian basins can have potential negative environmental impacts with a variety of natural as well as artificial chemical compounds being released into the surrounding environment.

1.2 Potential groundwater contamination hazards due to coal seam gas (CSG) exploration and production

Of particular concern to society is the potential release of contaminants from coal seam gas (CSG) exploration and production. This energy resource is regarded as “unconventional” as it is atypical to “conventional” equivalents in regards to its sourcing, storage, migration, and entrapment (e.g. Flores 2014; Song et al. 2013). The production of this resource relies on the extraction of water from coal seams to depressurize the areas of interest and allow natural gas to flow (e.g. Halliburton 2008; US-EPA 2004; Flores 2014). The total volume of CSG produced water extracted from the Surat and Bowen basins is estimated to be between 125 and 350 GL/year (National Water Commission 2010; Rutovitz et al. 2011).

Hydraulic fraccing is a technique that enhances the production efficiency of CSG by creating new and enlarging existing fractures in coal. Fracturing fluids usually consist of a mixture of water, various chemical additives and proppants (e.g. Halliburton 2008; US-EPA 2004; Flores 2014). The composition of these fracturing fluids varies depending on site-specific conditions and is usually tailored to project needs. In some instances hydrocarbon-rich liquids (e.g. diesel fuels) have been used as an additive to achieve fluid properties helpful in fraccing. The resulting efforts allows for increased flow of CSG from coal-bearing formations into a production well (e.g. Halliburton 2008; US-EPA 2004; Flores 2014). Notably, however, fraccing is not used for all CSG deposits. In the Surat Basin in 2013, for example, only about 10% of CSG wells employed this technique. However, it is believed that this figure will rise as wells are drilled into places that prove more difficult for gas extraction. See http://www.abc.net.au/science/articles/2013/12/04/3861669.htm for an Australian perspective on this technique.

While gases are generally present in all coals, a number of geologic factors influence their potential economic concentration. Key factors include the depositional environment, tectonic and structural setting, coal rank and burial history, gas content and composition, permeability and hydrogeology (e.g. Draper and Boreham 2006; Flores 2014).

For more than 60 years, hydraulic fraccing of CSG (also known as coalbed methane) has been undertaken in the US with over 1 million wells being fractured since the 1940s (Ely 1985, API 2010). Subsequent energy shortages, substantial tax concessions, and close proximity to gas pipeline networks led to the commencement of commercial production in 1982 (e.g. Day 2009). In Australia, the history of CSG extraction dates back to the mid-1970s with commercial production commencing through BHP in 1996 in the eastern Bowen Basin, Queensland (Day 2009). Ever since these early efforts, CSG has been regarded as a valuable energy resource with the pace of exploration efforts accelerating to address market demand. Such efforts have gained new impetus with proposals to export significant quantities of LNG. Queensland, in particular, is regarded as the centre of current CSG activities in Australia, with existing fields expanding and new projects being brought into production (e.g. Day 2009).

It is only in recent years that studies in the area of hydraulic fraccing and associated environmental legacies have been undertaken. Past research on fracturing fluids, for example, would emphasize operational efficiency and not potential environmental or human health impacts. To fill this knowledge gap, the US Environmental Protection Agency (US-EPA) released a study in 2004 focussing on the impacts on underground sources of drinking water by hydraulic fraccing of CSG reservoirs. The study by the US-EPA identified two mechanisms through which hydraulic fracturing could potentially impact groundwater. One was through direct injection of fracturing fluids into either an aquifer in which the coal is located or into a coal seam that is in hydraulic communication with an aquifer through a natural fracture system. The other mechanism was though the creation of a hydraulic connection between the coal formation and an adjacent groundwater source.

Both of the above mechanisms were reported as posing a low threat to drinking water aquifers due to the removal of significant quantities of groundwater that contains the fracturing fluid (US-EPA 2004). Nevertheless, as in any fracturing exercise, some fluids may not be recovered from the formation. For example, a US study has shown that between 68% and 82% of fracturing fluids were recovered based on samples collected from CSG wells over a 19-day period (Palmer et al. 1991). The recovery efficiency is influenced by a variety of site-specific factors (e.g. US-EPA 2004) and includes: flow and entrapment into secondary fractures or pores; trapping of fluids through formation pressure decreasing after the cessation of injection of fracturing fluids; adsorption onto coal; movement of fluids beyond the drainage radius of a pumping well; and incomplete mixing with groundwater.

More recently, the European Commission Directorate General for the Environment (AEA 2012) concluded that “the likelihood of properly injected fracturing liquid reaching underground sources of drinking water through fractures is remote where there is more than 600 metres separation between the drinking water sources and the producing zone. However, the potential of natural and manmade geological features to increase hydraulic connectivity between deep strata and more shallow formations and to constitute a risk of migration or seepage needs to be duly considered”. Typically these conduits between the production zone and an aquifer may include zones of naturally higher permeability or preferred pathways of natural or induced fault networks.

In Queensland, hydraulic fracturing is regulated under section 312W of the *Environmental Protection Act 1994*. Provisions include company requirements to complete detailed risk assessments and undertake comprehensive monitoring, and also to ensure that exposure to the water-soluble BTEX (benzene, toluene, ethyl benzene and xylenes) chemicals is restricted to concentrations prescribed under Australian water quality guidelines for human and environmental health.

Apart from the injection of fracturing fluids, the leaching of organic constituents from coal-bearing strata into groundwater is another mechanism of contamination that has been identified. CSG exploration and production, for example, may cause hydraulic communication between the coal seam and aquifers used for groundwater. Detailed studies looking into such effects are scarce, but have been noted for compounds such as BTEX (e.g. US-EPA 2004). There is also a paucity of data related to the leaching of coal-derived organic contaminants into groundwater through processes not related to CSG activity.

An important issue regarding groundwater contamination related to fraccing activity is the lack of baseline data (e.g. Cooley and Donnelly 2012). In the US, only 16 out of 50 states have proposed or established rules of guidance for baseline sampling of residential water wells and other water sources near unconventional oil and gas production wells (Jacobs 2014). Therefore, considerable future work, in Australia and worldwide, needs to be conducted to fill this knowledge gap in baseline water data and to rapidly identify instances of contamination proximal to the fraccing site.

There are several treatment technologies for treating CSG produced water. Of these techniques, nanofiltration and ultrafiltration have been shown to be able to remove aromatic compounds such as BTEX and light phenols (see Abousnina et al. (2014) for a review on these techniques).

1.3 Release of organic contaminants into groundwater

It is widely acknowledged that organic and inorganic contaminants can be absorbed, precipitated or otherwise released into the surrounding groundwater environment as a result of natural physico-chemical processes. Examples of contaminant release associated with induced physico-chemical perturbations have long been noted for underground coal gasification (UCG; e.g. Humenick and Mattox, 1978; Stuermer *et al.*, 1982; Kapusta and Stanczyk, 2011; Liu *et al.*, 2007; Yang, 2009; Younger, 2011). Groundwater contamination is typically introduced either through the release of gas products produced by pyrolysis of the coal seam during the gasification phase or through aqueous leaching of the residual coal ash during the post-gasification phase (Liu *et al.*, 2007).

Organic contaminants are typically produced as volatiles during the gasification phase. During the gasification process, air is injected at a pressure equal to or greater than the surrounding hydrostatic pressure. Some of the volatile products in the gas phase can therefore be dispersed into the surrounding strata. The connection between strata may be enhanced as a result of cracks created through the gasification process. However, where the integrity of aquitards between the coal seams and the surrounding aquifer units remains intact, contamination of these surrounding units is unlikely. Studies by

Campbell *et al.* (1979) and Liu *et al.* (2007) identified that the major organic groundwater contaminants produced through the UCG process are phenolic compounds, PAHs, BTEX and TPH.

The predominance of aromatic hydrocarbons as aqueous contaminants is not surprising. Previous experimental measurements (McAuliffe 1966; Peake and Hodgson 1966, 1967; Price 1976) have shown that solubilities of many hydrocarbons in water are extremely low, even in the range of temperature and pressure conditions encountered under geologic settings. The exception to this observation are gases and low molecular weight aromatics such as benzene, toluene and xylenes (Figure 2). Indeed, for compounds with the same carbon number, aromatics are three orders of magnitude more water soluble than saturates at 25 ºC (e.g. Vandenbroucke 1993).

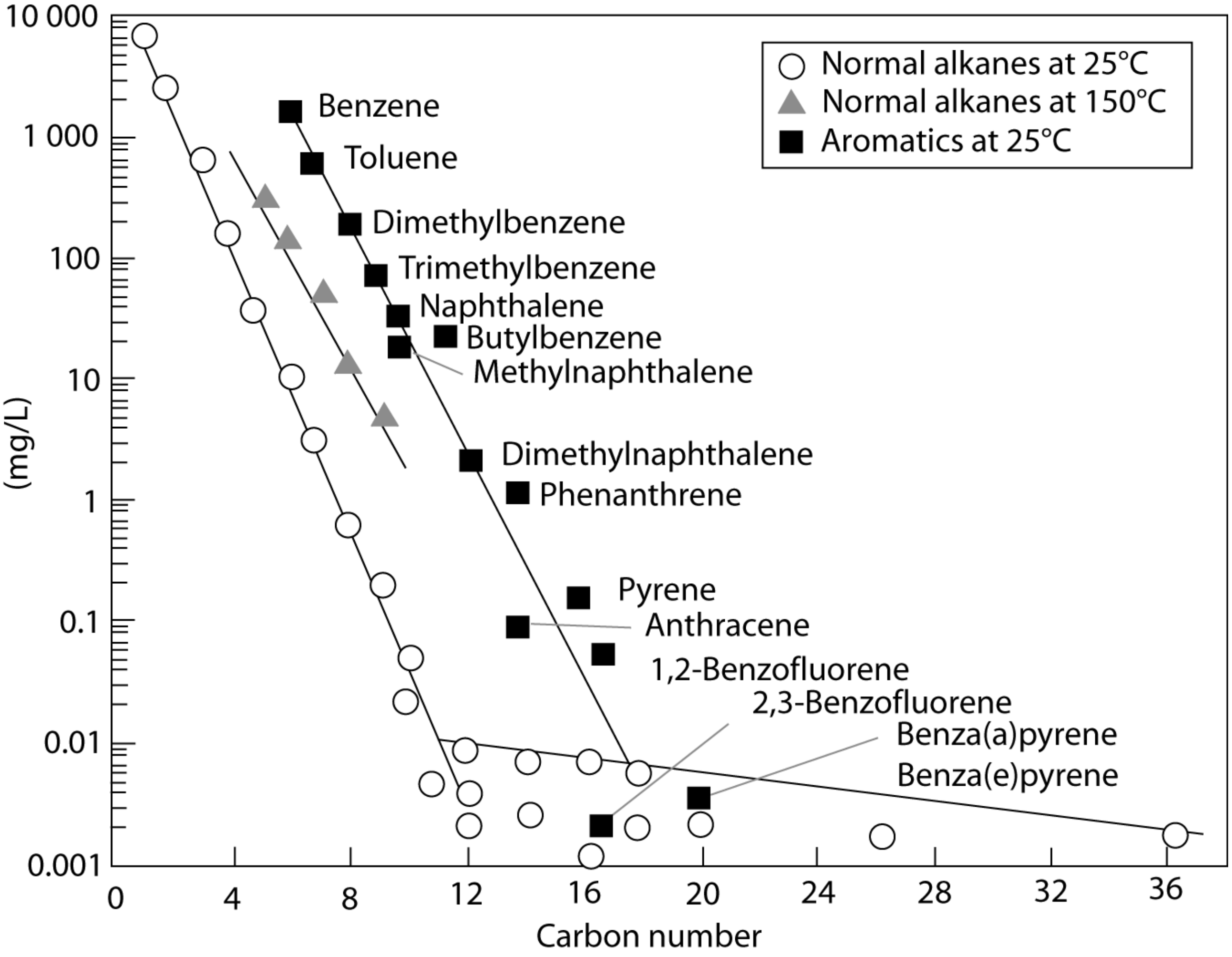


Figure 2: Solubility of n-alkane and aromatics in water according to carbon number. Y axis is in logarithmic scale. Source: Huc 2013 (After McAuliffe 1980).

1.4 Lessons to be learned from other unconventional petroleum sources

The success and rapid development in the exploitation of shale gas in the US has led to increased scrutiny over the environmental impact of high-density drilling activities required to maintain gas production. One key issue has been the risk of stray or fugitive gas migration into groundwater sources. Significant debate on this issue has focused on whether the sources of methane are the result of horizontal drilling/fraccing procedures or to naturally occurring methane sources in the environment (Figure 3).

Recently, Darrah et al. (2014) used the isotopes of noble gases to trace the source of methane contamination into groundwater. These gases mix with and accompany other natural gases as they are transported to areas of lower pressure. Since methane and noble gases such as helium and neon have different water solubilities, they will diffuse at different rates. Therefore, isotope ratios are expected to be different when gases migrate through rock layers rather than through a fracture in a casing. The study by Darrah et al. (2014) involved water sampling from 113 wells overlying the Marcellus Shale and a further 20 overlying the Barnett Shale during 2012 and 2013.

The outcome of this study pointed to well integrity problems with casing or cementing issues as the most likely culprit in fugitive gas contamination. Eight clusters of the sampled water wells were identified as having higher-than-normal concentrations of methane. All of these clusters were located within 1 km of producing natural gas wells.

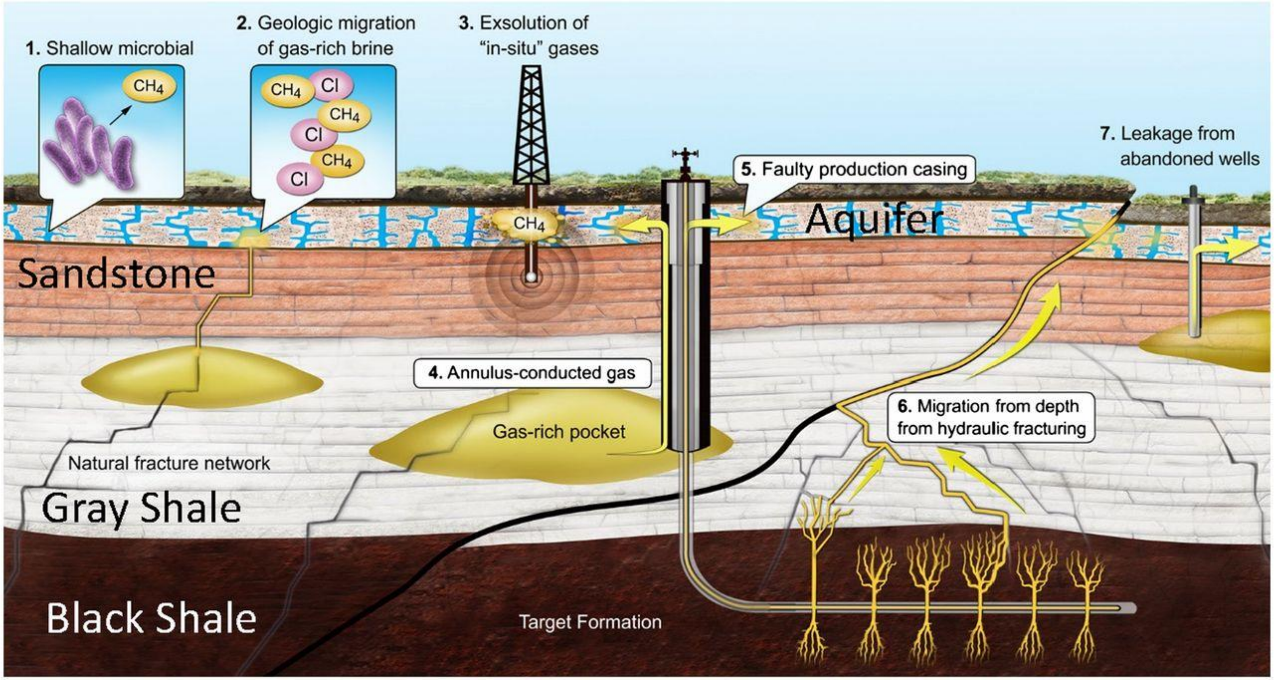


Figure 3: Seven possible sources of groundwater methane contamination, with the exception of coalbed methane and pipeline leaks. Source: Darrah et al. 2014

While most oil and gas companies use modern technology and apply best practice techniques for cementing and casing operations (e.g. through the use of centralizers) to maintain well integrity, hydraulic fracturing can introduce significant mechanical stresses (see article by Jacobs (2014) for a more detailed discussion).

As identified by Stearman et al. (2014), distinctions should be made between the extraction of CSG and other unconventional resources to avoid incorrectly applying environmental management strategies specific to other areas of the gas industry. See also Abousnina et al. (2014) for a review on the similarities and difference between conventional hydrocarbon and CSG exploitation. However, the above example by Darrah et al. (2014) demonstrates the importance of continued scientific research to identify and better understand potential contamination sources in unconventional petroleum resource settings. In addition, there is a need for more baseline studies and evidence-based research before exploiting unconventional gas resources. The need for such work has recently (2014) been raised in the following article: http://gastoday.com.au/news/reimagining_australias_shale_gas_revolution/087635/

1.5 Scope

This literature-based study provides a review of the release of hydrocarbon and other organic contaminants into groundwater with emphasis on Australia, particularly from the Bowen and Surat basins in Queensland. It is essentially an expanded and updated version of the report provided by Volk et al. (2011). It consists of two parts:

- Part one covers the introduction, methods and a detailed account on the organic chemistry of coal. The latter topic is designed to introduce the reader to the constituents of coals that may be introduced into groundwater. A section on bioassay experiments is also included.
- Part two contains a review of openly published information on the hydrochemistry of groundwater near CSG activity. Emphasis is again directed to the Surat and Bowen basins. However, we also included data from other areas in Australia for comparison. We conclude with a brief review of other published studies from around the world.

It should be emphasized that this review does not cover low molecular weight gases such as methane. By "hydrocarbon" or "organic" we denote heavier constituents, and in particular more soluble aromatic compounds such as BTEX.

2 Approach and methods

2.1 Information from scientific literature databases

2.1.1 INFORMATION FROM PERSONAL LITERATURE COLLECTIONS

References were selected from personal literature databases containing several thousand peer-reviewed publications in the areas of organic geochemistry, coal science, and conventional and unconventional oil and gas studies.

2.1.2 INFORMATION FROM EAOG MEMBER DATABASE

The European Association of Organic Geochemists (EAOG) compiles monthly databases on a range of topics of interest to organic geochemists, and provides this information to its members as searchable EndNote databases. Databases from 2005 - March 2015 were searched for the terms coal and water, and coal and Australia. Each year contains between 3000-5000 references which were keyword searched to identify relevant articles.

2.1.3 WEB OF KNOWLEDGE

Web of Science is a multidisciplinary index, with searchable author abstracts, covering the journal literature of the sciences (Science Citation Index Expanded), social sciences (Social Sciences Citation Index) and arts and humanities (Arts and Humanities Citation Index). It was our main source of information from scientific literature databases available for subscribers. Both Boolean and Field tags were used to customise search results.

2.1.4 AMERICAN GEOPHYSICAL UNION AGU DIGITAL LIBRARY

We browsed, searched content, and accessed full-text articles for the following AGU titles: Journal of Geophysical Research, Water Resources Research, Reviews of Geophysics, Geophysical Research Letters, Radio Science, Tectonics, Paleonoceanography, Global Biogeochemical Cycles, Geochemistry, Geophysics, Geosystems, and Space Weather.

Searches yielded information that was already discovered in Web of Science, and hence was not considered in more detail in this study.

2.1.5 ENERGY CITATIONS DATABASE

The Energy Citations Database (ECD) provides free access to over 2.4 million science research citations with continued growth through regular updates. There are over 267,000 electronic documents, primarily from 1943 forward, available via the database. Citations and documents are made publicly available by the U.S. Department of Energy (DOE). Many of the search results are linked to a PDF file that can be downloaded free of charge. Copyrighted, peer-reviewed articles and book chapters do not appear in the search results. The relevance of the articles was found to be low. Several of the search results were duplicated from Web of Knowledge, and no new relevant references were found.

2.1.6 ENVIRONMENTAL SCIENCES AND POLLUTION MANAGEMENT ON PROQUEST

This multidisciplinary database provides unparalleled and comprehensive coverage of the environmental sciences. Abstracts and citations are drawn from over 6000 serials including scientific journals, conference proceedings, reports, monographs, books and government publications.

2.1.7 GEOREF ON PROQUEST

The GeoRef database, established by the American Geological Institute (AGI) in 1966, provides access to the geoscience literature of the world. GeoRef is the most comprehensive AGI database in the geosciences and continues to grow by more than 80,000 references a year. The database contains over 3 million references to geoscience journal articles, books, maps, conference papers, reports and theses. The GeoRef database covers the geology of North America from 1693 to the present and the geology of the rest of the world from 1933 to the present. The database includes references to all publications of the U.S. Geological Survey. Masters theses and doctoral dissertations from US and Canadian universities are also covered. To maintain the database, GeoRef editor/indexers regularly scan more than 3,500 journals in 40 languages as well as new books, maps, and reports. They record the bibliographic data for each document and assign index terms to describe it. Each month between 4,000 and 7,000 new references are added to the database.

2.1.8 GEOSCIENCEWORLD

GeoScienceWorld (GSW) includes peer-reviewed articles and other materials with linked reference lists from 30 high-impact journals in a broad range of geoscience areas. The digital collection is updated continuously with the most current journal issues. A primary strength of GSW is the ability to search full text in a linked collection, but GSW is also integrated with GeoRef, a major abstracting and indexing database in the field, hence a separate search in GSW did not yield information that was not found by GeoRef.

2.2 Information from state and federal geological surveys

2.2.1 GEOLOGICAL SURVEY OF NEW SOUTH WALES

Geoscience information, open file and confidential company reports and well completion reports are accessible via the NSW Department of Primary Industries Digitally Imaging of Geological System (DIGS) database. The database is searchable for fields such as, for example, ‘keyword’, ‘location’ and ‘subject’, and search results are downloadable in portable document format (pdf).

2.2.2 GEOLOGICAL SURVEY OF QUEENSLAND

The Geological Survey of Queensland maintains the Queensland Digital Exploration (QDEX) reports system, which is a similar database to that of the NSW Department of Primary Industries. Various search fields are provided, although a preset list of keywords is accepted for certain search fields. It is a requirement that users register to access this database, although information (up to 50MB of data) can be downloaded free of charge. Search results are also downloadable in pdf format. A variation of keywords searches produced numerous documents related to coal and petroleum in general.

2.2.3 GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

Similar to the Geological Survey of Queensland, the Geological Survey of Western Australia maintains a comprehensive information management system (WA Petroleum and Geothermal Information

Management System, WAPIMS), archiving predominantly open file and confidential company reports, comprehensive well completion reports and maps. Users are also required to register to access this database and information can be download free of charge in various formats (xls, pdf, LAS) once found.

2.2.4 DEPARTMENT OF PRIMARY INDUSTRIES AND RESOURCES SOUTH AUSTRALIA, MINERAL RESOURCES TASMANIA AND GEOSCIENCE AUSTRALIA

Geoscience information (geology and resources) were obtained from the Department of Primary Industries and Resources South Australia, Mineral Resources Tasmania and Geoscience Australia websites for basins located in South Australia and Tasmania, as well as for general information on Australia's coal and petroleum resources.

2.3 Information from news-specific website searches

Internet-based search engines such as "Google" provide for the opportunity to scan news articles from throughout the world. Searches yielded unpublished news articles regarding the detection of hydrocarbon contaminants in groundwater.

3 Organic hydrogeochemistry of coals

3.1 Coal structure and ramifications for organic compounds found in coal-associated waters

In his comprehensive book documenting the typology, physics, chemistry and constitution of coal van Krevelen (1993) states that "coal is a rock, a sediment, a conglomerate, a biological fossil, a complex colloidal system, an enigma in solid-state physics and an intriguing object for chemical and physical analyses". This sentence captures the multicomponent, complex nature of coal, and it is important to recognise that the vast majority of organic material in all coals is tied up in macromolecules (Derbyshire *et al.*, 1989).

The majority of organic matter in coal is derived from lignin (Figure 4), but some originates from other material and is derived from highly modified carbohydrates, polymerised terpenes, and other alkenes (Wilson, 1994). Humic materials may be intermediates from oxidation, or the coals may be derived directly from lignin. The detection of the physically smaller volatile compounds, which are the subject of this review, is unlikely in any technique in which the macromolecular component is also observed. However, they may be present in significant quantities, much greater than would be expected given their volatility. This is because some compounds may be entrapped as guests in host-guest complexes in the coal (Derbyshire *et al.*, 1989).

In general, gas formation predominates over oil formation during the coalification (the formation of coal from plant material via bio- and geochemical means) in coal formations. Three main changes that occur during coalification involve the cracking of heteroatoms such as oxygen containing groups, degradation of hydrogen-containing alkyl side chains and increasing aromaticity (Stach 1975; Teichmüller and Teichmüller 1979). During this process, all types of coal exhibit an increase in C and a decrease in H and O content. The change in H/C ratio reflects increased aromatization of the lignin structure through loss of functional groups and an increase in the number of polynuclear aromatic structures (e.g. Orem and Finkelman 2005). The characteristics of the hydrocarbons generated by coal are fundamentally influenced by the constituent macerals and the degree and setting of coalification (e.g. Song et al. 2013).

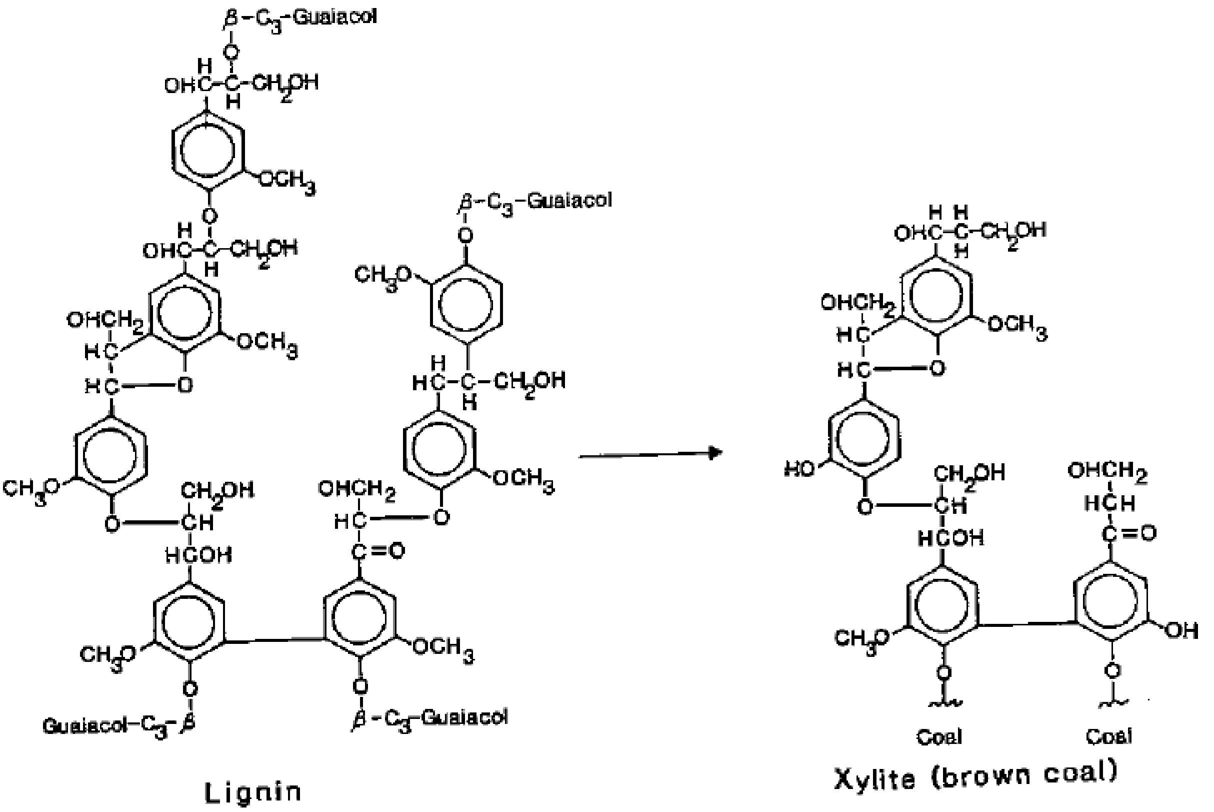


Figure 4: Proposed pathway for the transformation of lignin to xylite (brown coal), from van Krevelen (1993).

As a result of coalification, the constituents of coal are essentially aromatic in structure. This observation is important as the water-soluble components of coal are also aromatic compounds. Indeed, vitrinite reflectance, a key method for identifying thermal maturity of organic matter in coal, is based on the formation of planar aromatic sheets in the kerogen/coal structure as a result of increasing maturation. It is reported that the average number of aromatic rings is 2–3 from the lignite stage onwards, attaining more than 30 rings in the anthracite stage (Gerstein et al. 1982). Highly-substituted aromatic rings are the main aromatic structures in peat and low-rank coals, whereas condensed aromatic nuclei (3–4 rings) are found in the most evolved coals (Ibarra et al., 1996).

Van Krevelen (1993), p. 784, systematically lists the most important indications for the aromatic nature of coal, namely:

- Studies on the macerals – vitrinite being derived from lignin in woody tissues, and 60% of the carbon in lignin being aromatic.
- Indications from ultimate analyses – position of dominant macerals, vitrinite and inertinites on H/C-O/C diagrams.
- Indications from spectroscopic techniques – adsorption bands of Fourier Transform – Infrared (FTIR) and Nuclear Magnetic Resonance (NMR) providing the most direct proof of the aromatic character (see Figure 5).
- Identification from ultraviolet spectra – showing that coal extracts are typically aromatic.
- Identifications from the refractometric exaltation of coals and coal liquids – the specific refraction of coals and coal liquids shows a high incremental exaltation that can only be explained by the presence of aromatic ring clusters, since conjugated olefinic double bonds are absent in coals.
- Indications from electrical conductivity measurements – higher rank coals are semiconductors. The energy barriers of semiconductivity show a good correlation with those of polycyclic aromatic model compounds.

- Indication from magnetic susceptibility measurements – the numerical values found for the dia- and paramagnetic susceptibilities of coals cannot be explained without the assumption of appreciable aromaticity in coals.
- Indications from oxidation studies of coals – wet oxidation of coals produces mainly aromatic carboxylic acids as end products.
- Indications from pyrolytic studies – all organic chemical compounds which produce a considerable carbon residue on thermal decomposition are aromatic.

However, most of the aforementioned techniques reveal little about smaller compounds in the coal structure, specifically monoaromatics. The exceptions are techniques which may drive these compounds directly from the matrix in an organised way, often thermally, such as by using pyrolysis or thermovaporisation techniques. Flash pyrolysis coupled to gas chromatography – mass spectrometry (Py-GC-MS) may be useful since it allows small molecules to escape before they react as they may do in conventional, slow pyrolysis. An advantage of these techniques is that specific compound patterns, which may be found in the pyrolysates, could be used to classify organic matter that may be encountered in waters that have been in contact with such coals.

Solvent extraction of coal will liberate a large quantity of organic matter, but the nature of the extract depends on extraction time and solvents used, and may be difficult to correlate with water-borne organic compounds. Extraction with organic solvents will predominantly extract untrapped organic compounds, although many may eventually escape due to a change in equilibrium concentration. To maximise insights into the coal structure extractions should be carried out over weeks, with removal of extractant at each extraction step in order to maximise the disequilibrium between the coal and the extractant.

An understanding of the macromolecular structure of coal is still important for predicting the behaviour of small molecules. As coal rank increases, small molecules, especially those attached through weak bonds, evolve and can become internally trapped in the matrix as guests. Little work has been done to identify these *in situ*. It is probable that different macerals have different contents, since the macromolecular basis of these is different and they will mature with increase in rank in different ways. In lignin derived macromolecules there will be large structures capable of holding these small molecules. This may also be possible in semi-inertinite because it consists of highly oxidised macromolecules possibly derived from lignin. In liptinites, the structures are more hydrophobic and more likely to retain non-polar rather than polar compounds (Gupta *et al.*, 2007). These interdependencies highlight the importance of integrating organic petrology and organic geochemistry to study the nature of coal.

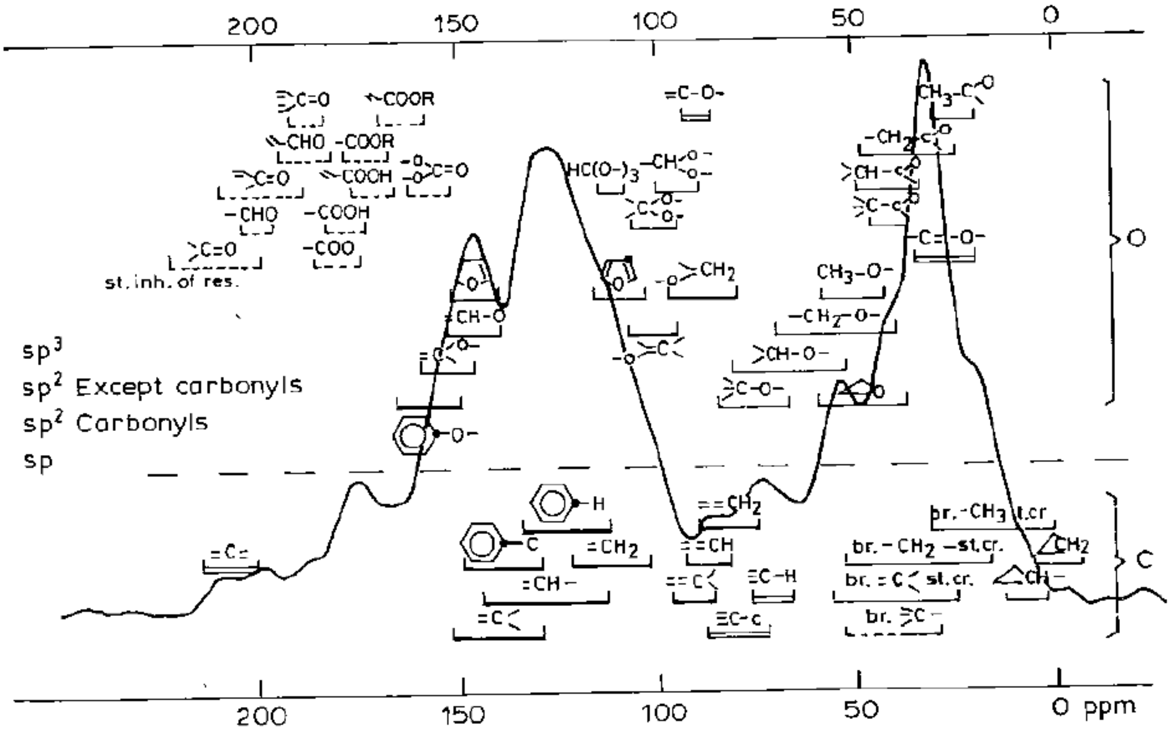


Figure 5: Carbon-13 NMR correlation chart. Source: van Krevelen (1993).

3.2 Microscopic studies and elemental analyses

Organic petrology is routinely undertaken to assess the character of the organic matter in coal for quality control purposes and to estimate potential coal utilisation. Therefore, microscopic studies on Australian coals are numerous. All Permian coals in Australia were deposited on the Gondwana supercontinent, which included all or parts of peninsular India, Australia, southern Africa, South America and Antarctica (e.g. Taylor *et al.*, 1998; Veevers, 2006). Gondwana coals tend to be less lustrous compared to Carboniferous coals, and on average contain, more mineral matter than most Carboniferous coals (Taylor *et al.*, 1998). Gondwana coals also tend to contain a higher proportion of inertinite. This association is believed to be a consequence of the environment of deposition and especially the climate, which is inferred to have been one of wet, cool summers and freezing winters (Taylor *et al.*, 1989). However, there are many exceptions to this rule. Studies using elemental analyses of coals are similarly numerous, and have often been combined with organic petrology to understand origin (e.g. Gurba and Ward, 2000).

The Jurassic coals of the Surat Basin, specifically the Walloon Coal Measures, are markedly different from a petrological perspective to the Permian coals of the Bowen Basin. Surat coals are of sub-bituminous to high volatile bituminous rank, with vitrinite reflectance values varying between 0.35 and 0.65% (Scott *et al.*, 2006). They also have high liptinite contents (>10%; Goscombe and Coxhead (1995)), present in the form of suberinite, a liptinite maceral originating from suberin which is a fatty acid found in corkified cell walls of barks, roots, stems and fruits (Taylor *et al.*, 1998) . Although the bulk of the organic matter is comprised of vitrinite, depositional conditions have resulted in the presence of significant proportions of mineral matter (>5%; Goscombe and Coxhead (1995)), which is closely associated with the organic matter. The Surat coals are described as high-volatile, perhydrous in composition due to the high hydrogen contents (5-7%; Scott *et al.* (2006)).

The coals in the Bowen Basin are contained within the basin's numerous structures and their maturities extend over a wide range from high volatile bituminous to anthracite (Middleton, 1989). This is evident in documented vitrinite reflectances which range between 0.58 and 2.59% (Mallett et al., 1995). The coals are rich in vitrinite (60-80%) (Hunt, 1989), and inertinite, with some having low mineral matter contents. In contrast to coal formation in the Surat Basin were the Walloon coals are thinly interbedded with non-coal layers, depositional conditions in the Bowen Basin have led to the formation of distinct coal units (as found in other Permian coal basins). These properties have been studied using petrological techniques in conjunction with elemental analyses to characterise the nature of Australian coal for many decades, and such information would provide insights into the organic structure of coal and its influence on hydrochemistry .

3.3 Fourier Transform Infrared Spectroscopy and NMR analysis

Fourier Transformed Infrared Spectroscopy (FTIR) and Nuclear Magnetic Resonance (NMR) are useful tools to gain insights into the structure of organic matter, and have been widely applied to coals (e.g. Guillen *et al.*, 1992; Ibarra *et al.*, 1996; Solomon and Carangelo, 1982; Supaluknari *et al.*, 1988a; 1988b). FTIR spectrometry has the ability to quantify the abundance of chemical functional groups and has been shown to be a versatile analytical technique for determining coal structure (e.g. Iglesias et al. 1995). NMR, especially Carbon-13 NMR spectroscopy, has become a method of choice for the elucidation of coal structure. This type of spectroscopy has the ability to obtain a detailed description of the chemical structure of carbon atoms and provide information on the motion of the molecules (e.g. Wershaw and Mikita 1987). Both solid-state and liquid-state NMR spectroscopy has been used on humic substances and coal. Excellent reviews on the use of NMR to identify coal structures have been conducted by Allen *et al.* (1984) and Genetti *et al.* (1999).

While many of the groundbreaking publications in this domain have been published in the 1970s-1990s, more recent studies still widely apply spectroscopic techniques as well as take advantage of new innovations to assess the distribution of different molecular moieties in the coal matrix. For example, one study (Wollenweber *et al.*, 2006) carried out a comprehensive organic-geochemical investigation of Permian, Carboniferous and Devonian coals with the aim to quantify differences in organic matter composition of the coals on a molecular level and to associate these differences with precursor plant matter, depositional environment and diagenesis. Li *et al.* (2010) investigated different macerals in bituminous coals of variable organic sulfur content using micro-Attenuated Total Reflectance – Fourier Transformed Infrared Spectroscopy (ATR–FTIR). ATR-FTIR spectra of vitrinite and inertinite macerals in low S and high S coals show distinct differences in IR absorbance from various aliphatic and aromatic functional groups. Traditional FTIR techniques (e.g. global KBr and the diffuse reflectance method) are limited to the analysis of bulk coal or a fraction of coal rather than individual macerals and results reflect weighted averages (D'Angelo and Zodrow 2011; Supaluknari et al. 1988a). A number of studies applied the technique of reflectance micro-FTIR, which provides the benefits of easier sample preparation and the ability to share the same maceral area with standard light microscopy. Studies include the in situ characterization of functional groups in coal macerals (e.g. Mastalerz and Bustin 1993a,b, 1995; 1996), mapping the abundance of functional groups across an area (Garcia and Black 1997), the characterization of coal structures (Guo and Bustin 1998, Morga 2010) and to document the chemical evolution within and among coal macerals with increasing rank (Chen et al. 2012).

With regards to NMR, Carbon-13 NMR spectroscopy has become a powerful non-destructive method for identifying structural parameters, including aromatics, in coals (e.g. see review by Smith et al. 1994 and references therein). Other NMR studies involving the elucidation of coal structure include ^{1}H-NMR, which can identify different kinds of hydrogen (including aromatic and phenolic; eg. Bartle and Jones 1978 and references therein), as well as ^{15}N NMR for elucidating nitrogen structures (e.g. Knicker et al. 1996).

While it may be expected that the propensity of coals to dissociate water-soluble organic compounds into water will depend on the structure of the coal, no studies that specifically look at this interrelationship using FTIR and NRM spectroscopy were found in our literature review.

3.4 Pyrolysis and thermovaporisation

Both temperature and time may synergistically affect the process of hydrocarbon generation/transformation in coal-bearing strata by influencing chemical reaction kinetics. Organic matter in coal constitutes a heterogeneous mixture with numerous functional groups and an interlinking of molecules forming a three dimensional molecular network. Therefore, the nature of the reactions and the types of chemical bonds that decompose can vary continuously during pyrolysis – the thermochemical decomposition of organic matter (e.g. Song et al. 2013).

Rock-Eval pyrolysis has been applied on coals of Australia. In this technique, a sample is placed in a vessel and progressively heated under an inert atmosphere. Conventional guidelines for interpreting Rock-Eval data (e.g. Peters, 1986) have to be adjusted when assessing coal-bearing source rocks for their petroleum generation potential (Sykes and Snowdon, 2002). This review found many reports on Rock-Eval data in databases maintained by the state geological surveys and in the open literature (e.g. Ahmed *et al.*, 2009). However, a systematic compilation of Rock-Eval data was outside the scope of this present study. Thermovaporisation of coals and oil shows was also mentioned in a range of reports, but did not include any specific details on molecular distributions of products.

Pyrolysis - gas chromatography (Py-GC) coupled with mass spectrometry (MS) or other detectors (e.g. flame ionisation detector (FID) or thermal conductivity detector (TCD)) has been widely applied to gain insights into the structure of coal and kerogen (e.g. Solli and Leplat, 1986; Hartgers *et al.*, 1992; 1994a,b; Nip *et al.*, 1992; Figure 6) and to classify kerogen (Horsfield, 1989). This technique has also been applied to Australian coals. One study by Kralert *et al.* (1995) applied *in situ* methylation using aqueous tetramethylammonium hydroxide (TMAH) to study oxygen-containing organic constituents in a solvent-extracted Victorian brown coal. Pyrolysis has also been applied to reconstruct the kinetic behaviour of Australian coals during geological heating. Powell *et al.* (1991) investigated a series of Australian coals and terrestrial sediments ranging in age from Permian through to the Cainozoic using a combination of organic petrography, Rock-Eval pyrolysis, elemental analysis and quantitative Py- GC measurements. One of their findings was that the distribution and abundance of phenols in flash pyrolysates is related to depositional setting as well as degree of maturation. Boreham *et al.* (1999) conducted open system pyrolysis on a set of Bowen Basin coals and inferred two stages of thermogenic methane generation from these coals.

Recently, Li and Zhu (2014) investigated structural and compositional changes in coal vitrinite during pyrolysis. The authors coupled this analysis with X-ray diffraction analysis, FTIR and ^{13}C NMR. The results indicated a linear relationship between average vitrinite reflectance and temperature. It was shown that the aliphatic carbon content progressively decreased with increasing temperature for the replacement of aromatic hydrogen by condensation.

A multitude of studies investigated Australian torbanites of Permian age, since these sediments are of interest to characterise biopolymers derived from *Botryococcus* algae (e.g. Derenne *et al.*, 1994; Greenwood *et al.*, 1996; Han *et al.*, 1995; Hutton *et al.*, 1996; Largeau *et al.*, 1986). However, torbanites are not typical coals for CSG production, and no further detail on these studies is provided in this review. Ellis *et al.* identified a range of aromatic compounds which can be directly correlated to specific precursor organisms, e.g. phenylalkanes related to fossil algae (Ellis *et al.*, 1996a), dihydro-*ar*-curcumene derived from sesquiterpenoids of the bisabolane skeletal type, and hence from higher plants (Ellis *et al.*, 1995a), and isohexylalkylnaphthalenes associated with specific higher plant precursors as a result of rearrangement and A-ring opening of diterpenoid and triterpenoid natural products during aromatization (Ellis *et al.*, 1996b). A range of papers was also devoted to the formation of geosynthetic aromatic compounds (e.g. Alexander *et al.*, 1995; Bastow *et al.*, 1996; 2000; Ellis *et al.*, 1995b; Ioppolo-Armanios *et al.*, 1995). The majority of these papers also investigated Permian coals. Free hydrocarbons were also described in coals of the Late Permian Avon and Stratford coal measures in the Gloucester Basin, however, no absolute concentrations are provided in this report, and the analytical detail of this report is sparse (Hunt et al., 1983).

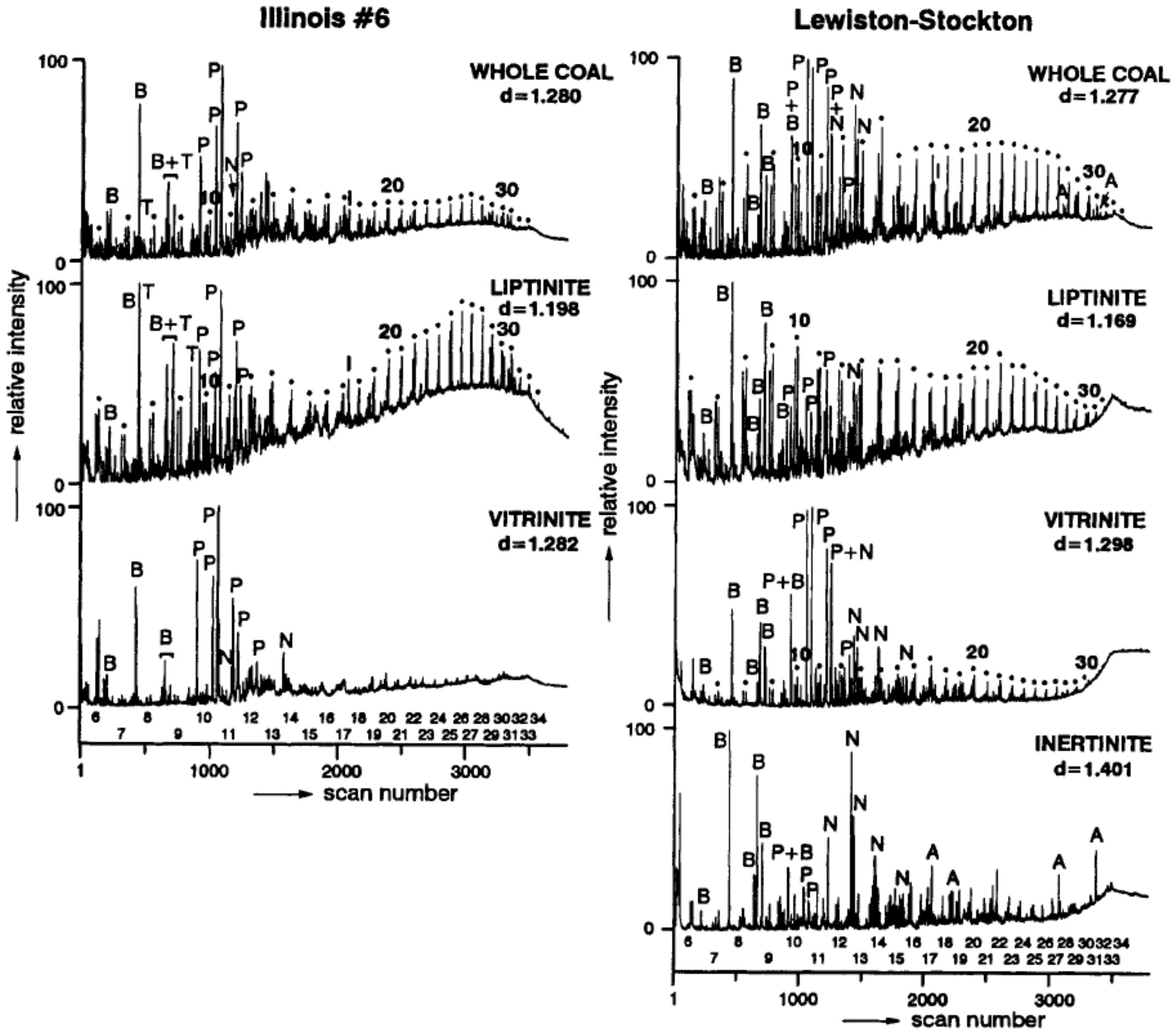


Figure 6: Example of Py-GC/MS traces, from Hartgers et al. (1994b) n-Alkanes are indicated by filled circles. Small numbers along the z-axis indicate total numbers of carbon atoms of n-alkanelnalk-1-ene doublets. Key: B = (alky1)benzenes; T = (alky1)thiophenes; P = (alky1)phenols; N = (alkyl)-naphthalenes; A = polyaromatics; I = monounsaturated acyclic isoprenoids.

3.5 Solvent-extraction of organic matter followed by detailed geochemical analysis

Solvent extraction of coals is a technique with a long history, and was first applied systematically by de Marsilli around 1860, who obtained abundant extracts from coals with boiling benzene, alcohol, ether, chloroform and carbon disulphide. Soon after, heterocyclic compounds with nitrogen such as pyridine and quinoline were used to obtain even higher yields of up to 50% for some coals (van Krevelen, 1993). Depending on type and rank of coal, variable proportions of coal can be extracted with organic solvents. The nature and quantity of the extracts also depend on the length of extraction, the solvent used, and the grain size to which the coal has been ground. Around 1930 more investigators came to support the theory that coal extracts are colloidal systems and therefore coal itself must be regarded as a solid colloid (van Krevelen, 1993). Products that can be extracted from coal are intimately bonded to the higher molecular weight proportion of the coal. Due to the importance of solvent extraction to gain insights into the nature and properties of coal, van Krevelen (1993) dedicated an entire chapter of this monograph to the action of solvents on coal. Detailed analyses of solvent extracts, however, are usually confined to the maltene fraction of coal extracts, i.e. the fraction that is soluble in *n*-pentane, *n*-hexane or *n*-heptane.

High relative abundances of certain alkylbenzenes (i.e. 1,2,3-trimethylbenzene; 1,2,3,4-tetramethylbenzene and dihydro-ar-curcumene) in low maturity sediments and crude oils has led to the suggestion that they originate from natural products such as carotenoids, terpenoids and alkaloids (e.g. Erdman, 1961; Hartgers *et al.*, 1992; 1994a; 1994b). Other, more stable aromatic compounds with non-isoprenoidal carbon skeletons are thought to be the products of sedimentary reactions (Bastow *et al.*, 1999; van Aarssen *et al.*, 1999). The unique distribution or fingerprint of alkylbenzenes (including BTEX) present in individual coals (and associated water) resulting from natural products and sedimentary reactions could potentially be used to clarify whether or not the source of aromatic compounds in groundwater that may be encountered in coal basins is related to the coal.

Oil fields and oil shows are common in basins with Permian coals, most notably in the Cooper-Eromanga basin, in the Bowen-Surat basin, and in the Canning, Carnarvon, Petrel and Perth basins. However, almost all of these basins also contain organic-rich sediments from stratigraphic intervals other than Permian coals that may have given rise to these oil shows. Molecular and isotope geochemistry has been applied to pinpoint the origin of these oils. Alexander *et al.* (1988) used the distribution of aromatic and saturated diterpane land plant markers to distinguish oils sourced from Permian versus younger source rocks. The advent of trees of the plant family *Araucariaceae*, related to the Kauri pine, that assumed prominence for the first time in the Early to Middle Jurassic resulted in a different distribution of these land plant markers for Permian and Jurassic oils that could be exploited for oil source correlation. Using this approach, Alexander *et al.* (1988) found evidence for both types of oils being present in the basin (Figure 7). Al-Arouri (1998) conducted a geochemical study of crude oils and samples of various Permian, Triassic and Jurassic organic-rich rock units from the southern Taroom Trough to test the prevailing Permian-source hypothesis for the petroleum reserves of the Bowen-Surat basin. Based on molecular and isotopic evidence they defined two oil families, of which one was interpreted to be derived from Late Permian coal measures of the Blackwater Group along the south-eastern and south-western margins of the trough. Ahmed *et al.* (2009) presented a detailed study on molecular and isotopic characteristics of six oil shows and seeps from the Southern Coalfield of the Sydney Basin, and suggested that Permian coals to be the most likely source of these petroleum occurrences. Kinnon *et al.* (2010) aimed to determine whether water quality and stable isotope data can be correlated with gas and groundwater production and flow pathways, and identify zones of recharge and water mixing.

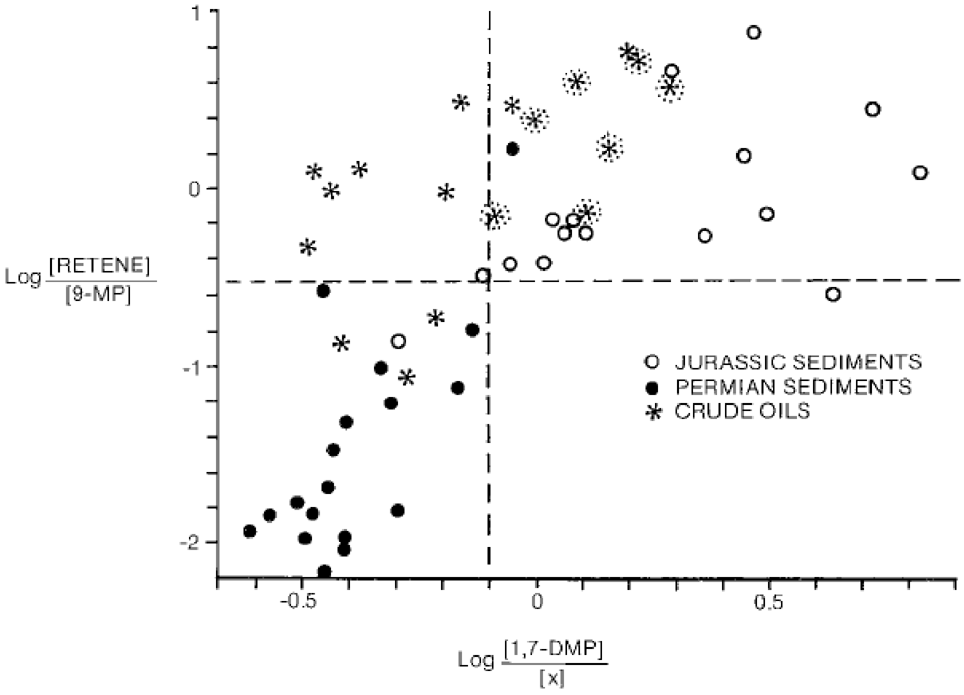


Figure 7: Log·log plot of source parameters based upon retene and dimethylphenanthrenes for Jurassic sediments, Permian sediments, and crude oils (from Alexander et al., 1988).

3.6 Aqueous leaching experiments

Aqueous leaching experiments can be conducted to simulate groundwater leaching of organic compounds from coals. The results provide evidence of the water-soluble, water-leachable and water-extractable organic compounds from coal and allow for a comparison with equivalent compounds from well and spring waters (Maharaj et al. 2014). Leaching experiments have been conducted for many decades. Carlson et al. (1979), for example, conducted such experiments to ascertain the aromatic hydrocarbons from coal of the Northern Great Plains, USA.

Maharaj et al. (2014) conducted aqueous leaching experiments to better understand Balkan endemic nephropathy (BEN), a chronic kidney disease that some (e.g. Feder et al. 1991, 2002) have linked to organic contaminants from lignite coal deposits leaching into drinking water supplies. The disease is geographically confined to countries of the Balkan Peninsula. However, other non-coal associated causes have also been hypothesised for the disease (see Maharaj et al. 2014 and references therein). Maharaj et al. (2014) also conducted leaching experiments on a variety of coal samples to simulate groundwater leaching of organic compounds. Pliocene lignites from endemic BEN areas of Romania and Serbia as well as lignite and bituminous coals from nonendemic areas of Romania and the USA were used for the experiments. Room temperature, hot water bath and Soxhlet aqueous extraction experiments were conducted between 25 and 80ºC and lasted from 5 to 128 days. Tables 1 and 2 list the percentages and concentrations, respectively, of aliphatic and aromatic compounds obtained and their match quality against mass spectral databases. The results of that study showed that many aromatic compounds present in endemic lignite coals are soluble in water and can be leached/extracted with water. While many compounds leached in this experiment were also present in non-endemic coals, indicating that they may not play a role in BEN, the authors suggested that some causative agents may still be present – especially since many samples contain compounds that are poorly matched with the mass spectral databases. Therefore, a better understanding of the compounds leached from coal samples may potentially lead to the identification of BEN-causative agents (Maharaj et al. 2014).

Toxicity characteristic leaching procedure (TCLP) is a standard method established by the US-EPA. In the US, the Resource Conservation and Recovery Act of 1976 led to the establishment of federal standards for the disposal of solid and hazardous waste. The act required that such wastes be characterised following testing protocols, such as the TCLP, published by the US-EPA (US-EPA 2008). TCLP allows the mobility of both organic and inorganic analytes present in liquid and solid materials to be determined.

In a study by Stearman et al. (2014), TCLP experiments were adapted to solid coal samples from open cut coal operations in eastern Australia (Gippsland Basin, Moreton Basin, Sydney-Gunnedah basin). The aim of their study was to determine the potential leachability of semi-volatile PAHs and phenolic compounds of coal with different ranks (lignite to bituminous – (Hv) high volatile to (Mv) medium volatile bituminous; Tables 3 and 4, Figure 8). Solutes used as leachant comprised an acetic acid solution, deionized water and synthetic CSG water. While no compounds were reported to be leached using the acetic acid solution, experiments with the other two solutes did result in some leaching.

The results suggest *higher molecular weight PAHs* (including benzo[a]pyrene) leach from *higher rank coals*, while *lower molecular weight* counterparts leach at greater concentrations from *lower rank coal*. Naphthalene and phenanthrene leached from lignite were detected at concentrations of 0.42 to 0.67 µg/L and 0.01 µg/L, respectively. In contrasts to the lignite samples, bituminous coal leached PAHs with less consistency. PAH compounds leached from HvA-bituminous coal were pyrene from 0.01 to 0.02 µg/L and fluoranthene from 0.01 to 0.03 µg/L. PAHs from that sample was leached in only two of the five TCLPs and only in deionized water. For the more mature Mv-bituminous coal, leached PAHs consisted of phenanthrene to 0.01 µg/L, fluoranthene to 0.03 µg/L, Pyrene to 0.05 µg/L, Benz[a]anthracene to 0.02 µg/L, Chrysene to 0.01 µg/L, Benzo[b+k]fluoranthene to 0.1 µg/L, Benzo[a]Pyrene to 0.01 µg/L. The Mv-bituminous coal leached PAH compounds in three of the five TCLPs performed with that coal and only in deionized water.

Stearman et al. (2014) showed that extract composition from natural waters will likely differ depending on PAH absorbtion/desorption behaviour, the ability of coal to act as a geosorbent, PAH solubility in natural waters, and the co-elution of PAHs to other dissolved humic material. As an example, they point out that the very low concentrations of the higher molecular weight PAHs detected in their bituminous leachates may be better explained by their very low solubilities in water and higher binding affinities (Log Kow) for organic matter (Table 5), rather than their relative abundances in coal samples. Stearman et al. (2014) also showed that naphthalene and phenanthrene are the most water soluble PAHs, likely accounting for their increased presence in CSG waters relative to the higher molecular weight PAHs (Table 5).

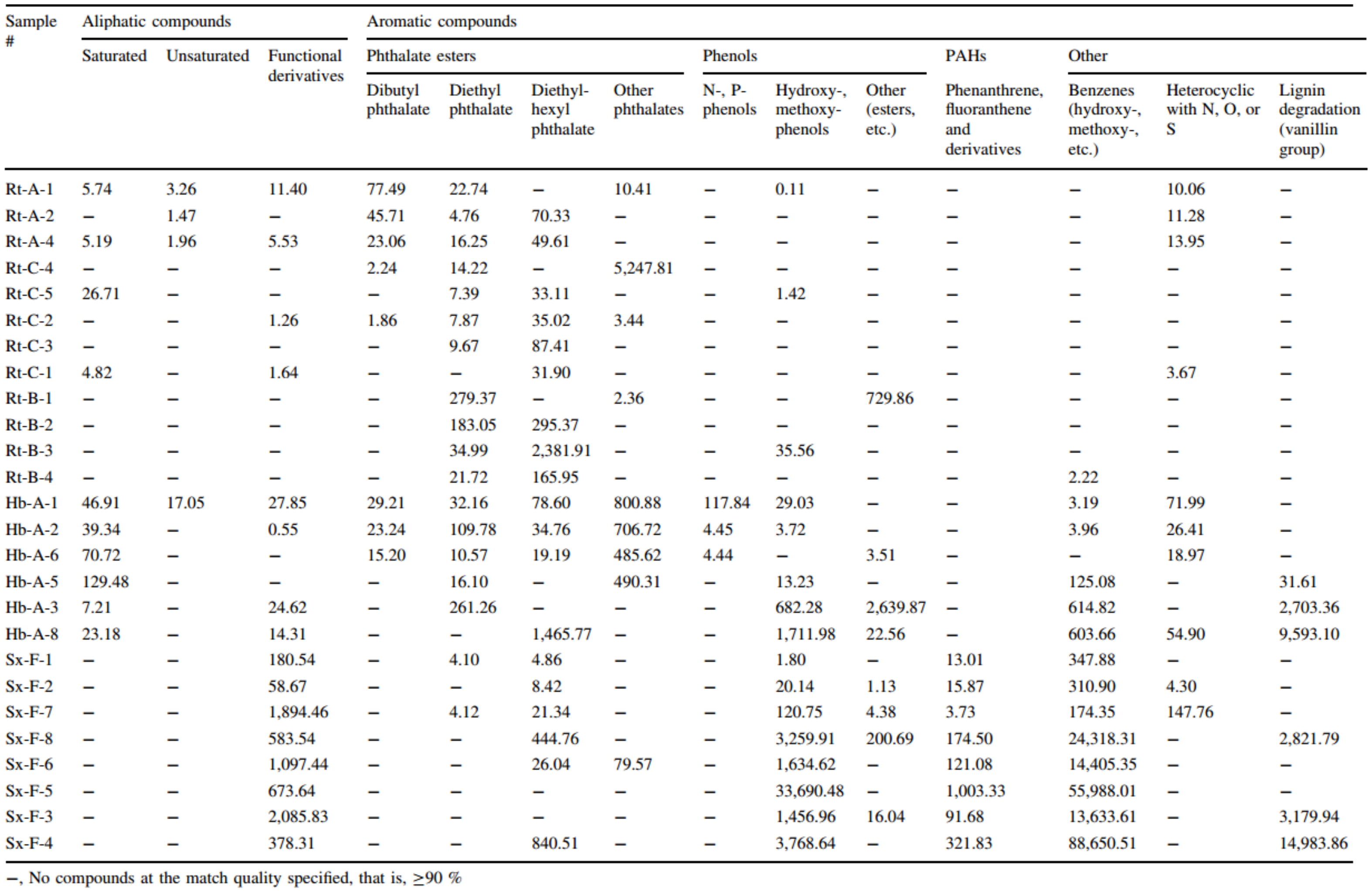
Stearman et al. (2014) states that while some of the identified organic compounds have carcinogenic or health risk potential, they are unlikely to be acutely toxic at the observed concentrations. They also point to the hydrophobicity of these compounds, which lessens their potential toxicity (Stearman et al. 2014).

Table 1: Percentages of aliphatic and aromatic compounds (≥90% match) in samples. Rt-A-1, Rt-A-2 = nonendemic bituminous; Rt-A-4 = endemic lignite; Rt-C-4 = nonendemic bituminous; Rt-C-5, Rt-C-2, Rt-C-3 = nonendemic lignite; Rt-C-1 = endemic lignite; Rt-B-*1, Rt-B-2=nonendemic bituminous; Rt–B-3, Rt-B-4 = endemic lignite; Hb-A-1, Hb-A-2, Hb-A-6 = nonendemic bituminous; Hb-A-5 = nonendemic lignite; Hb-A-3, Hb-A-8 = endemic lignite; Sx-F-1, Sx-F-2, Sx-F-7 =nonendemic bituminous; Sx-F-8, Sx-F-6 = nonendemic lignite; Sx-F-5, Sx-F-3, Sx-F-4 = endemic lignite. Source: Maharaj et al. 2014.*

Sample #	Aliphatic compounds			Aromatic compounds										
	Saturated	Unsaturated	Functional derivatives	Phthalate esters				Phenols			PAHs	Other		
				Dibutyl phthalate	Diethyl phthalate	Diethyl-hexyl phthalate	Other phthalates	N-, P-phenols	Hydroxy-, methoxy-phenols	Other (esters, etc.)	Phenanthrene, fluoranthene and derivatives	Benzenes (hydroxy-, methoxy-, etc.)	Heterocyclic with N, O, or S	Lignin degradation (vanillin group)
Rt-A-1	8	8	42	8	8	–	8	–	8	–	–	–	8	–
Rt-A-2	–	20	–	20	20	20	–	–	–	–	–	–	20	–
Rt-A-4	36	9	9	9	9	18	–	–	–	–	–	–	9	–
Rt-C-4	–	–	–	25	25	–	50	–	–	–	–	–	–	–
Rt-C-5	78	–	–	–	8	8	–	–	8	–	–	–	–	–
Rt-C-2	–	–	20	20	20	20	20	–	–	–	–	–	–	–
Rt-C-3	–	–	–	–	50	50	–	–	–	–	–	–	–	–
Rt-C-1	40	–	20	–	–	20	–	–	–	–	–	–	20	–
Rt-B-1	–	–	–	–	33	–	33	–	–	33	–	–	–	–
Rt-B-2	–	–	–	–	50	50	–	–	–	–	–	–	–	–
Rt-B-3	–	–	–	–	25	25	–	–	50	–	–	–	–	–
Rt-B-4	–	–	–	–	33	33	–	–	–	–	–	33	–	–
Hb-A-1	39	3	11	3	3	6	11	8	6	–	–	3	6	–
Hb-A-2	46	–	4	4	4	13	13	4	4	–	–	4	4	–
Hb-A-6	64	–	–	5	5	5	5	5	–	5	–	–	5	–
Hb-A-5	11	–	–	–	11	–	11	–	22	–	–	33	–	11
Hb-A-3	14	–	23	–	5	–	–	–	18	9	–	27	–	5
Hb-A-8	22	–	13	–	–	3	–	–	22	6	–	22	3	9
Sx-F-1	–	–	25	–	8	8	–	–	8	–	8	42	–	–
Sx-F-2	–	–	7	–	–	13	–	–	7	7	7	53	7	–
Sx-F-7	–	–	43	–	4	4	–	–	13	4	4	23	4	–
Sx-F-8	–	–	5	–	–	5	–	–	19	19	10	38	–	5
Sx-F-6	–	–	27	–	–	7	7	–	13	–	13	33	–	–
Sx-F-5	–	–	6	–	–	–	–	–	47	–	18	29	–	–
Sx-F-3	–	–	12	–	–	–	–	–	32	4	8	40	–	4
Sx-F-4	–	–	18	–	–	6	–	–	24	–	6	35	–	12

–, No compounds at the match quality specified, that is, ≥90 %

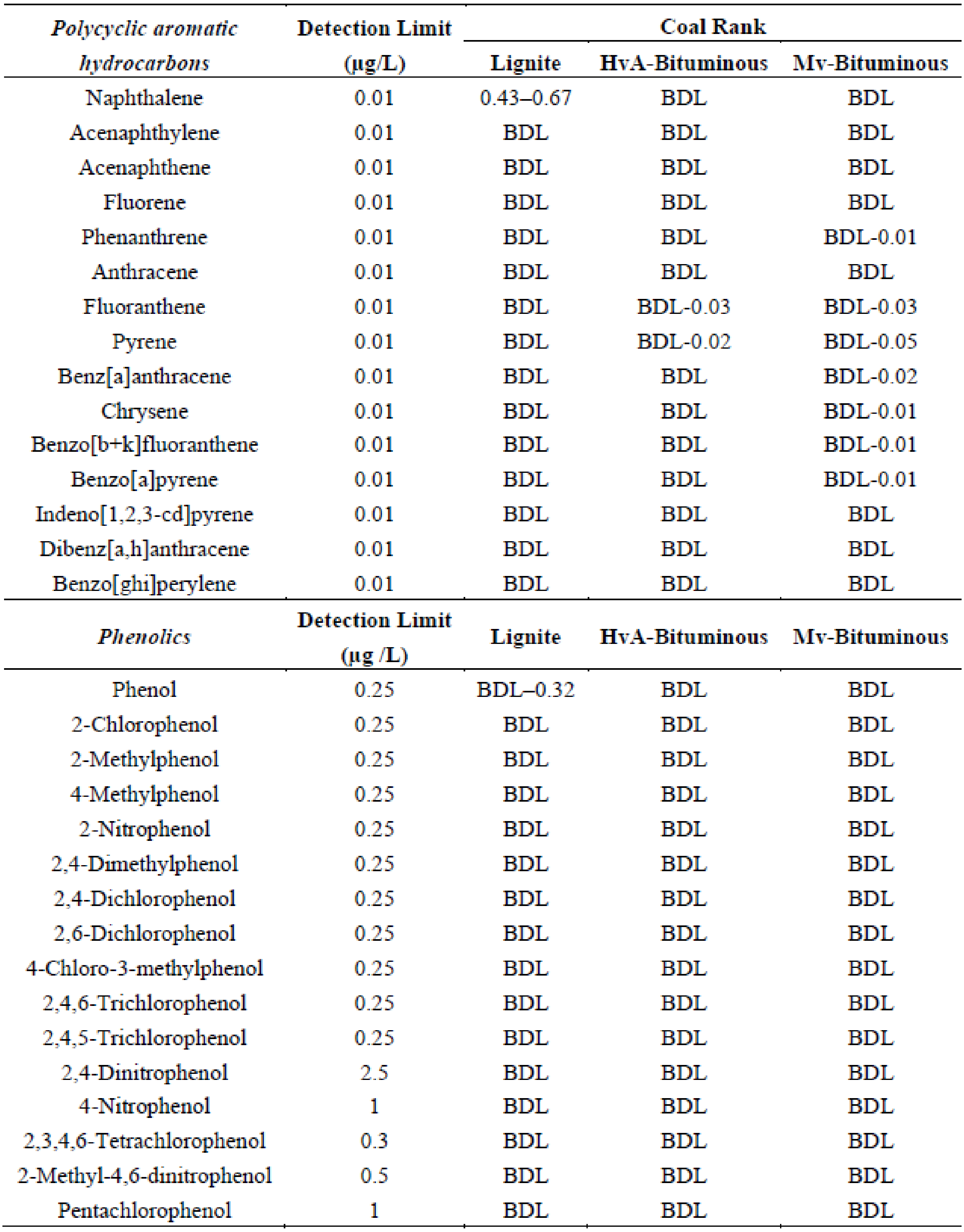
Table 2: Concentration (ng/g) of aliphatic and aromatic compounds (≥90% match) in samples. Rt-A-1, Rt-A-2 = nonendemic bituminous; Rt-A-4 = endemic lignite; Rt-C-4 = nonendemic bituminous; Rt-C-5, Rt-C-2, Rt-C-3 = nonendemic lignite; Rt-C-1 = endemic lignite; Rt-B-1, Rt-B-2=nonendemic bituminous; Rt–B-3, Rt-B-4 = endemic lignite; Hb-A-1, Hb-A-2, Hb-A-6 = nonendemic bituminous; Hb-A-5 = nonendemic lignite; Hb-A-3, Hb-A-8 = endemic lignite; Sx-F-1, Sx-F-2, Sx-F-7 =nonendemic bituminous; Sx-F-8, Sx-F-6 = nonendemic lignite; Sx-F-5, Sx-F-3, Sx-F-4 = endemic lignite. Source: Maharaj et al. 2014.



Sample #	Aliphatic compounds			Aromatic compounds										
	Saturated	Unsaturated	Functional derivatives	Phthalate esters				Phenols			PAHs	Other		
				Dibutyl phthalate	Diethyl phthalate	Diethyl-hexyl phthalate	Other phthalates	N-, P-phenols	Hydroxy-, methoxy-phenols	Other (esters, etc.)	Phenanthrene, fluoranthene and derivatives	Benzenes (hydroxy-, methoxy-, etc.)	Heterocyclic with N, O, or S	Lignin degradation (vanillin group)
Rt-A-1	5.74	3.26	11.40	77.49	22.74	–	10.41	–	0.11	–	–	–	10.06	–
Rt-A-2	–	1.47	–	45.71	4.76	70.33	–	–	–	–	–	–	11.28	–
Rt-A-4	5.19	1.96	5.53	23.06	16.25	49.61	–	–	–	–	–	–	13.95	–
Rt-C-4	–	–	–	2.24	14.22	–	5,247.81	–	–	–	–	–	–	–
Rt-C-5	26.71	–	–	–	7.39	33.11	–	–	1.42	–	–	–	–	–
Rt-C-2	–	–	1.26	1.86	7.87	35.02	3.44	–	–	–	–	–	–	–
Rt-C-3	–	–	–	–	9.67	87.41	–	–	–	–	–	–	–	–
Rt-C-1	4.82	–	1.64	–	–	31.90	–	–	–	–	–	–	3.67	–
Rt-B-1	–	–	–	–	279.37	–	2.36	–	–	729.86	–	–	–	–
Rt-B-2	–	–	–	–	183.05	295.37	–	–	–	–	–	–	–	–
Rt-B-3	–	–	–	–	34.99	2,381.91	–	–	35.56	–	–	–	–	–
Rt-B-4	–	–	–	–	21.72	165.95	–	–	–	–	–	2.22	–	–
Hb-A-1	46.91	17.05	27.85	29.21	32.16	78.60	800.88	117.84	29.03	–	–	3.19	71.99	–
Hb-A-2	39.34	–	0.55	23.24	109.78	34.76	706.72	4.45	3.72	–	–	3.96	26.41	–
Hb-A-6	70.72	–	–	15.20	10.57	19.19	485.62	4.44	–	3.51	–	–	18.97	–
Hb-A-5	129.48	–	–	–	16.10	–	490.31	–	13.23	–	–	125.08	–	31.61
Hb-A-3	7.21	–	24.62	–	261.26	–	–	–	682.28	2,639.87	–	614.82	–	2,703.36
Hb-A-8	23.18	–	14.31	–	–	1,465.77	–	–	1,711.98	22.56	–	603.66	54.90	9,593.10
Sx-F-1	–	–	180.54	–	4.10	4.86	–	–	1.80	–	13.01	347.88	–	–
Sx-F-2	–	–	58.67	–	–	8.42	–	–	20.14	1.13	15.87	310.90	4.30	–
Sx-F-7	–	–	1,894.46	–	4.12	21.34	–	–	120.75	4.38	3.73	174.35	147.76	–
Sx-F-8	–	–	583.54	–	–	444.76	–	–	3,259.91	200.69	174.50	24,318.31	–	2,821.79
Sx-F-6	–	–	1,097.44	–	–	26.04	79.57	–	1,634.62	–	121.08	14,405.35	–	–
Sx-F-5	–	–	673.64	–	–	–	–	–	33,690.48	–	1,003.33	55,988.01	–	–
Sx-F-3	–	–	2,085.83	–	–	–	–	–	1,456.96	16.04	91.68	13,633.61	–	3,179.94
Sx-F-4	–	–	378.31	–	–	840.51	–	–	3,768.64	–	321.83	88,650.51	–	14,983.86

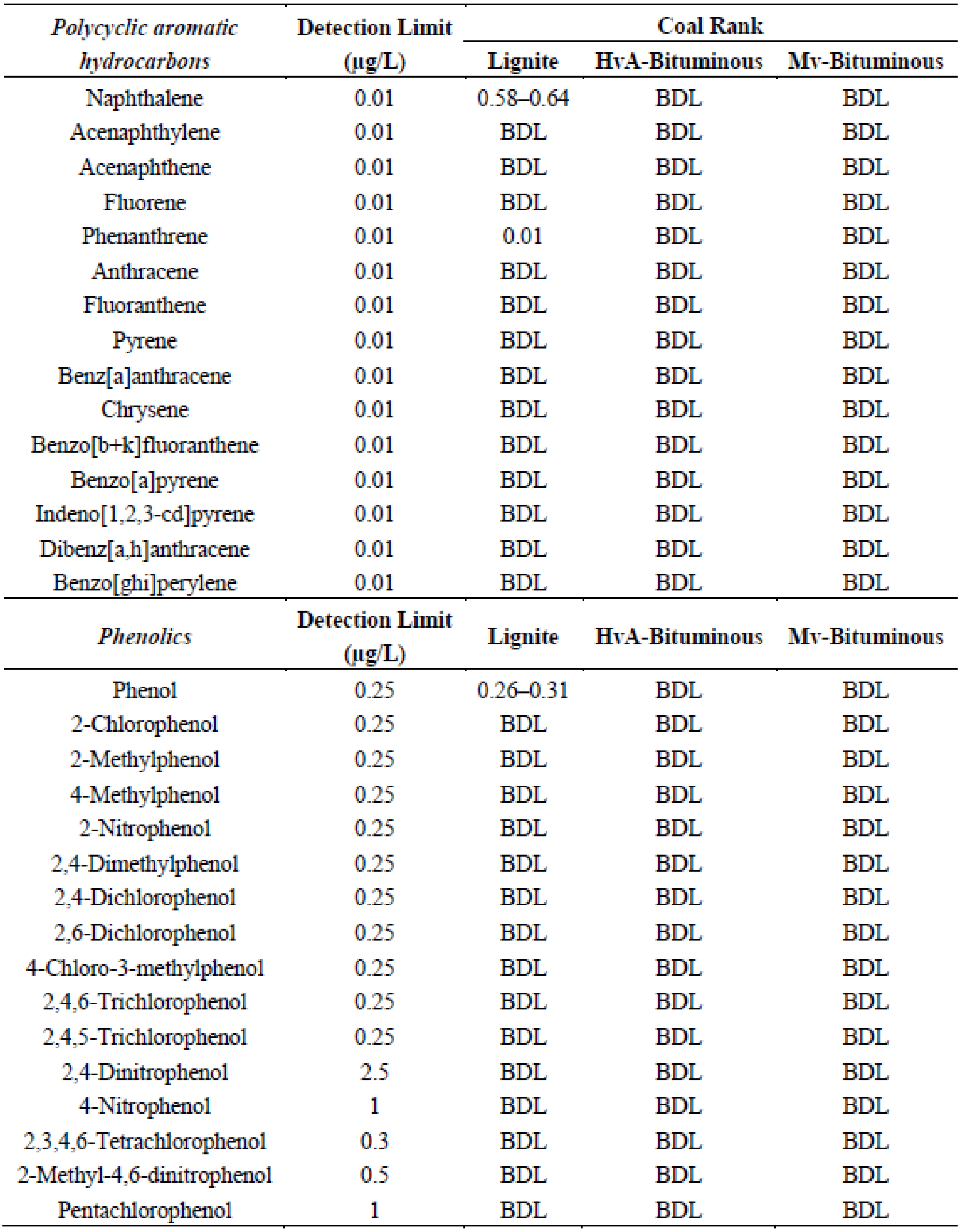
–, No compounds at the match quality specified, that is, ≥90 %

Table 3: Concentration ranges of selected organics from toxicity characteristic leaching procedure experiments performed with deionised water. BDL = below detection limit. Source: Stearman et al. 2014.

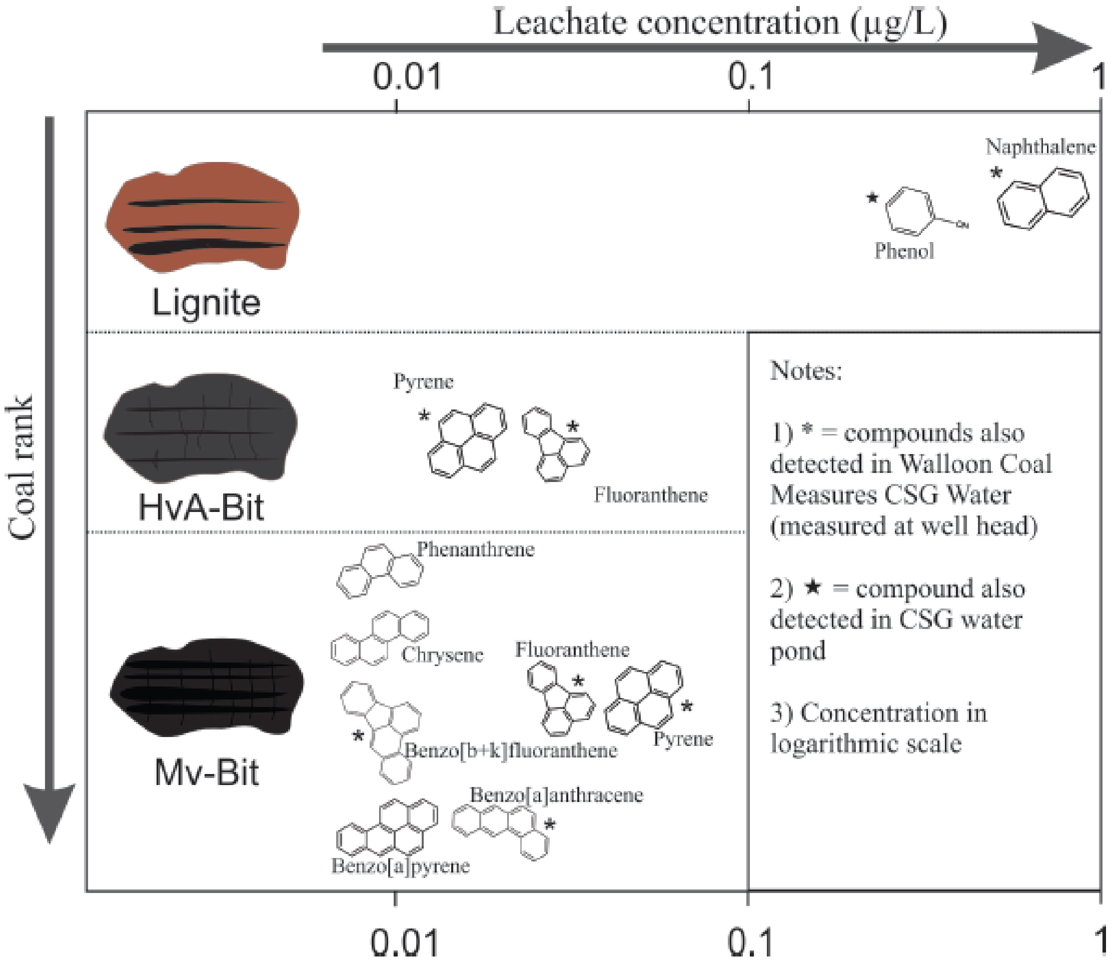


Polycyclic aromatic hydrocarbons	**Detection Limit (µg/L)**	**Coal Rank** **Lignite**	 **HvA-Bituminous**	 **Mv-Bituminous**
Naphthalene	0.01	0.43–0.67	BDL	BDL
Acenaphthylene	0.01	BDL	BDL	BDL
Acenaphthene	0.01	BDL	BDL	BDL
Fluorene	0.01	BDL	BDL	BDL
Phenanthrene	0.01	BDL	BDL	BDL-0.01
Anthracene	0.01	BDL	BDL	BDL
Fluoranthene	0.01	BDL	BDL-0.03	BDL-0.03
Pyrene	0.01	BDL	BDL-0.02	BDL-0.05
Benz[a]anthracene	0.01	BDL	BDL	BDL-0.02
Chrysene	0.01	BDL	BDL	BDL-0.01
Benzo[b+k]fluoranthene	0.01	BDL	BDL	BDL-0.01
Benzo[a]pyrene	0.01	BDL	BDL	BDL-0.01
Indeno[1,2,3-cd]pyrene	0.01	BDL	BDL	BDL
Dibenz[a,h]anthracene	0.01	BDL	BDL	BDL
Benzo[ghi]perylene	0.01	BDL	BDL	BDL
Phenolics	**Detection Limit (µg /L)**	**Lignite**	**HvA-Bituminous**	**Mv-Bituminous**
Phenol	0.25	BDL–0.32	BDL	BDL
2-Chlorophenol	0.25	BDL	BDL	BDL
2-Methylphenol	0.25	BDL	BDL	BDL
4-Methylphenol	0.25	BDL	BDL	BDL
2-Nitrophenol	0.25	BDL	BDL	BDL
2,4-Dimethylphenol	0.25	BDL	BDL	BDL
2,4-Dichlorophenol	0.25	BDL	BDL	BDL
2,6-Dichlorophenol	0.25	BDL	BDL	BDL
4-Chloro-3-methylphenol	0.25	BDL	BDL	BDL
2,4,6-Trichlorophenol	0.25	BDL	BDL	BDL
2,4,5-Trichlorophenol	0.25	BDL	BDL	BDL
2,4-Dinitrophenol	2.5	BDL	BDL	BDL
4-Nitrophenol	1	BDL	BDL	BDL
2,3,4,6-Tetrachlorophenol	0.3	BDL	BDL	BDL
2-Methyl-4,6-dinitrophenol	0.5	BDL	BDL	BDL
Pentachlorophenol	1	BDL	BDL	BDL

Table 4: Concentration ranges of selected organics from toxicity characteristic leaching procedure experiments performed with synthetic CSG water. BDL = below detection limit. Source: Stearman et al. 2014.



Polycyclic aromatic hydrocarbons	Detection Limit (µg/L)	Coal Rank		
		Lignite	HvA-Bituminous	Mv-Bituminous
Naphthalene	0.01	0.58–0.64	BDL	BDL
Acenaphthylene	0.01	BDL	BDL	BDL
Acenaphthene	0.01	BDL	BDL	BDL
Fluorene	0.01	BDL	BDL	BDL
Phenanthrene	0.01	0.01	BDL	BDL
Anthracene	0.01	BDL	BDL	BDL
Fluoranthene	0.01	BDL	BDL	BDL
Pyrene	0.01	BDL	BDL	BDL
Benz[a]anthracene	0.01	BDL	BDL	BDL
Chrysene	0.01	BDL	BDL	BDL
Benzo[b+k]fluoranthene	0.01	BDL	BDL	BDL
Benzo[a]pyrene	0.01	BDL	BDL	BDL
Indeno[1,2,3-cd]pyrene	0.01	BDL	BDL	BDL
Dibenz[a,h]anthracene	0.01	BDL	BDL	BDL
Benzo[ghi]perylene	0.01	BDL	BDL	BDL
Phenolics	Detection Limit (µg/L)	Lignite	HvA-Bituminous	Mv-Bituminous
Phenol	0.25	0.26–0.31	BDL	BDL
2-Chlorophenol	0.25	BDL	BDL	BDL
2-Methylphenol	0.25	BDL	BDL	BDL
4-Methylphenol	0.25	BDL	BDL	BDL
2-Nitrophenol	0.25	BDL	BDL	BDL
2,4-Dimethylphenol	0.25	BDL	BDL	BDL
2,4-Dichlorophenol	0.25	BDL	BDL	BDL
2,6-Dichlorophenol	0.25	BDL	BDL	BDL
4-Chloro-3-methylphenol	0.25	BDL	BDL	BDL
2,4,6-Trichlorophenol	0.25	BDL	BDL	BDL
2,4,5-Trichlorophenol	0.25	BDL	BDL	BDL
2,4-Dinitrophenol	2.5	BDL	BDL	BDL
4-Nitrophenol	1	BDL	BDL	BDL
2,3,4,6-Tetrachlorophenol	0.3	BDL	BDL	BDL
2-Methyl-4,6-dinitrophenol	0.5	BDL	BDL	BDL
Pentachlorophenol	1	BDL	BDL	BDL



Notes:

1) * = compounds also detected in Walloon Coal Measures CSG Water (measured at well head)

2) ★ = compound also detected in CSG water pond

3) Concentration in logarithmic scale

Figure 8: Aromatic compounds leached from coal samples with deionised water and their relative concentrations. HvA = high volatile-A bituminous; Mv = medium volatile bituminous. Source: Stearman et al. 2014.

Table 5: Aromatic compounds detected in Walloon Coal Measure CSG water and leaching experiments with their physico-chemical properties. Source: Stearman et al. 2014. See also Neff (1979); US-EPA (1980).

Compound	Molecular Mass (g/mol)	Solubility at 25ºC (µg/L)	Log KoW*	No. of Aromatic Rings
Phenol	94.1	83,000,000	1.46	1
Naphthalene	128.2	31,000	3.37	2
Phenanthrene	178.2	465	4.46	3
Fluoranthene	202.3	260	4.9	3
Pyrene	202.1	133	4.88	4
Benz[a]anthracene	228.3	11	5.63	4
Chrysene	228.3	1.9	5.63	4
Benzo[b]fluoranthene	252.3	2.4	6.04	4
Benzo[k]fluoranthene	252.3	2.4	6.21	4
Benzo[a]pyrene	252.3	3.8	6.06	5
Dibenz[a]anthracene	278.3	0.4	6.86	5

*Log KoW refers to the octanol-water partition coefficient whereby higher values denote compounds more likely to partition into organic rather than aqueous phases.

3.7 Bioassay experiments of hydrocarbons present in CSG waters

Bioassays are experimental procedures whereby the biological activity of a chemical substance can be determined by measuring the effect on an organism, tissue, cells, enzyme or receptor. Bioassays of these types can also be used to determine acute or chronic ecotoxicity. Such experiments are typically conducted to measure the effects of certain substances on living organisms and have been employed in monitoring the biological effects of environmental pollutants (e.g. Machala et at al. 2001; Pieterse et al. 2013; Tang et al. 2014).

Important studies that need to be conducted are comparisons between the hydrocarbon constituents present in coal seam groundwater and measured effects from bioassays. Several PAHs, for example, are known ligands of the aryl hydrocarbon receptor (AhR; Figure 9), which mediates toxic effects related to these compounds (e.g. Pieterse et al. 2013). Therefore, bioassays can open new and important research areas into potential environmental and health impacts and any future monitoring strategies of waters associated with CSG.

Recently, Tang et al. (2014) reported for the first time the application of bioassay tools for the assessment of groundwater samples associated with coals. The water samples were derived from private wells tapping into the Walloon Coal Measures of the Surat Basin. Since these samples have not been affected by hydraulic fracturing, the samples are regarded as entirely geogenic; untreated groundwater in proximity to the coal seams that contain commercial CSG wells. Low concentrations of PAHs were detected in the waters (see section 4.3). The compounds were benzo[b]fluoranthene, benzo[k]fluoranthene, pyrene, fluoranthene, phenanthrene and napththalene. In this study, five of fourteen bioassay tests yielded positive responses. The five tests investigated aryl hydrocarbon-receptor gene activation, estrogenic endocrine activity, oxidative stress response, interference with cytokine production and non-specific toxicity. The observed effects were benchmarked against known water sources and were regarded as similar to secondary treated wastewater effluent, stormwater and surface water. Based on toxicity modelling, the detected PAHs explained less than 5% of the observed biological effects. The study shows that not all the observed biological effects could be explained solely by the presence of individually identified compounds in the sampled waters and many chemicals may be overlooked.

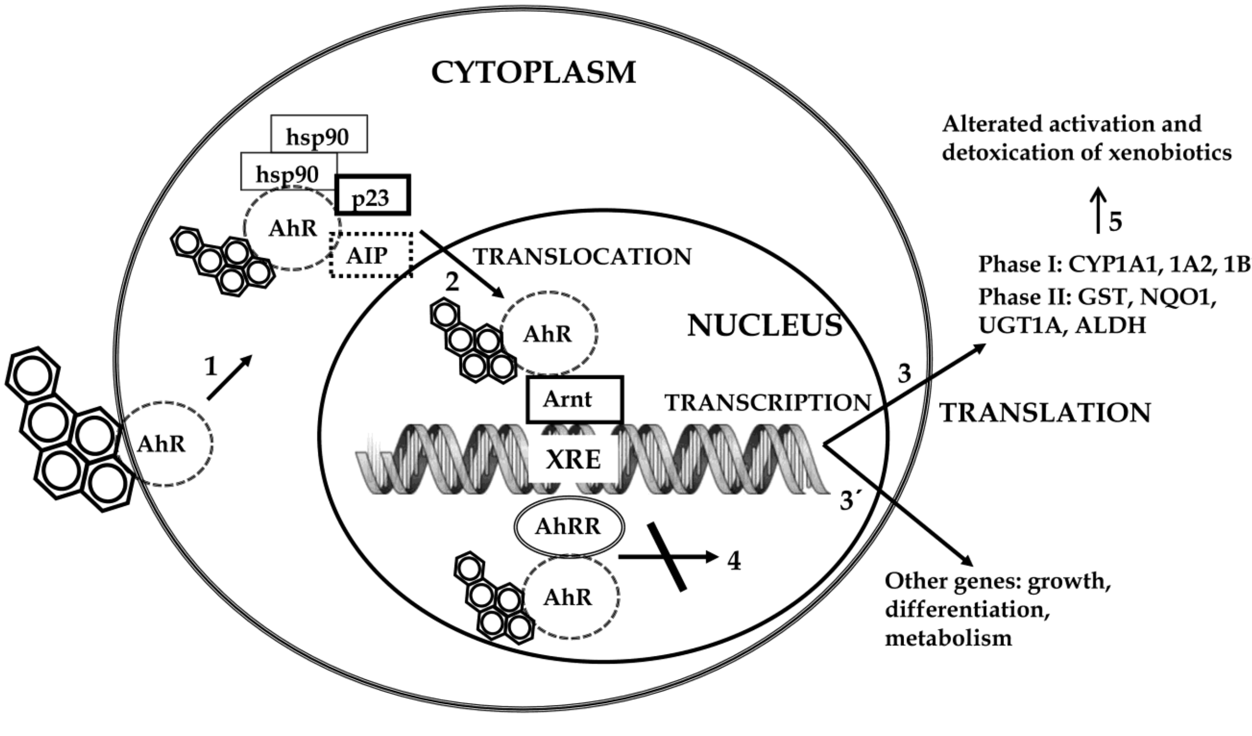


Figure 9: Activation of molecular pathways by a PAH. PAH interact with the receptor AhR (1) and is assisted with other proteins - hsp90, p23 and AIP. AhR-PAH complex is translocated to the nucleus (2) and makes a complex with Arnt to activate transcription of several genes as Phase I and Phase II (3), and genes participating in other cellular responses (3'). If AhRR interacts with the AhR-PAH complex, the transcription is inhibited (4). The transcription is performed as a response to the detoxification of xenobiotics and other molecules (5). Source: Arenas-Huertero et al. 2011.

PART 2

Organic hydrogeochemistry of groundwater associated with coals in Australia and other parts of the world

4 Organic hydrochemistry of groundwater associated with Australian coals

The organic hydrochemistry of groundwater associated with coals can include a wide variety of oxygen-bearing aromatic compounds (e.g. phenols, aldehydes, ketones, and various carboxy-, hydroxyl- and methoxy-bearing compounds), nitrogen-bearing compounds (pyridines and amines), mono- and polycyclic aromatic hydrocarbons (PAHs), and aliphatic compounds (Santamaria and Fisher, 2003). These water-soluble organics are produced by the cleavage of the aromatic structures within the coal matrix either by thermal stress accompanied by burial, other forms of heating, chemical oxidation during burial, or as the consequence of the introduction of oxygenated water or air. Coals can also be solubilised to a limited extent by microorganisms (Klein *et al.*, 2001).

Lower rank coals contain a greater abundance of more easily cleaved bridge structures than higher rank coals, and therefore solubilisation of lignite by microorganisms is more extensive than solubilisation of bituminous coal. The volatile matter and oxygen content of the coal are also principal factors influencing the extent of bioconversion (Reiss, 1992). For these reasons, groundwater associated with lower rank coals should have higher organic concentrations than those associated with higher rank coals. Coals containing more volatiles and more oxygen should also yield more dissolved organics. However, as shown in the preceding part of this report, higher rank coals can release higher molecular weight PAHs.

There is only limited published or publically available information globally on the organic hydrochemistry of groundwater associated with coal seams. A literature search of geo-databases, international journals, State groundwater databases, publicly available reports from mining and CSG companies and the Queensland Government CSG portal (http://www.derm.qld.gov.au/environmental_management/coal-seam-gas/groundwater.html) has yielded only limited organic geochemistry data for groundwater associated with coal deposits in Australia. Recently, Stearman et al. (2014) reported the presence of organic compounds from government-held CSG water quality data from the Bowen and Surat basins, Queensland. This work is extensively referred to in this literature review.

4.1 Benzene, toluene, ethylbenzene and xylenes (BTEX)

The term BTEX (**B**enzene, **T**oluene, **E**thylbenzene and **X**ylenes) is an abbreviation used for four related compounds that are found in coal, crude oil and a variety of petroleum-derived products (e.g. Leush and Bartkow 2010). BTEX compounds have a number of different sources and can be introduced into the environment through natural and artificial means. Importantly, these compounds may dissolve and are highly mobile in water and can be detected in surface and groundwater contaminated sites, including those in close proximity to natural oil, coal and gas deposits (e.g. Leush and Bartkow 2010). In the US, these compounds are regulated under the Safe Drinking Water Act (SDWA) National Primary Drinking Water Regulations (NPDWRs) because of the risks they pose to human health.

In a report by the US Environmental Protection Agency (US-EPA), it was estimated that if BTEX was used as an additive to fraccing fluids for coalbed methane, the concentration at the point of injection would be 45-4,400 ppb for benzene, 120-31,000 ppb for toluene, 120-8,700 ppb for ethylbenzene and 330-26,000 ppb for xylenes (US-EPA 2004). While these concentrations were regarded as high, the report concluded that the risk of contaminating groundwater sources of drinking water was minimal due to recovery of injected fluids (68-82%) combined with the mitigating effects of dilution, dispersion, adsorption and biodegradation (US-EPA 2004).

Several factors determine the harmfulness of BTEX compounds to human health. Such factors include the amount and the length of time of exposure, as well as to which BTEX compound one is exposed to (Leush and Bartkow 2010). Of the four BTEX compounds, benzene is regarded as the most toxic. Currently, most toxicity data are available for airborne exposure to BTEX, as this is the most common route of exposure to these volatile compounds. See Leush and Bartkow (2010) for a brief review of such toxicity data.

The Australian Drinking Water Guidelines (ADWG; NHMRC 2004) describe public health guidelines for BTEX in drinking water. Such guidelines are based on an acceptable daily intake of drinking water (i.e. the amount of a chemical that can be ingested daily over a lifetime without adverse effect based on a 70 kg person drinking 2 litres of water every day for 70 years). Since most people do not drink 2 litres of water daily and are not constantly exposed to guideline concentrations of contaminants in their drinking water supply, such guidelines provide a significant safety margin. Therefore, exceeding these guidelines for a short-term does not necessarily represent a significant health risk *per se*, but will depend on how often and how long the exceedance of these concentrations occur (enHealth 2002). Current Australian and selected international guidelines for BTEX compounds in drinking and environmental waters are summarised in Table 6.

While benzene is a known carcinogen, toluene, ethylbenzene and xylenes are not recognized as carcinogenic (IARC 1989). It is specified by the ADWG that benzene should not be detected in drinking water with a guideline of 1 ppb (the analytical detection limit) (NHMRC 2004). Drinking water guidelines for the remaining chemicals are much higher. Two mechanisms of introduction for BTEX have been identified: 1) the use of BTEX compounds in the fluids used for fraccing; and 2) through hydraulic communication between the coal seam and aquifers used for groundwater extraction.

While the use of BTEX compounds as additives in fraccing fluids has in the past been permitted in US CSG extraction, it has since 2003 been voluntarily discontinued due to the availability of safer alternatives (US-EPA 2004). In Queensland by comparison, BTEX compounds are strictly regulated and must not be used in stimulation fluids in amounts greater than that provided by the legislation (SoQ 2010). In effect, due to the stringent standard and low concentrations allowed, BTEX chemicals cannot be added to fraccing fluids. The Australian environmental and human health standards used by Queensland laws require the amount of BTEX chemicals in fraccing fluids to be below the concentrations outlined in Table 7.

There have been three reported instances in Queensland relating to BTEX compounds in groundwater sources associated with CSG and underground coal gasification (UCG). Two of these occurrences were in the Permian Bowen Basin, and the third was in the Surat Basin. It is important to note, however, that CSG extractions are very different to UCG extractions and therefore the occurrences of BTEX compounds in CSG and UCG sites are likely due to different processes and/or sources. Coal seam gas extraction methods always involve dewatering and fracture stimulation whereas UCG technology involves the combustion of coal seams *in-situ* by introducing air and an ignition source, and then harvesting the generated gases (e.g. Huc 2013).

Table 6: Water quality guidelines for benzene, toluene, ethylbenzene and xylene (BTEX). All values are in ppb (µg/L). Adopted with modifications from Leusch and Bartkow (2010).

Compound	QPHR[1]	ADWG[2]	WHO DWG[3]	US NPDWS[4]	ANZECC (99% protection)[5]
Benzene	1	1	10	5	600
Toluene	800	800 (25 for aesthetics)*	700	1000	180
Ethylbenzene	300	300 (3 for aesthetics)*	300	700	50
Xylene	600	600 (20 for aesthetics)*	500	10000 (total xylenes)	200

[1] Queensland Public Health Regulation (QPHR 2005); [2] Australian Drinking Water Guidelines (NHMRC 2004); [3] World Health Organisation Drinking Water Guidelines (WHO 2008); [4] United States National Primary Drinking Water Standards (USEPA 2003); [5] Australian and New Zealand Environment Conservation Council Environmental Protection Guidelines (ANZECC 2000). * Toluene, ethylbenzene and xylenes have a lower aesthetics guidelines than a health guideline. This is because these compounds will be noticeable by smell or taste before they become a health risk.

Table 7: Water quality guidelines for BTEX chemicals set out by the Australian environmental and human health standards and used by Queensland laws. Source: Queensland Government, 2015 (https://www.ehp.qld.gov.au/management/non-mining/documents/fraccing-btex.pdf)

Compound	Concentration
Benzene	1 µg/L[1]
Toluene	180 µg/L[2]
Ethylbenzene	80 µg/L[2]
m-Xylene	75 µg/L[2]
o-Xylene	350 µg/L[2]
p-Xylene	200 µg/L[2]

[1]Australian Drinking Water Guidelines (NHMRC, 2000); [2]Australian and New Zealand Environmental Conservation Council Guidelines for Freshwater and Marine Water Quality.

Australian Pacific LNG (APLNG) provided a summary of water chemistry from 47 wells within the Talinga gas field in south central Queensland (Surat Basin) as part of their Condabri CSG Water Management Plan to DERM (APLNG, 2010). Average concentrations of BTEX compounds were below detection limits, while ranges of detected concentrations were not reported (Table 8).

Table 8: Average concentrations of BTEX compounds in wells from the Talinga Gas Field, Surat Basin. Source: APLNG 2010.

Compound	Average value (µg/L)
Benzene	<1
Toluene	<2
Xylene (Meta, Para, Ortho)	<6

APLNG made an announcement in October 2010 regarding the discovery of BTEX traces in fluid samples in eight CSG exploration gas wells in the Surat Basin, but no specific information is publicly available. The samples were collected from wells that had been stimulated by hydraulic fracturing; however, APLNG stated that BTEX had not been used in fracture fluids and this was confirmed by APLNG's supplier (Sherrif *et al.*, 2010). An investigation identified possible sources of BTEX contaminants, including small amounts of lubricants and diesel which may have been introduced inadvertently during operations. BTEX chemicals were identified as being present in trace amounts in mineral oil which was used as in additive in hydraulic fracture stimulation (APLNG, 2010; http://origintogether.com/wpcontent/factsheets/press/APLNG%20BTEX%20Investigation%20Results.pdf accessed 18 July, 2011). The investigation also indicated that trace concentrations of BTEX may naturally occur under certain conditions (APLNG, 2010; http://origintogether.com/wpcontent/factsheets/press/APLNG%20BTEX%20Investigation%20Results.pdf accessed 18 July, 2011).

In November 2010, Arrow Energy announced that traces of benzene (1 to 3 ppb) were detected in three wells in its CSG permits in the northern Bowen Basin. Arrow Energy stated that chemicals containing benzene (or BTEX compounds) were not used in hydraulic fracturing (Arrow Energy, 2010a http://www.arrowenergy.com.au/icms_docs/ 87336_Notification_of_Results_Media_Release.pdf, accessed 18 July 2011). Investigations were undertaken to determine if benzene is naturally occurring at this site or elevated due to Arrow's activities (Arrow Energy, 2010b, http://www.arrowenergy.com.au/icms_docs/87070_Arrow_Secondary_Results_Notification.pdf, accessed 11 August 2011).

In May 2010, Cougar Energy found traces (up to 45 µg/L) of toluene in a monitoring well at its pilot UCG plant near Kingaroy in Queensland. In June 2010, benzene was detected in a monitoring well at a level of 2 ppb. Cougar Energy received an Environmental Protection Order from the Queensland Government in July 2010 to cease operations of its pilot underground gasification plant (Sherrif et al., 2010). In July 2011, the Queensland government banned any further trials at the site.

Apart from the three reported instances of BTEX occurrence in groundwater associated with CSG and UCG operations in QLD, there is very little readily or publicly available information. In March 2005, Sydney Gas reported that BTEX concentrations were below the limit of reporting (LOR) (<1 µg/L for benzene; <2 µg/L for toluene, ethylbenzene, meta & para-Xylene, and ortho-Xylene) in their gas exploration well, Jilliby 1 at Wyong, which penetrated the Great Northern Seam of the Permian Newcastle Coal Measures (Parsons Brinckerhoff, 2005).

AGL (Parsons Brinkerhoff, 2010) reported BTEX concentrations were below the LOR in gas exploration well HB02 at Broke in the Hunter Valley. The gas well penetrated the Blakefield Seam of the Permian Wittingham Coal Measures.

In the second annual quality report in 2012 regarding the Talinga Water Treatment Facility, BTEX compounds were detected and their concentrations are shown in Table 9 (Australia Pacific LNG, 2012). The Talinga Water Treatment Facility near Chinchilla, Queensland, has been designed to treat water produced as part of the gas extraction process in the Talinga CSG field. Among its numerous uses, treated water is also discharged into the Condamine River. BTEX compound concentrations ranged from <2 to <1 µg/L.

In a quarterly produced water quality monitoring report from 2013, AGL measured BTEX concentrations as part of groundwater monitoring activities for the Camden Gas Project, NSW (AGL 2013). Data from two monitoring points at separate locations were presented and are shown in Table 10. BTEX concentrations were mostly reported to be between <0.001 and <0.005 µg/L. Only one sample recorded toluene at 0.005 µg/L.

Recently, Geoscience Australia (GA) and the Geological Survey of Queensland (GSQ), Queensland Department of Mines and Energy, worked collaboratively to characterise the regional hydrochemistry of the Denison Trough (Bowen Basin) and Surat Basin and trialled different groundwater monitoring strategies (Feitz et al. 2014). The output from this project constitutes part of a regional baseline reference set for future site-specific and semi-regional monitoring and verification programmes conducted by geological storage proponents. BTEX compounds were detected in this study and are shown in Table 11. While the majority of data exhibit compound concentrations below <1 or 0.5 µg/L, there are some cases where the concentrations are <2 µg/L for meta- and para-xylene. One sample from the Gubberamunda Sandstone exhibits relatively high concentrations of BTEX compounds from 7.7 µg/L for Toluene, 6.08 µg/L for meta- and para-xylene and 3.19 µg/L for ortho-xylene (Table 11).

In January 2015, AGL suspended its Waukivory CSG Pilot Project near Gloucester in northern NSW after traces of BTEX chemicals were found in water samples (http://www.abc.net.au/news/2015-01-28/csg-project-suspended/6050650). According to ABC News, the chemicals were detected in wells and in an aboveground water storage tank. In AGL's fact sheet on BTEX for the Gloucester Gas Project - March 2015 (http://www.agl.com.au/~/media/AGL/About%20AGL/Documents/How%20We%20Source%20Energy/Gloucester%20Document%20Repository/Fact%20Sheets/20150302__Fact%20Sheet%20GGP%20%20%20BTEX_V3.pdf), it is stated that BTEX chemicals were detected in five samples of which four were within the range of 12-70 µg/L and another one sample containing 555 µg/L (see also AGL ASX statement, 27 January 2015). AGL believes that these BTEX chemicals have naturally occurring sources.

4.2 Phenols

Phenols naturally occur in coal seams and will partition into produced water depending on their molecular weight. Phenols with side chains greater than five carbon atoms are mainly associated with oil droplets (OGP 2005).

Public health guidelines for some phenolic compounds are available for drinking water in the Australian Drinking Water Guidelines (ADWG; NHMRC 2004) and water quality criteria for ecosystem protection are available in the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC 2000) (Table 12). However, halogenated phenols do not naturally occur in coals (they are man-made chemicals), and nitrophenols, although natural compounds in many plants, are not commonly occurring in hard coals.

There is very little readily or publicly available information on the presence of phenols in groundwater associated with Australian coals. Sydney Gas reported total phenol concentrations of 0.115 mg/L in groundwater (1 sample from 1 well) associated with the Permian Wittingham Coal Measures in the Hunter Coalfield of the Sydney Basin (Parsons Brinckerhoff 2006).

Australian Pacific LNG (APLNG) provided a summary of water chemistry from 47 wells within the Talinga gas field in south central Queensland (Surat Basin) as part of their Condabri CSG Water Management Plan to

DERM (APLNG 2010). Average concentrations of phenol compounds were below detection limits, while ranges of detected concentrations were not reported (Table 13).

AGL (PB 2010) reported concentrations of phenolic compounds below the laboratory LOR in one of their gas exploration wells (6 samples from one well) in the Hunter Coalfield. The gas well penetrated the Blakefield Seam of the Permian Wittingham Coal Measures. The specific phenol compounds analysed are listed in Table 14 (noting that not all of these phenols will naturally occur in coals).

In the second annual quality report in 2012 regarding the Talinga Water Treatment Facility, phenol compounds were detected and their concentrations are shown in Table 9 (Australia Pacific LNG, 2012). Compound concentrations for these phenols ranged from <10 µg/L. Concentrations for bisphenol A and nonylphenol were reported as <1 µg/L.

In a quarterly produced water quality monitoring report from 2013, AGL measured Phenol concentrations as part of groundwater monitoring activities for the Camden Gas Project, NSW (AGL 2013). Data from two monitoring points at separate locations were presented and are shown in Table 10. Phenol concentrations were reported to be below the limit of reporting.

Stearman et al. (2014) recently investigated the presence of phenols from government-held water quality data of gas producing wells from the Bandanna Formation or the Walloon Coal Measures in the Bowen Basin and the eastern Surat Basin, respectively. The data were originally measured by the CSG industry and supplied to the Queensland government to satisfy regulatory requirements. No phenolic compounds were reported to be above detection limits in the wells.

However, while none of these compounds were above detection in well data, Stearman et al. (2014) did note the detection of phenol in a CSG water holding pond of the Walloon production area. The pond was sampled six times over a one month period in 2010 and phenol was detected once at 0.3 µg/L.

Tang et al. (2014) conducted an organic chemical assessment of private wells tapping into the Walloon Coal Measures. However, phenols were detected in very low concentrations in that study (Table 15). The control water bore in that study showed a phenol concentration of 0.5 µg/L. Tang et al. (2014) suggested that this occurrence may be a naturally occurring result or due to contamination. The authors also noted that most phenolic compounds analysed in that study had a high LOR.

Phenol compounds were also reported in the survey conducted by Geoscience Australia and the Geological Survey of Queensland to characterise the regional hydrochemistry of the Denison Trough (Bowen Basin) and Surat Basin (Feitz et al. 2014). Compounds and their concentrations are shown in Table 16 and are between <1 or <2 µg/L.

Table 9: Concentrations of hydrocarbon compounds from the Talinga water treatment facility. Concentrations are in µg/L. LOR=Limit of Reporting. Source: AP, LNG, 2012.

Parameters		Units	LOR	Discharge Tank			Feed Pond			Chinchilla Weir			Condamine Weir			Field Blank		
				24/05/2012	30/05/2012	4/06/2012	24/05/2012	30/05/2012	4/06/2012	24/05/2012	30/05/2012	4/06/2012	24/05/2012	29/05/2012	5/06/2012	24/05/2012	30/05/2012	5/06/2012
BTEX	Benzene	µg/L	1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
	Ethylbenzene	µg/L	1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
	Toluene	µg/L	1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
	Xylene (m & p)	µg/L	2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
	Xylene (o)	µg/L	2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
	Xylene Total	µg/L		<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4
PAH/Phenols	2,3,4,6-tetrachlorophenol	µg/L	10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
	2,4,5-trichlorophenol	µg/L	10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
	2,4,6-trichlorophenol	µg/L	10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
	2,4-dichlorophenol	µg/L	10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
	2,4-dimethylphenol	µg/L	10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
	2,4-dinitrophenol	µg/L	10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
	2,6-dichlorophenol	µg/L	10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
	2-Chlorophenol	µg/L	10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
	2-methylphenol	µg/L	10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
	2-nitrophenol	µg/L	10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
	4,6-Dinitro-2-methylphenol	µg/L	10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
	4-chloro-3-methylphenol	µg/L	10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
	4-methylphenol	µg/L	10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
	4-nitrophenol	µg/L	10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
	Acenaphthene	µg/L	1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
	Acenaphthylene	µg/L	1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
	Anthracene	µg/L	1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
	Benz(a)anthracene	µg/L	1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
	Benzo(a) pyrene	µg/L	1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
	Benzo(b)fluoranthene	µg/L	1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
	Benzo(g,h,i)perylene	µg/L	1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
	Benzo(k)fluoranthene	µg/L	1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
	Chrysene	µg/L	1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
	Dibenz(a,h)anthracene	µg/L	1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
	Fluoranthene	µg/L	1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
	Fluorene	µg/L	1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
	Indeno(1,2,3-c,d)pyrene	µg/L	1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
	Naphthalene	µg/L	1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
	Pentachlorophenol	µg/L	10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
	Phenanthrene	µg/L	1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
	Phenol	µg/L	0.1	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
	Pyrene	µg/L	1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
TPH	C6 - C9	µg/L	10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
	C10-C16	µg/L	50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50
	C16-C34	µg/L	100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100
	C34-C40	µg/L	100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100
Organics	Bisphenol A	µg/L	1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
	Nonylphenol	µg/L	1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
	N-Nitrosodimethylamine	µg/L	0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
	Total Organic Halogen	µg/L	1	14	12	8	74	79	81	66	44	44	70	40	44	2	16	5

Table 10: Concentrations of BTEX, PAH, phenol and TPH compounds measured as part of groundwater monitoring activities for the Camden Gas Project, NSW. Concentrations are in µg/L. LOR = Limit of Reporting. Source: AGL 2013.

	Analyte	Units	LOR	Monitoring point/Location: 10/RB10	Monitoring point/Location: 13/MP30
BTEX	Benzene	mg/L	0.001	<0.001	<0.005
	Ethylbenzene	mg/L	0.002	<0.002	<0.005
	Toluene	mg/L	0.002	<0.002	0.005
	Xylene (m & p)	mg/L	0.002	<0.002	<0.005
	Xylene (o)	mg/L	0.002	<0.002	<0.005
PAH/Phenols	Acenaphthene	mg/L	0.001	<0.001	<0.001
	Acenapthylene	mg/L	0.001	<0.001	<0.001
	Anthracene	mg/L	0.001	<0.001	<0.001
	Benz(a)anthracene	mg/L	0.001	<0.001	<0.001
	Benzo(a) pyrene	mg/L	0.0005	<0.0005	<0.0005
	Benzo(b)fluoranthene	mg/L	0.001	<0.001	<0.001
	Benzo(g,h,i)perylene	mg/L	0.001	<0.001	<0.001
	Benzo(k)fluoranthene	mg/L	0.001	<0.001	<0.001
	Chrysene	mg/L	0.001	<0.001	<0.001
	Dibenz(a,h)anthracene	mg/L	0.001	<0.001	<0.001
	Fluoranthene	mg/L	0.001	<0.001	<0.001
	Fluorene	mg/L	0.001	<0.001	<0.001
	Indeno(1,2,3-c,d)pyrene	mg/L	0.001	<0.001	<0.001
	Naphthalene	mg/L	0.001	<0.001	<0.001
	Phenanthrene	mg/L	0.001	<0.001	<0.001
	Phenol	mg/L	0.001	<0.001	<0.001
	Pyrene	mg/L	0.001	<0.001	<0.001
	2,4,5-trichlorophenol	mg/L	0.001	<0.001	<0.001
	2,4,6-trichlorophenol	mg/L	0.001	<0.001	<0.001
	2,4-dichlorophenol	mg/L	0.001	<0.001	<0.001
	2,6-dichlorophenol	mg/L	0.001	<0.001	<0.001
	2-chlorophenol	mg/L	0.001	<0.001	<0.001
	Pentachlorophenol	mg/L	0.002	<0.002	<0.002
TPH	C6 - C9	mg/L	0.02	<0.02	<0.1
	C10 - C14	mg/L	0.05	<0.05	1.97
	C15 - C28	mg/L	0.1	1.02	7.78
	C29-C36	mg/L	0.05	0.5	0.28

Table 11: Concentrations of BTEX compounds in waters from the Bowen and Surat basins. Concentrations are in µg/L. Source: Feitz et al. 2014.

Latitude	Longitutde	Total depth (m)	Stratigraphy	Benzene	Toluene	Ethylbenzene	meta- & para-Xylene	ortho-Xylene
-27.99278	150.00948	1290	Gubberamunda Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-28.43664	150.30852	679.7	Gubberamunda Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-28.16288	150.25992	822.9	Gubberamunda Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-27.71839	150.36981	767.6	Gubberamunda Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-27.71839	150.36981	767.6	Gubberamunda Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-28.00104	150.16122	1266	Gubberamunda Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-27.84651	149.49654	1386	Gubberamunda Sandstone	1.67	7.7	1.42	6.08	3.19
-27.87448	149.49352	2591	Gubberamunda Sandstone	0.19	0.5	0.61	2.6	1.43
-27.63362	149.60791	1355	Gubberamunda Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-27.3235	149.88503	1122	Gubberamunda Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-27.31893	149.76184	1210	Gubberamunda Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-27.66323	150.55312	737.6	Gubberamunda Sandstone	<0.05	1.8	<0.05	<0.05	<0.05
-27.42737	150.39252	738	Gubberamunda Sandstone	<0.05	1.1	<0.05	<0.05	<0.05
-28.03758	150.01965	1006.5	Mooga Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-28.3978	150.16003	682.14	Mooga Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-27.87649	150.25952	771.8	Mooga Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-27.84495	150.28867	716.7	Mooga Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-27.84495	150.28867	716.7	Mooga Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-27.41539	150.26814	743.2	Mooga Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-27.88952	150.28571	802.1	Mooga Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-27.72224	150.35107	522.73	Mooga Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-27.73603	150.3096	645.5	Mooga Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-27.77055	150.29915	642.5	Mooga Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-27.62183	150.32379	436.47	Mooga Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-28.10855	150.48013	272.5	Mooga Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-28.09348	150.48383	266.7	Mooga Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-27.739561	150.166630	732	Mooga Sandstone	<1	<1	<1	<2	<1
-27.763202	150.067891	811	Mooga Sandstone	<1	<1	<1	<2	<1
-27.920319	149.714753	984	Mooga Sandstone	<1	<1	<1	<2	<1
-28.147975	149.675988	1323.1	Mooga Sandstone	<1	<1	<1	<2	<1
-27.61462	150.08210	780.29	Mooga Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-27.62515	150.15533	701	Mooga Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-27.57047	149.85201	1047	Mooga Sandstone	<0.05	0.5	<0.05	<0.05	<0.05
-27.42803	150.20969	609.6	Mooga Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-27.30085	150.25905	410.8	Mooga Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-27.5305	150.20219	728	Mooga Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-27.5305	150.20219	728	Mooga Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-27.32934	150.16608	548.6	Mooga Sandstone	<0.05	1.1	<0.05	<0.05	<0.05
-26.996708	150.849592	727.6	Hutton Sandstone	<1	<1	<1	<2	<1
-26.996708	150.849592	727.6	Hutton Sandstone	<1	<1	<1	<2	<1
-26.565730	150.729527	172	Hutton Sandstone	<1	<1	<1	<2	<1
-26.531090	150.733952	155	Hutton Sandstone	<1	<1	<1	<2	<1
-26.595224	150.722260	40	Hutton Sandstone	<1	<1	<1	<2	<1
-27.199443	150.590278	246	Hutton Sandstone	<1	<1	<1	<2	<1
-26.549722	150.763891	240	Hutton Sandstone	<1	<1	<1	<2	<1
-28.490132	150.417824	756	Hutton Sandstone	<1	<1	<1	<2	<1
-28.528836	150.314654	1031.6	Hutton Sandstone	<1	<1	<1	<2	<1
-27.674954	150.872004	914	Hutton Sandstone	<1	<1	<1	<2	<1
-26.06422	149.02917	220	Hutton Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-26.08525	148.9696	136	Hutton Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-26.00205	149.44104	427	Hutton Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-25.99607	149.30992	204	Hutton Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-25.98061	149.34673	221	Hutton Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-25.85374	149.34074	305	Hutton Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-26.29982	150.18268	422	Hutton Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-26.15858	149.0974	329	Hutton Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-25.93223	149.40669	296	Hutton Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-25.63296	149.76134	240	Hutton Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-25.51113	149.72897	274	Hutton Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-25.39592	149.76805	24.4	Hutton Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-25.54716	149.38191	285	Hutton Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-25.67007	149.58881	464	Hutton Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-25.83217	149.79073	499	Hutton Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-28.30648	150.28629	1247	Hutton Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-28.13936	150.37395	273.4	Kumbarilla Beds	<0.05	<0.5	<0.05	<0.05	<0.05
-27.730710	150.926427	88.4	Kumbarilla Beds	<1	<1	<1	<2	<1
-26.05461	150.09824	945	Precipice Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-25.55885	149.43571	381	Precipice Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-26.12259	149.95959	1149	Precipice Sandstone	<0.05	<0.5	<0.05	<0.05	<0.05
-26.04273	149.31187	360	Injune Creek Group	<0.05	<0.5	<0.05	<0.05	<0.05
-26.12733	149.27512	547	Injune Creek Group	<0.05	<0.5	<0.05	<0.05	<0.05
-26.0595324	149.973883	580	Walloon Coal Measures	<0.05	<0.5	<0.05	<0.05	<0.05
-26.12446	149.14238	464	Walloon Coal Measures	<0.05	<0.5	<0.05	<0.05	<0.05
-26.13112	149.20021	380	Eurombah Formation	<0.05	<0.5	<0.05	<0.05	<0.05
-27.733860	150.106108	821.4	Bungil Formation	<1	<1	<1	<2	<1

Table 12: Water quality guidelines for phenolic compounds. Concentrations are in µg/L.

Compound	ADWG[1]	ANZECC (99% protection)[2]
Phenol		85
2,4-dimethylphenol		ID†
Nonylphenol		ID
2-chlorophenol*	0.3 (health), 0.0001 (aesthetic)	340
3-chlorophenol*		ID
4-chlorophenol*		160
2,3-dichlorophenol*		ID
2,4-dichlorophenol*	0.2 (health), 0.0003 (aesthetic)	120
2,5-dichlorophenol*		ID
2,6-dichlorophenol*		ID
3,5-dichlorophenol*		ID
2,3,4-trichlorophenol*		ID
2,3,5-trichlorophenol*		ID
2,3,6-trichlorophenol*		ID
2,4,5-trichlorophenol*		ID
2,4,6-trichlorophenol*	0.02 (health), 0.002 (aesthetic)	3
2,3,4,5-tetrachlorophenol*		ID
2,3,4,6-tetrachlorophenol*		10
2,3,5,6-tetrachlorophenol*		ID
2-nitrophenol		ID
3-nitrophenol		ID
4-nitro-phenol		13
2,4,6-trinitrophenol		ID

[1]Australian Drinking Water Guidelines (NHMRC, 2004); 2Australian and New Zealand Environment Conservation Council Environmental Protection Guidelines (ANZECC, 2000); † ID insufficient data. * denotes anthropogenic, halogenated compounds.

Table 13: Average concentrations of phenol compounds in wells from the Talinga Gas Field, Surat Basin. Source: APLNG 2010.

Compound	Average concentration (µg/L)
2,4,5-Trichlorophenol*	<0.3
2,4,6-Trichlorophenol*	<0.3
2-Chlorohphenol*	<0.3
4-Methyphenol	<0.3
4-Nitrophenol*	<0.26

* denotes compounds that are either not derived or unlikely to be derived from coals.

Table 14: Concentrations of phenolic compounds in waters associated with the Permian Wittingham Coal Measures (PB 2010).

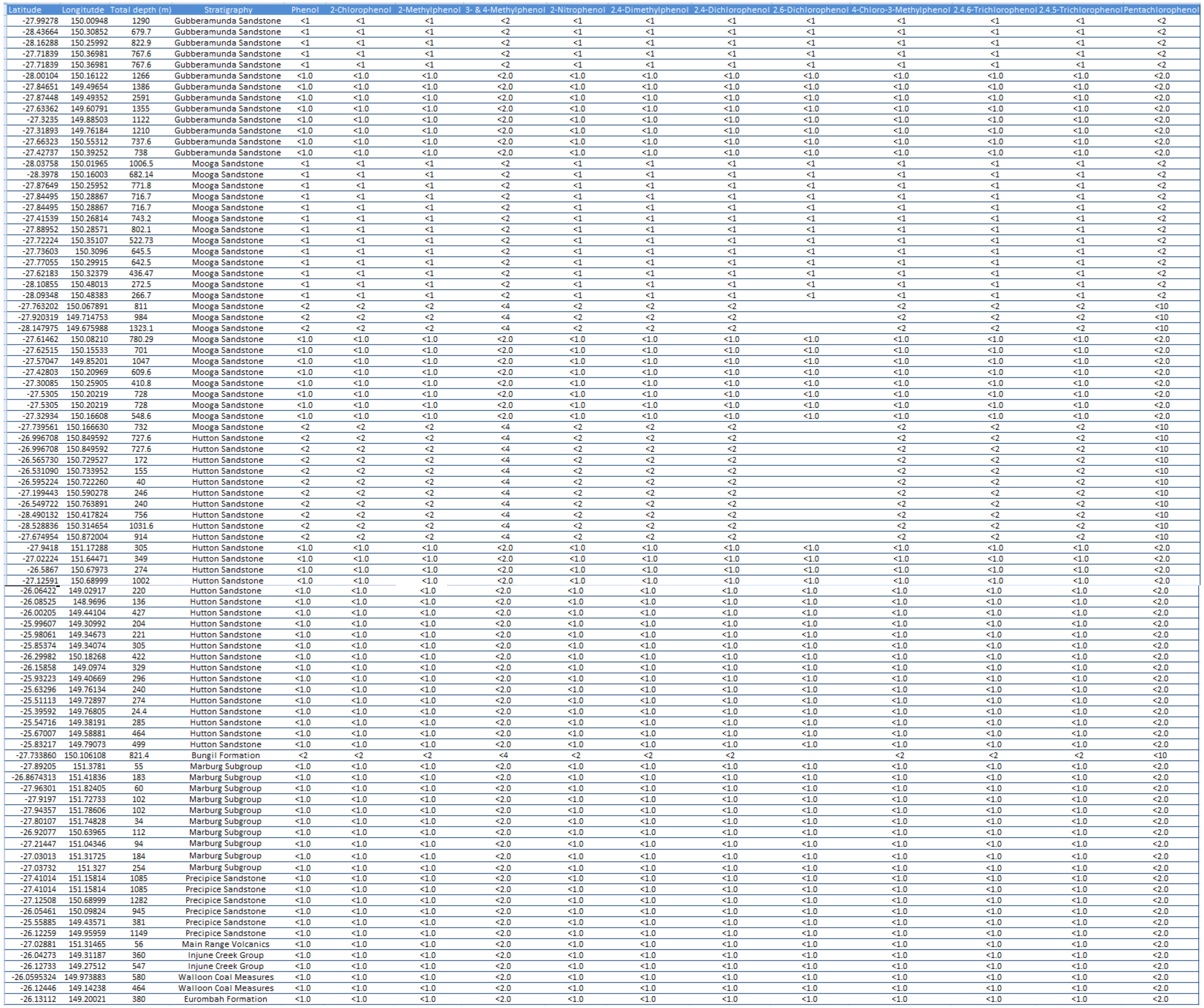
Compound	Concentration
Phenol	<1.0
2-Chlorophenol*	<1.0
2-Methylphenol	<1.0
3-&4-Methylphenol	<2.0
2-Nitrophenol*	<1.0
2.4-Dimethylphenol	<1.0
2.4-Dichlorophenol*	<1.0
2.6-Dichlorophenol*	<1.0
4-Chloro-3-Methylphenol*	<1.0
2.4.6-Trichlorophenol	<1.0
2.4.6-Trichlorophenol*	<1.0
Pentachlorophenol*	<2.0

*denotes phenols that are not, or unlikely to be derived from coals.

Table 15: Phenolic compounds in coal seam gas associated water, Surat Basin, Queensland. LOR = limit of reporting; PH Reg Std = Public Health Regulation standard; RN = Well registration number; WB = non-coal seam gas water bore; FB = field blank; TB = transport blank. All concentration units are in micrograms per litre. Source: Tang et al. (2014)

Phenol compounds	LOR	PH Reg Std	Sample identity and sampling date								
			RN 15811 20 March 2012	RN 15811 14 November 2013	RN 107761 20 March 2012	RN 107761 14 November 2013	RN 107739 20 March 2012	RN 24467 14 November 2013	WB 14 November 2013	FB 14 November 2013	TB 14 November 2013
Phenol	0.25	150	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.5	<0.25	<0.25
2-Chlorophenol	1	300	<1	<1	<1	<1	<1	<1	<1	<1	<1
4-Chlorophenol	0.3	10	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
2-Methylphenol	1		<1	<1	<1	<1	<1	<1	<1	<1	<1
4-Methylphenol	0.01	600	<1	<1	<1	<1	<1	<1	<1	<1	<1
2-Nitrophenol	1		<1	<1	<1	<1	<1	<1	<1	<1	<1
2,4-Dimethylphenol	1		<1	<1	<1	<1	<1	<1	<1	<1	<1
2,4-Dichlorophenol	1	200	<1	<1	<1	<1	<1	<1	<1	<1	<1
4-Chloro-3-methylphenol	1	10	<1	<1	<1	<1	<1	<1	<1	<1	<1
2,4,6-Trichlorophenol	1		<1	<1	<1	<1	<1	<1	<1	<1	<1
2,4,5-Trichlorophenol	1	20	<1	<1	<1	<1	<1	<1	<1	<1	<1
2,4-Dinitrophenol	1	350	<1	<1	<1	<1	<1	<1	<1	<1	<1
4-Nitrophenol	1		<1	<1	<1	<1	<1	<1	<1	<1	<1
2,3,4,6-Tetrachlorophenol	1	30	<1	<1	<1	<1	<1	<1	<1	<1	<1
2-Methyl-4,6-dinitrophenol	1		<1	<1	<1	<1	<1	<1	<1	<1	<1
Pentachlorophenol	1	10	<1	<1	<1	<1	<1	<1	<1	<1	<1
Coumarin	0.3	0.5	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3

Table 16: Concentrations of phenol compounds in waters from the Bowen and Surat basins. Concentrations are in µg/L. Source: Feitz et al. 2014.



Latitude	Longitutde	Total depth (m)	Stratigraphy	Phenol	2-Chlorophenol	2-Methylphenol	3- & 4-Methylphenol	2-Nitrophenol	2.4-Dimethylphenol	2.4-Dichlorophenol	2.6-Dichlorophenol	4-Chloro-3-Methylphenol	2.4.6-Trichlorophenol	2.4.5-Trichlorophenol	Pentachlorophenol
-27.99278	150.00948	1290	Gubberamunda Sandstone	<1	<1	<1	<2	<1	<1	<1	<1	<1	<1	<1	<2
-28.43664	150.30852	679.7	Gubberamunda Sandstone	<1	<1	<1	<2	<1	<1	<1	<1	<1	<1	<1	<2
-28.16288	150.25992	822.9	Gubberamunda Sandstone	<1	<1	<1	<2	<1	<1	<1	<1	<1	<1	<1	<2
-27.71839	150.36981	767.6	Gubberamunda Sandstone	<1	<1	<1	<2	<1	<1	<1	<1	<1	<1	<1	<2
-27.71839	150.36981	767.6	Gubberamunda Sandstone	<1	<1	<1	<2	<1	<1	<1	<1	<1	<1	<1	<2
-28.00104	150.16122	1266	Gubberamunda Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.84651	149.49654	1386	Gubberamunda Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.87448	149.49352	2591	Gubberamunda Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.63362	149.60791	1355	Gubberamunda Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.3235	149.88503	1122	Gubberamunda Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.31893	149.76184	1210	Gubberamunda Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.66323	150.55312	737.6	Gubberamunda Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.42737	150.39252	738	Gubberamunda Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-28.03758	150.01965	1006.5	Mooga Sandstone	<1	<1	<1	<2	<1	<1	<1	<1	<1	<1	<1	<2
-28.3978	150.16003	682.14	Mooga Sandstone	<1	<1	<1	<2	<1	<1	<1	<1	<1	<1	<1	<2
-27.87649	150.25952	771.8	Mooga Sandstone	<1	<1	<1	<2	<1	<1	<1	<1	<1	<1	<1	<2
-27.84495	150.28867	716.7	Mooga Sandstone	<1	<1	<1	<2	<1	<1	<1	<1	<1	<1	<1	<2
-27.84495	150.28867	716.7	Mooga Sandstone	<1	<1	<1	<2	<1	<1	<1	<1	<1	<1	<1	<2
-27.41539	150.26814	743.2	Mooga Sandstone	<1	<1	<1	<2	<1	<1	<1	<1	<1	<1	<1	<2
-27.88952	150.28571	802.1	Mooga Sandstone	<1	<1	<1	<2	<1	<1	<1	<1	<1	<1	<1	<2
-27.72224	150.35107	522.73	Mooga Sandstone	<1	<1	<1	<2	<1	<1	<1	<1	<1	<1	<1	<2
-27.73603	150.3096	645.5	Mooga Sandstone	<1	<1	<1	<2	<1	<1	<1	<1	<1	<1	<1	<2
-27.77055	150.29915	642.5	Mooga Sandstone	<1	<1	<1	<2	<1	<1	<1	<1	<1	<1	<1	<2
-27.62183	150.32379	436.47	Mooga Sandstone	<1	<1	<1	<2	<1	<1	<1	<1	<1	<1	<1	<2
-28.10855	150.48013	272.5	Mooga Sandstone	<1	<1	<1	<2	<1	<1	<1	<1	<1	<1	<1	<2
-28.09348	150.48383	266.7	Mooga Sandstone	<1	<1	<1	<2	<1	<1	<1	<1	<1	<1	<1	<2
-27.763202	150.067891	811	Mooga Sandstone	<2	<2	<2	<4	<2	<2	<2		<2	<2	<2	<10
-27.920319	149.714753	984	Mooga Sandstone	<2	<2	<2	<4	<2	<2	<2		<2	<2	<2	<10
-28.147975	149.675988	1323.1	Mooga Sandstone	<2	<2	<2	<4	<2	<2	<2		<2	<2	<2	<10
-27.61462	150.08210	780.29	Mooga Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.62515	150.15533	701	Mooga Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.57047	149.85201	1047	Mooga Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.42803	150.20969	609.6	Mooga Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.30085	150.25905	410.8	Mooga Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.5305	150.20219	728	Mooga Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.5305	150.20219	728	Mooga Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.32934	150.16608	548.6	Mooga Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.739561	150.166630	732	Mooga Sandstone	<2	<2	<2	<4	<2	<2	<2		<2	<2	<2	<10
-26.996708	150.849592	727.6	Hutton Sandstone	<2	<2	<2	<4	<2	<2	<2		<2	<2	<2	<10
-26.996708	150.849592	727.6	Hutton Sandstone	<2	<2	<2	<4	<2	<2	<2		<2	<2	<2	<10
-26.565730	150.729527	172	Hutton Sandstone	<2	<2	<2	<4	<2	<2	<2		<2	<2	<2	<10
-26.531090	150.733952	155	Hutton Sandstone	<2	<2	<2	<4	<2	<2	<2		<2	<2	<2	<10
-26.595224	150.722260	40	Hutton Sandstone	<2	<2	<2	<4	<2	<2	<2		<2	<2	<2	<10
-27.199443	150.590278	246	Hutton Sandstone	<2	<2	<2	<4	<2	<2	<2		<2	<2	<2	<10
-26.549722	150.763891	240	Hutton Sandstone	<2	<2	<2	<4	<2	<2	<2		<2	<2	<2	<10
-28.490132	150.417824	756	Hutton Sandstone	<2	<2	<2	<4	<2	<2	<2		<2	<2	<2	<10
-28.528836	150.314654	1031.6	Hutton Sandstone	<2	<2	<2	<4	<2	<2	<2		<2	<2	<2	<10
-27.674954	150.872004	914	Hutton Sandstone	<2	<2	<2	<4	<2	<2	<2		<2	<2	<2	<10
-27.9418	151.17288	305	Hutton Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.02224	151.64471	349	Hutton Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-26.5867	150.67973	274	Hutton Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.12591	150.68999	1002	Hutton Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-26.06422	149.02917	220	Hutton Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-26.08525	148.9696	136	Hutton Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-26.00205	149.44104	427	Hutton Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-25.99607	149.30992	204	Hutton Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-25.98061	149.34673	221	Hutton Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-25.85374	149.34074	305	Hutton Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-26.29982	150.18268	422	Hutton Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-26.15858	149.0974	329	Hutton Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-25.93223	149.40669	296	Hutton Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-25.63296	149.76134	240	Hutton Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-25.51113	149.72897	274	Hutton Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-25.39592	149.76805	24.4	Hutton Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-25.54716	149.38191	285	Hutton Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-25.67007	149.58881	464	Hutton Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-25.83217	149.79073	499	Hutton Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.733860	150.106108	821.4	Bungil Formation	<2	<2	<2	<4	<2	<2	<2		<2	<2	<2	<10
-27.89205	151.3781	55	Marburg Subgroup	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-26.8674313	151.41836	183	Marburg Subgroup	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.96301	151.82405	60	Marburg Subgroup	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.9197	151.72733	102	Marburg Subgroup	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.94357	151.78606	102	Marburg Subgroup	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.80107	151.74828	34	Marburg Subgroup	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-26.92077	150.63965	112	Marburg Subgroup	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.21447	151.04346	94	Marburg Subgroup	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.03013	151.31725	184	Marburg Subgroup	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.03732	151.327	254	Marburg Subgroup	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.41014	151.15814	1085	Precipice Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.41014	151.15814	1085	Precipice Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.12508	150.68999	1282	Precipice Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-26.05461	150.09824	945	Precipice Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-25.55885	149.43571	381	Precipice Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-26.12259	149.95959	1149	Precipice Sandstone	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-27.02881	151.31465	56	Main Range Volcanics	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-26.04273	149.31187	360	Injune Creek Group	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-26.12733	149.27512	547	Injune Creek Group	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-26.0595324	149.973883	580	Walloon Coal Measures	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-26.12446	149.14238	464	Walloon Coal Measures	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
-26.13112	149.20021	380	Eurombah Formation	<1.0	<1.0	<1.0	<2.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0

4.3 Polycyclic aromatic hydrocarbons

Polycyclic aromatic hydrocarbons (PAHs) are produced in coal as lignin-rich organic matter that undergoes defunctionalisation and condensation during the normal coalification processes (Orem *et al.*, 1999). Their presence in groundwater is a result of leaching of coals (Orem *et al.*, 1999). Some PAHs are considered carcinogens. In Australia, drinking water guideline values have only been established for benzo-(a)-pyrene (0.01 µg/L) (NHMRC, 2004). Water quality criteria for naphthalene have been established for aquatic ecosystems in the ANZECC (2000) guidelines (16 µg/L; 99% trigger value) (ANZECC, 2000).

Australian Pacific LNG (APLNG) provided a summary of water chemistry from 47 wells within the Talinga gas field in south central QLD (Surat Basin) as part of their Condabri CSG Water Management Plan to DERM (APLNG, 2010). Average concentrations of PAH compounds were below detection limits, although ranges of detected concentrations, if any, were not reported (Table 17).

Table 17: Average concentrations of PAH compounds in wells from the Talinga Gas Field, Surat Basin. Source: APLNG 2010.

Compound	Average concentration (µg/L)
Acenaphthene	<0.01
Acenaphthylene	<0.01
Anthracene	<0.01
Benzo(a)pyrene	<0.01
Phenanthrene	<0.01
Pyrene	<0.01

In the second annual quality report in 2012 regarding the Talinga Water Treatment Facility, PAH compounds were detected and their concentrations are shown in Table 9 (Australia Pacific LNG, 2012). Compound concentrations for these PAHs were reported as <1 µg/L.

In a quarterly produced water quality monitoring report from 2013, AGL measured PAH concentrations as part of groundwater monitoring activities for the Camden Gas Project, NSW (AGL 2013). Data from two monitoring points at separate locations were presented and are shown in Table 10. PAH concentrations were reported to be below the limit of reporting.

Stearman et al. (2014) recently reported the detection of PAHs in 27% of the collected CSG water samples from the Walloon Coal Measures (eastern Surat Basin) at concentrations <1 µg/L (Table 18). The detection limit for these samples was ~0.01 µg/L. The authors suggested that these compounds leached from *in situ* coals. The PAHs include naphthalene, phenanthrene, chrysene and dibenz[a,h]anthracene. Naphthalene and phenanthrene (with a maximum concentration of 0.046 µg/L and 0.02 µg/L, respectively) were the most commonly detected PAHs and were observed in seven well samples. After naphthalene, the PAH with the second highest concentration was benzo[b+k]fluoranthene at 0.033 µg/L. Out of 47 well samples only five were observed to produce CSG water with more than one individual PAH. The maximum PAH concentration reported from any single well was 0.083 µg/L. CSG waters from production wells targeting the Bandanna Formation (Bowen Basin), by contrast, did not yield PAH compounds above the detection limit. The minimum detection limit for PAHs in the Bandanna Formation analyses was 1 µg/L whilst for benzo[a]pyrene it was 0.5 µg/L.

Table 18: Concentrations of PAHs from Walloon Coal Measure CSG production well waters. Only detected PAHs are shown. BDL = below detection limit. Source: Stearman et al. 2014.

PAHs	Detection Limit (µg/L)	Range (µg/L)	% of Wells with Detections
Naphthalene	0.01	BDL-0.046	23
Phenanthrene	0.01	BDL-0.046	20
Pyrene	0.01	BDL-0.01	2
Chrysene	0.01	BDL-0.016	2
Benzo[b+k]fluoranthene	0.01	BDL-0.033	9
Dibenz[a,h]anthracene	0.01	BDL-0.014	9

Tang et al. (2014) detected low concentrations of PAHs in CSG water from private wells tapping into the Walloon Coal Measures, Surat Basin (Table 19). A total of 16 PAHs were analysed, with naphthalene and phenanthrene being generally the most commonly detected compound. The authors noted that whenever naphthalene and phenanthrene were detected, it was likely that other PAHs of higher molecular weight were also detected. They also observed that whenever naphthalene and phenanthrene were not detected, higher molecular weight PAHs were also not detected. This observation was attributed to the fact that solubility of lower molecular weight PAHs is higher than that of their heavier counterparts.

Sydney Gas reported PAH concentrations below laboratory LORs for their gas wells penetrating the Permian Wittingham Coal Measures (Parsons Brinkerhoff 2006). The specific PAHs analysed are listed in Table 20.

PAH compounds were also reported in the survey conducted by Geoscience Australia and the Geological Survey of Queensland to characterise the regional hydrochemistry of the Denison Trough (Bowen Basin) and Surat Basin (Feitz et al. 2014). Compounds and their concentrations are shown in Table 21 and are predominantly <1 µg/L.

Table 19: PAH compounds in coal seam gas associated water, Surat Basin, Queensland. LOR = limit of reporting; PH Reg Std = Public Health Regulation standard; RN = Well registration number; WB = non-coal seam gas water bore; FB = field blank; TB = transport blank; n.a. = not analysed. All concentration units are in µg/L. Source: Tang et al. (2014).

PAHs	LOR	PH Reg Std	Sample identity and sampling date								
			RN 15811 20 March 2012	RN 15811 14 November 2013	RN 107761 20 March 2012	RN 107761 14 November 2013	RN 107739 20 March 2012	RN 24467 14 November 2013	WB 14 November 2013	FB 14 November 2013	TB 14 November 2013
Benzo[ghi]perylene	0.01		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Dibenz[a,h]anthracene	0.01		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Indeno[1,2,3-cd]Pyrene	0.01		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Benzo[a]pyrene	0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Benzo[b+k]fluoranthene	0.01		0.01	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Chrysene	0.01		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Benz[a]anthracene	0.01		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Pyrene	0.01	150	0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Fluoranthene	0.01		<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Anthracene	0.01	150	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Phenanthrene	0.01	150	0.01	0.02	<0.01	<0.01	<0.01	<0.01	0.02	<0.01	<0.01
Fluorene	0.01		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Acenaphthene	0.01		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Acenaphthylene	0.01	0.014	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Napththalene	0.02	70	<0.01	0.04	<0.01	<0.02	<0.01	<0.02	0.09	<0.02	<0.01
1,2-Dimethylnapththalene	0.01		n.a.	<0.01	n.a.	<0.01	n.a.	<0.01	<0.01	<0.01	<0.01
1,4-Dimethylnapththalene	0.01		n.a.	0.06	n.a.	<0.01	n.a.	<0.01	<0.01	<0.01	<0.01
1,7-Dimethylnapththalene	0.01		n.a.	0.05	n.a.	<0.01	n.a.	<0.01	<0.01	<0.01	<0.01
1,8-Dimethylnapththalene	0.01		n.a.	<0.01	n.a.	<0.01	n.a.	<0.01	<0.01	<0.01	<0.01
1-Methylfluorene	0.01		n.a.	<0.01	n.a.	<0.01	n.a.	<0.01	<0.01	<0.01	<0.01
2,2-Dimethylbiphenyl	0.01		n.a.	0.01	n.a.	<0.01	n.a.	<0.01	<0.01	<0.01	<0.01
2,6-Dimethylnaphthalene	0.01		n.a.	0.01	n.a.	<0.01	n.a.	<0.01	<0.01	<0.01	<0.01
2-Ethylnapthalene	0.01		n.a.	<0.01	n.a.	<0.01	n.a.	<0.01	<0.01	<0.01	<0.01
2-Methylanthracene	0.01		n.a.	0.03	n.a.	<0.01	n.a.	<0.01	<0.01	<0.01	<0.01
3,3-Dimethylbiphenyl	0.01		n.a.	<0.01	n.a.	<0.01	n.a.	<0.01	<0.01	<0.01	<0.01
4,4-Dimethylbiphenyl	0.01		n.a.	<0.01	n.a.	<0.01	n.a.	<0.01	<0.01	<0.01	<0.01
9-Methylanthracene	0.01		n.a.	<0.01	n.a.	<0.01	n.a.	<0.01	<0.01	<0.01	<0.01
Biphenyl	0.01		n.a.	0.01	n.a.	<0.01	n.a.	<0.01	<0.01	<0.01	<0.01

Table 20: Concentrations (µg/L) of PAHs in waters associated with the Permian Wittingham Coal Measures. Source: Parsons Brinkerhoff (2006).

Compound	Blakefield Seam	Warkworth/Piercefield/Mt Arthur Seams
Naphthalene	<1.0	<1.0
Acenaphthylene	<1.0	<1.0
Acenaphthene	<1.0	<1.0
Fluorene	<1.0	<1.0
Phenanthrene	<1.0	<1.0
Anthracene	<1.0	<1.0
Fluoranthene	<1.0	<1.0
Pyrene	<1.0	<1.0
Benz(a)anthracene	<1.0	<1.0
Chrysene	<1.0	<1.0
Benzo(b)fluoranthene	<1.0	<1.0
Benzo(k)fluoranthene	<1.0	<1.0
Benzo(a)pyrene	<0.5	<0.5
Indeno(1,2,3,cd)pyrene	<1.0	<1.0
Dibenz(a,h)anthracene	<1.0	<1.0
Benzo(g,h)perylene	<1.0	<1.0

4.4 Total petroleum hydrocarbons

Total petroleum hydrocarbon (TPH) is defined as the measurable amount of petroleum-based hydrocarbons in an environmental medium. There are over several hundred chemical compounds that are defined as petroleum-based. Because there are so many different chemicals in crude oil and in other petroleum products, it is not practical to measure each one separately. However, it is useful to measure the

Table 21: Concentrations of PAH compounds in waters from the Bowen and Surat basins. Concentrations are in µg/L. Source: Feitz et al. 2014.

Latitude	Longitutde	Total depth (m)	Stratigraphy	Napthalene	Acenaphtylene	Acenaphthene	Fluorene	Phenanthrene	Anthracene	Fluoranthene	Pyrene	Benz(a)anthracene	Chrysene	Benzo(b)fluoranthene	Benzo(k)fluoranthene	Benzo(a)pyrene	Indeno(1.2.3.cd)pyrene	Dibenzo(a.h)anthracene	Benzo(g.h.i)perylene
-27.99278	150.00948	1290	Gubberamunda Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<0.5	<1	<1	<1
-28.43664	150.30852	679.7	Gubberamunda Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<0.5	<1	<1	<1
-28.16288	150.25992	822.9	Gubberamunda Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<0.5	<1	<1	<1
-27.71839	150.36981	767.6	Gubberamunda Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<0.5	<1	<1	<1
-28.00104	150.16122	1266	Gubberamunda Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.84651	149.49654	1386	Gubberamunda Sandstone	1.4	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.87448	149.49352	2591	Gubberamunda Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.63362	149.60791	1355	Gubberamunda Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.3235	149.88503	1122	Gubberamunda Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.31893	149.76184	1210	Gubberamunda Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.66323	150.55312	737.6	Gubberamunda Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.42737	150.39252	738	Gubberamunda Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-28.03758	150.01965	1006.5	Mooga Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<0.5	<1	<1	<1
-28.3978	150.16003	682.14	Mooga Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<0.5	<1	<1	<1
-27.87649	150.25952	771.8	Mooga Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<0.5	<1	<1	<1
-27.84495	150.28867	716.7	Mooga Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<0.5	<1	<1	<1
-27.84495	150.28867	716.7	Mooga Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<0.5	<1	<1	<1
-27.41539	150.26814	743.2	Mooga Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<0.5	<1	<1	<1
-27.88952	150.28571	802.1	Mooga Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<0.5	<1	<1	<1
-27.72224	150.35107	522.73	Mooga Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<0.5	<1	<1	<1
-27.73603	150.3096	645.5	Mooga Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<0.5	<1	<1	<1
-27.77055	150.29915	642.5	Mooga Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<0.5	<1	<1	<1
-27.62183	150.32379	436.47	Mooga Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<0.5	<1	<1	<1
-28.10855	150.48013	272.5	Mooga Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<0.5	<1	<1	<1
-28.09348	150.48383	266.7	Mooga Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<0.5	<1	<1	<1
-27.739561	150.166630	732	Mooga Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<2	<2	<1	<1	<1	<1
-27.763202	150.067891	811	Mooga Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<2	<2	<1	<1	<1	<1
-27.920319	149.714753	984	Mooga Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<2	<2	<1	<1	<1	<1
-28.147975	149.675988	1323.1	Mooga Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<2	<2	<1	<1	<1	<1
-27.61462	150.08210	780.29	Mooga Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.62515	150.15533	701	Mooga Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.57047	149.85201	1047	Mooga Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.42803	150.20969	609.6	Mooga Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.30085	150.25905	410.8	Mooga Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.5305	150.20219	728	Mooga Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.5305	150.20219	728	Mooga Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.32934	150.16608	548.6	Mooga Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-26.996708	150.849592	727.6	Hutton Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<2	<2	<1	<1	<1	<1
-26.996708	150.849592	727.6	Hutton Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<2	<2	<1	<1	<1	<1
-26.565730	150.729527	172	Hutton Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<2	<2	<1	<1	<1	<1
-26.531090	150.733952	155	Hutton Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<2	<2	<1	<1	<1	<1
-26.595224	150.722260	40	Hutton Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<2	<2	<1	<1	<1	<1
-27.199443	150.590278	246	Hutton Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<2	<2	<1	<1	<1	<1
-26.549722	150.763891	240	Hutton Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<2	<2	<1	<1	<1	<1
-28.490132	150.417824	756	Hutton Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<2	<2	<1	<1	<1	<1
-28.528836	150.314654	1031.6	Hutton Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<2	<2	<1	<1	<1	<1
-27.674954	150.872004	914	Hutton Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<2	<2	<1	<1	<1	<1
-28.30648	150.28629	1247	Hutton Sandstone	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<0.5	<1	<1	<1
-27.9418	151.17288	305	Hutton Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.02224	151.64471	349	Hutton Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-26.5867	150.67973	274	Hutton Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.12591	150.68999	1002	Hutton Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-26.06422	149.02917	220	Hutton Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-26.08525	148.9696	136	Hutton Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-26.00205	149.44104	427	Hutton Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-25.99607	149.30992	204	Hutton Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-25.98061	149.34673	221	Hutton Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-25.85374	149.34074	305	Hutton Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-26.29982	150.18268	422	Hutton Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-26.15858	149.0974	329	Hutton Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-25.93223	149.40669	296	Hutton Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-25.63296	149.76134	240	Hutton Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-25.51113	149.72897	274	Hutton Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-25.39592	149.76805	24.4	Hutton Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-25.54716	149.38191	285	Hutton Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-25.67007	149.58881	464	Hutton Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-25.83217	149.79073	499	Hutton Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.733860	150.106108	821.4	Bungil Formation	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<2	<2	<1	<1	<1	<1
-27.89205	151.3781	55	Marburg Subgroup	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-26.86743129	151.41836	183	Marburg Subgroup	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.96301	151.82405	60	Marburg Subgroup	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.9197	151.72733	102	Marburg Subgroup	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.94357	151.78606	102	Marburg Subgroup	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.80107	151.74828	34	Marburg Subgroup	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-26.92077	150.63965	112	Marburg Subgroup	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.03013	151.31725	184	Marburg Subgroup	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.03732	151.327	254	Marburg Subgroup	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.21447	151.04346	94	Marburg Subgroup	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.41014	151.15814	1085	Precipice Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.41014	151.15814	1085	Precipice Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.12508	150.68999	1282	Precipice Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-26.05461	150.09824	945	Precipice Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-25.55885	149.43571	381	Precipice Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-26.12259	149.95959	1149	Precipice Sandstone	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-27.02881	151.31465	56	Main Range Volcanics	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-26.04273	149.31187	360	Injune Creek Group	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-26.12733	149.27512	547	Injune Creek Group	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.6	<1.0	<1.0	<1.0
-26.05953236	149.973883	580	Walloon Coal Measures	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-26.12446	149.14238	464	Walloon Coal Measures	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-26.13112	149.20021	380	Eurombah Formation	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<0.5	<1.0	<1.0	<1.0
-28.13936	150.37395	273.4	Kumbarilla Beds	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<0.5	<1	<1	<1
-27.730710	150.926427	88.4	Kumbarilla Beds	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<2	<2	<1	<1	<1	<1

total amount of TPH at a site. TPH is a mixture of chemicals comprising aliphatic hydrocarbons, cycloalkanes, monoaromatics, alkanes and polar aliphatics and aromatics (containing N, O or S). TPH can be divided into groups of petroleum hydrocarbons that act alike in soil or water (hydrocarbon fractions) but may contain many individual chemicals.

Hydrocarbons associated with produced waters can be present as both dispersed droplets of non-aqueous phase liquid (i.e. oil), as colloidal and dispersed solids and in the dissolved phase. Due to their low solubility, some compounds such as the aliphatic hydrocarbons are found predominantly in the dispersed phase, while others such as aromatic compounds can be present in either phase depending on their molecular weight and structural complexity (OGP 2005). It usually requires very careful and detailed analyses to determine the phase of the TPH in environmental samples. The phase also critically impinges on the interpretation of the results.

Australian Pacific LNG (APLNG) provided a summary of water chemistry from 47 wells within the Talinga gas field in south central Queensland (Surat Basin) as part of their Condabri CSG Water Management Plan to DERM (APLNG 2010). Average concentrations of TPH compounds were below detection limits, while ranges of detected concentrations were not reported (Table 22).

TPH data are available for Permian coal seams in the Bowen Basin at the Middlemount Mine (Middlemount Coal 2011). TPH concentrations in the Middlemount Seam, Pisces Coal Seam and Fort Cooper Coal Measures were generally low, with maximum concentrations summarised in Table 23.

TPH was also analysed in water associated with the Permian Wittingham and Newcastle Coal Measures by ALS Environmental (Sydney) for Sydney Gas and AGL at their exploration sites in the Yarramalong and Hunter valleys (PB 2005; 2006; 2010) using standard methods (USEPA SW 846 - 8015A and USEPA SW 846 – 8260B; USEPA 2008). Maximum measured values are reported in Table 24.

Table 22: Average TPH concentrations (µg/L) in wells from the Talinga Gas Field, Surat Basin. Source: APLNG 2010.

Compound	Average value (µg/L)
C_6-C_9 fraction	<25
C_{10}-C_{14} fraction	83.5
C_{15}-C_{28} fraction	74.7
C_{28}-C_{36} fraction	94.4

In the second annual quality report in 2012 regarding the Talinga Water Treatment Facility, TPH compounds were detected (Australia Pacific LNG, 2012). Compound concentrations for these TPHs are shown in Table 9.

In a quarterly produced water quality monitoring report from 2013, AGL measured TPH concentrations as part of groundwater monitoring activities for the Camden Gas Project, NSW (AGL 2013). Data from two monitoring points at separate locations were presented and are shown in Table 10.

Tang et al. (2014) detected TPHs through chemical analyses of CSG water from private wells tapping into the Walloon Coal Measures, Surat Basin (Table 25). The C15–C28 and C29–C36 fractions of the TPHs were above the LOR. These fractions include semi-volatiles (C10–C36) and aliphatic hydrocarbons as well as aromatic hydrocarbons in the C16–C35 band. The C15–C28 fractions were above the LOR in the field blank and the trip blank but at lower concentrations than in the surrogate CSGW samples. It was also noted that the control water bore exhibited more than ten times higher C10–C14 and C15–C28 concentrations. Tang et al. (2014) suggested that these observations could stem from contamination during drilling of the bore.

PAH compounds were also reported in the survey conducted by Geoscience Australia and the Geological Survey of Queensland to characterise the regional hydrochemistry of the Denison Trough (Bowen Basin) and Surat Basin (Feitz et al. 2014). Compounds and their concentrations are shown in Table 26.

Table 23: Maximum TPH concentrations (µg/L) for the Middlemount Seam, Pisces Coal Seam and Fort Cooper Coal Measures (Middlemount Coal 2011).

Total Petroleum Hydrocarbons	Middlemount Seam	Pisces Coal Seam	Fort Cooper Coal Measures
C_6-C_9 fraction	80	340	<20
C_{10}-C_{14} fraction	210	120	<50
C_{15}-C_{28} fraction	130	200	<100
C_{29}-C_{36} fraction	<50	90	<50
C_6-C_{36} fraction	220	350	<50

Table 24: TPH concentrations (µg/L) fin the Newcastle and Wittingham Coal Measures.

Total Petroleum	Great	Blakefield	Warkworth/	Blakefield Seam
Coal Measures	Newcastle	Wittingham	Wittingham	Wittingham
Reference	PB 2005	PB 2006	PB 2006	PB 2010
C_6-C_9 fraction	<20	<20	<20	<20
C_{10}-C_{14} fraction	<50	<50	<50	<50
C_{15}-C_{28} fraction	400	400	6,800	300
C_{29}-C_{36} fraction	660	500	5,190	240

Table 25: TPH compounds (µg/L) in coal seam gas associated water, Surat Basin, Queensland. LOR = limit of reporting; PH Reg Std = Public Health Regulation standard; RN = Well registration number; WB = non-coal seam gas water bore; FB = field blank; TB = transport blank; n.a. = not analysed. Source: Tang et al. (2014).

TPH compounds	LOR	PH Reg Std	Sample identity and sampling date								
			RN 15811 20 March 2012	RN 15811 14 November 2013	RN 107761 20 March 2012	RN 107761 14 November 2013	RN 107739 20 March 2012	RN 24467 14 November 2013	WB 14 November 2013	FB 14 November 2013	TB 14 November 2013
C6-C9	25		<25	n.a	<25	n.a	<25	n.a	n.a	n.a	n.a
C10-C14	10		<10	<10	<10	<10	<10	<10	200	<10	<10
C15-C28	10		78	35	17	82	60	34	810	22	13
C29-C36	10		27	<10	<10	25	<10	20	<10	<10	<10

4.5 Other organic compounds

A variety of alkylated and halogenated aromatic compounds, ketones and alkanes were also reported in the survey conducted by Geoscience Australia and the Geological Survey of Queensland to characterise the regional hydrochemistry of the Denison Trough (Bowen Basin) and Surat Basin (Feitz et al. 2014). Compounds and their concentrations are shown in Tables 27 to 30. However, many of these compounds are unlikely to have been derived from coal.

A number of organic compounds are frequently used in hydraulic fracturing for CSG. These compounds are often associated with negative health impacts.

- Acrylamide is often used as a friction reducer in fraccing fluids and is a probable human carcinogen (e.g. IARC 2004).
- Alcohol ethoxylates and alkylphenol ethoxylates are a class of surfactants that have also been used in fraccing fluids. These latter two compounds are considered toxic to many aquatic species and are a major contributor to nonylphenol; a endocrine-disrupting compound, in the environment (Soto et al. 1991; White et al. 1994).
- Glycols and glycol ethers are frequently used as solvents or viscosity agents and can be a component of fraccing fluids. Health effects include central nervous system depressions including vomiting, drowsiness, coma, respiratory failure, convulsions, and metabolic changes (e.g. ATSDR 1997).

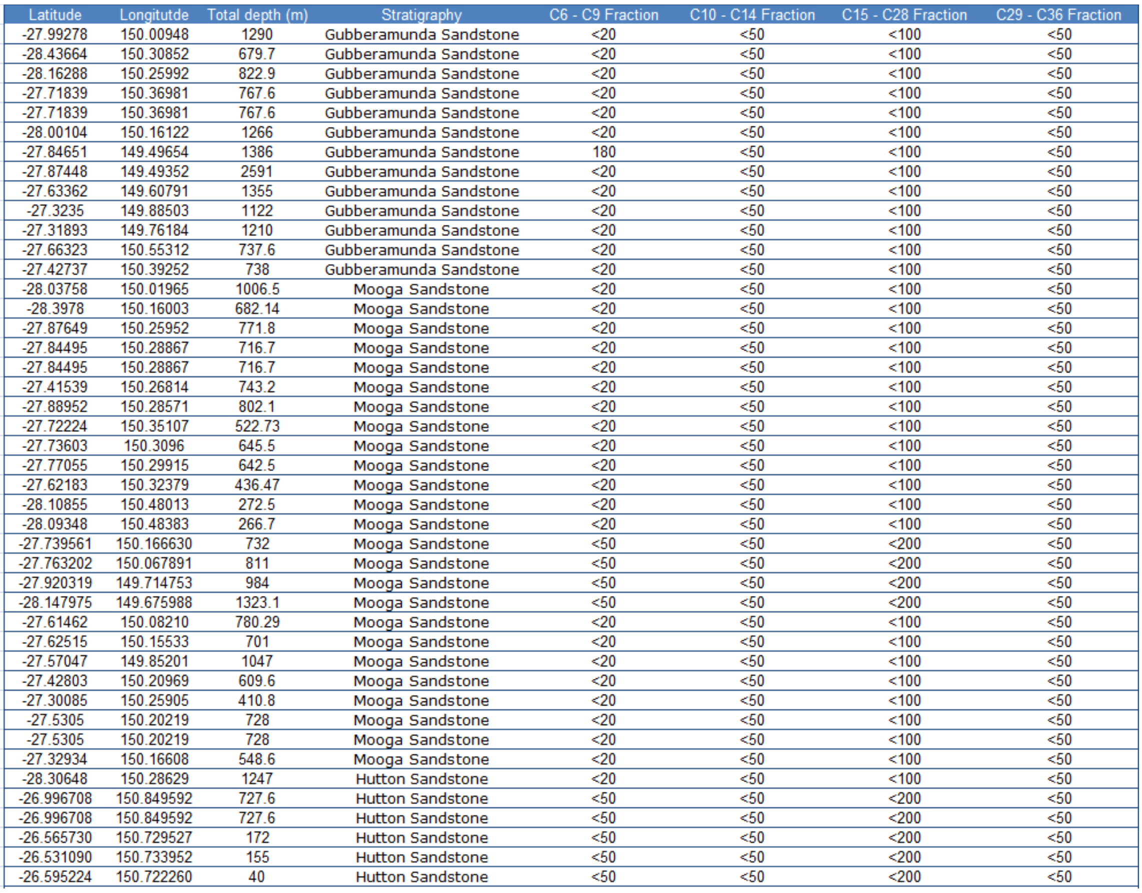
A literature search for any study involving hydraulic fracturing and the detection of these organic compounds in Australian groundwater has yielded no information. The US Environmental Protection Agency recently published a number of peer-reviewed technical papers to better detect these organic compounds in environmental samples for future studies:

- “Characterization of liquid chromatography-tandem mass spectrometry method for the determination of acrylamide in complex environmental samples”
  Patrick DeArmond and Amanda DiGoregorio. Analytical and Bioanalytical Chemistry. May 2013.
- “Rapid liquid chromatography–tandem mass spectrometry-based method for the analysis of alcohol ethoxylates and alkylphenol ethoxylates in environmental samples”
  Patrick DeArmond and Amanda DiGoregorio. Journal of Chromatography A. August 2013.
- "The verification of a method for detecting and quantifying diethylene glycol, triethylene glycol, tetraethylene glycol, 2-butoxyethanol and 2-methoxyethanol in ground and surface waters" Brian A. Schumacher and Lawrence Zintek. EPA Report. July 2014.

AGL pointed out in a website on the Gloucester Gas Project (http://www.agl.com.au/~/media/AGL/About%20AGL/Documents/How%20We%20Source%20Energy/Gloucester%20Document%20Repository/Fact%20Sheets/20150302__Fact%20Sheet%20GGP%20%20%20BTEX_V3.pdf) that monoethanolamine is added to hydraulic fracturing fluid (as monoethanolamine borate) to increase viscosity. According to their baseline study, AGL noted background concentrations (before the onset of hydraulic fraccing) of monoethanolamine in ground and surface water. AGL attributed this occurrence to “agricultural land and bush areas” as this compound is a constituent of mammalian urine.

On the same website, AGL also noted that Tetrakis(hydroxymethyl)phosphonium sulfate (THPS) is added to fracturing fluid to prevent microbial growth in coal seams. They announced that some surface water monitoring results showed concentrations of this compound at 57 and 59 µg/L. While AGL noted that this result is 7 and 9 µg/L over the level they have to advice the EPA, they pointed out that these results fall within the margin of error limits of laboratory tests (which are ±50 µg/L) (see also http://www.agl.com.au/about-agl/media-centre/article-list/2015/january/water-testing-results-shows-no-anti-bacterial-agent-in-gloucester-groundwater).

Table 26: Concentrations of TPH compounds in waters from the Bowen and Surat basins. Concentrations are in µg/L. Source: Feitz et al. 2014.



Latitude	Longitutde	Total depth (m)	Stratigraphy	C6 - C9 Fraction	C10 - C14 Fraction	C15 - C28 Fraction	C29 - C36 Fraction
-27.99278	150.00948	1290	Gubberamunda Sandstone	<20	<50	<100	<50
-28.43664	150.30852	679.7	Gubberamunda Sandstone	<20	<50	<100	<50
-28.16288	150.25992	822.9	Gubberamunda Sandstone	<20	<50	<100	<50
-27.71839	150.36981	767.6	Gubberamunda Sandstone	<20	<50	<100	<50
-27.71839	150.36981	767.6	Gubberamunda Sandstone	<20	<50	<100	<50
-28.00104	150.16122	1266	Gubberamunda Sandstone	<20	<50	<100	<50
-27.84651	149.49654	1386	Gubberamunda Sandstone	180	<50	<100	<50
-27.87448	149.49352	2591	Gubberamunda Sandstone	<20	<50	<100	<50
-27.63362	149.60791	1355	Gubberamunda Sandstone	<20	<50	<100	<50
-27.3235	149.88503	1122	Gubberamunda Sandstone	<20	<50	<100	<50
-27.31893	149.76184	1210	Gubberamunda Sandstone	<20	<50	<100	<50
-27.66323	150.55312	737.6	Gubberamunda Sandstone	<20	<50	<100	<50
-27.42737	150.39252	738	Gubberamunda Sandstone	<20	<50	<100	<50
-28.03758	150.01965	1006.5	Mooga Sandstone	<20	<50	<100	<50
-28.3978	150.16003	682.14	Mooga Sandstone	<20	<50	<100	<50
-27.87649	150.25952	771.8	Mooga Sandstone	<20	<50	<100	<50
-27.84495	150.28867	716.7	Mooga Sandstone	<20	<50	<100	<50
-27.84495	150.28867	716.7	Mooga Sandstone	<20	<50	<100	<50
-27.41539	150.26814	743.2	Mooga Sandstone	<20	<50	<100	<50
-27.88952	150.28571	802.1	Mooga Sandstone	<20	<50	<100	<50
-27.72224	150.35107	522.73	Mooga Sandstone	<20	<50	<100	<50
-27.73603	150.3096	645.5	Mooga Sandstone	<20	<50	<100	<50
-27.77055	150.29915	642.5	Mooga Sandstone	<20	<50	<100	<50
-27.62183	150.32379	436.47	Mooga Sandstone	<20	<50	<100	<50
-28.10855	150.48013	272.5	Mooga Sandstone	<20	<50	<100	<50
-28.09348	150.48383	266.7	Mooga Sandstone	<20	<50	<100	<50
-27.739561	150.166630	732	Mooga Sandstone	<50	<50	<200	<50
-27.763202	150.067891	811	Mooga Sandstone	<50	<50	<200	<50
-27.920319	149.714753	984	Mooga Sandstone	<50	<50	<200	<50
-28.147975	149.675988	1323.1	Mooga Sandstone	<50	<50	<200	<50
-27.61462	150.08210	780.29	Mooga Sandstone	<20	<50	<100	<50
-27.62515	150.15533	701	Mooga Sandstone	<20	<50	<100	<50
-27.57047	149.85201	1047	Mooga Sandstone	<20	<50	<100	<50
-27.42803	150.20969	609.6	Mooga Sandstone	<20	<50	<100	<50
-27.30085	150.25905	410.8	Mooga Sandstone	<20	<50	<100	<50
-27.5305	150.20219	728	Mooga Sandstone	<20	<50	<100	<50
-27.5305	150.20219	728	Mooga Sandstone	<20	<50	<100	<50
-27.32934	150.16608	548.6	Mooga Sandstone	<20	<50	<100	<50
-28.30648	150.28629	1247	Hutton Sandstone	<20	<50	<100	<50
-26.996708	150.849592	727.6	Hutton Sandstone	<50	<50	<200	<50
-26.996708	150.849592	727.6	Hutton Sandstone	<50	<50	<200	<50
-26.565730	150.729527	172	Hutton Sandstone	<50	<50	<200	<50
-26.531090	150.733952	155	Hutton Sandstone	<50	<50	<200	<50
-26.595224	150.722260	40	Hutton Sandstone	<50	<50	<200	<50

Table 27: Concentrations of alkylated benzene and toluene compounds in waters from the Bowen and Surat basins. Concentrations are in µg/L. Source: Feitz et al. 2014.

Latitude	Longitutde	Total depth (m)	Stratigraphy	Isopropylbenzene	n-Propylbenzene	sec-Butylbenzene	tert-Butylbenzene	p-Isopropyltoluene	n-Butylbenzene	Styrene	1.3.5-Trimethylbenzene	1.2.4-Trimethylbenzene
-27.99278	150.00948	1290	Gubberamunda Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-28.43664	150.30852	679.7	Gubberamunda Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-28.16288	150.25992	822.9	Gubberamunda Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-27.71839	150.36981	767.6	Gubberamunda Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-27.71839	150.36981	767.6	Gubberamunda Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-28.00104	150.16122	1266	Gubberamunda Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-27.84651	149.49654	1386	Gubberamunda Sandstone	<5	<5	<5	<5	<5	<5	<0.05	0.56	2.73
-27.87448	149.49352	2591	Gubberamunda Sandstone	<5	<5	<5	<5	<5	<5	<0.05	0.28	1.17
-27.63362	149.60791	1355	Gubberamunda Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-27.3235	149.88503	1122	Gubberamunda Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-27.31893	149.76184	1210	Gubberamunda Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-27.66323	150.55312	737.6	Gubberamunda Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-27.42737	150.39252	738	Gubberamunda Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-28.03758	150.01965	1006.5	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-28.3978	150.16003	682.14	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-27.87649	150.25952	771.8	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-27.84495	150.28867	716.7	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-27.84495	150.28867	716.7	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-27.41539	150.26814	743.2	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-27.88952	150.28571	802.1	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-27.72224	150.35107	522.73	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-27.73603	150.3096	645.5	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-27.77055	150.29915	642.5	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-27.62183	150.32379	436.47	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-28.10855	150.48013	272.5	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-28.09348	150.48383	266.7	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-27.739561	150.166630	732	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.763202	150.067891	811	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.920319	149.714753	984	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5
-28.147975	149.675988	1323.1	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.61462	150.08210	780.29	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-27.62515	150.15533	701	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-27.57047	149.85201	1047	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	0.06
-27.42803	150.20969	609.6	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-27.30085	150.25905	410.8	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	0.05
-27.5305	150.20219	728	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-27.5305	150.20219	728	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-27.32934	150.16608	548.6	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-28.30648	150.28629	1247	Hutton Sandstone	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05
-26.996708	150.849592	727.6	Hutton Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5
-26.996708	150.849592	727.6	Hutton Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5
-26.565730	150.729527	172	Hutton Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5
-26.531090	150.733952	155	Hutton Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5
-26.595224	150.722260	40	Hutton Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.199443	150.590278	246	Hutton Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5
-26.549722	150.763891	240	Hutton Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5
-28.490132	150.417824	756	Hutton Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5
-28.528836	150.314654	1031.6	Hutton Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.674954	150.872004	914	Hutton Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5
-26.06422	149.02917	220	Hutton Sandstone							<0.05	<0.05	<0.05
-26.08525	148.9696	136	Hutton Sandstone							<0.05	<0.05	<0.05
-26.00205	149.44104	427	Hutton Sandstone							<0.05	<0.05	<0.05
-25.99607	149.30992	204	Hutton Sandstone							<0.05	<0.05	<0.05
-25.98061	149.34673	221	Hutton Sandstone							<0.05	<0.05	<0.05
-25.85374	149.34074	305	Hutton Sandstone							<0.05	<0.05	<0.05
-26.29982	150.18268	422	Hutton Sandstone							<0.05	<0.05	<0.05
-26.15858	149.0974	329	Hutton Sandstone							<0.05	<0.05	<0.05
-25.93223	149.40669	296	Hutton Sandstone							<0.05	<0.05	<0.05
-25.63296	149.76134	240	Hutton Sandstone							<0.05	<0.05	<0.05
-25.51113	149.72897	274	Hutton Sandstone							<0.05	<0.05	<0.05
-25.39592	149.76805	24.4	Hutton Sandstone							<0.05	<0.05	<0.05
-25.54716	149.38191	285	Hutton Sandstone							<0.05	<0.05	<0.05
-25.67007	149.58881	464	Hutton Sandstone							<0.05	<0.05	<0.05
-25.83217	149.79073	499	Hutton Sandstone							<0.05	<0.05	<0.05
-26.05461	150.09824	945	Precipice Sandstone							<0.05	<0.05	<0.05
-25.55885	149.43571	381	Precipice Sandstone							<0.05	<0.05	<0.05
-26.12259	149.95959	1149	Precipice Sandstone							<0.05	<0.05	<0.05
-26.13112	149.20021	380	Eurombah Formation							<0.05	<0.05	<0.05
-26.04273	149.31187	360	Injune Creek Group							<0.05	<0.05	<0.05
-26.12733	149.27512	547	Injune Creek Group							<0.05	<0.05	<0.05
-27.733860	150.106108	821.4	Bungil Formation	<5	<5	<5	<5	<5	<5	<5	<5	<5
-26.05953236	149.9738832	580	Walloon Coal Measures							<0.05	<0.05	<0.05
-26.12446	149.14238	464	Walloon Coal Measures							<0.05	<0.05	<0.05
-27.730710	150.926427	88.4	Kumbarilla Beds	<5	<5	<5	<5	<5	<5	<5	<5	<5
-28.13936	150.37395	273.4	Kumbarilla Beds	<5	<5	<5	<5	<5	<5	<0.05	<0.05	<0.05

Table 28: Concentrations of halogenated benzene and toluene compounds in waters from the Bowen and Surat basins. Concentrations are in μg/L. Source: Feitz et al. 2014.

Latitude	Longitutde	Total depth (m)	Stratigraphy	Chlorobenzene	Bromobenzene	Benzychloride	1.3-Dichlorobenzene	1.4-Dichlorobenzene	1.2-Dichlorobenzene	2-Chlorotoluene	4-Chlorotoluene	1.2.4-Trichlorobenzene	1.2.3-Trichlorobenzene
-27.99278	150.00948	1290	Gubberamunda Sandstone	<0.1	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
-28.43664	150.30852	679.7	Gubberamunda Sandstone	<0.1	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
-28.16288	150.25992	822.9	Gubberamunda Sandstone	<0.1	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
-27.71839	150.36981	767.6	Gubberamunda Sandstone	<0.1	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
-27.71839	150.36981	767.6	Gubberamunda Sandstone	<0.1	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
-28.00104	150.16122	1266	Gubberamunda Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-27.84651	149.49654	1386	Gubberamunda Sandstone	<0.10	<0.10	0.6	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-27.87448	149.49352	2591	Gubberamunda Sandstone	<0.10	<0.10	0.3	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-27.63362	149.60791	1355	Gubberamunda Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-27.3235	149.88503	1122	Gubberamunda Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-27.31893	149.76184	1210	Gubberamunda Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-27.66323	150.55312	737.6	Gubberamunda Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-27.42737	150.39252	738	Gubberamunda Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-28.03758	150.01965	1006.5	Mooga Sandstone	<0.1	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
-28.3978	150.16003	682.14	Mooga Sandstone	<0.1	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
-27.87649	150.25952	771.8	Mooga Sandstone	<0.1	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
-27.84495	150.28867	716.7	Mooga Sandstone	<0.1	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
-27.84495	150.28867	716.7	Mooga Sandstone	<0.1	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
-27.41539	150.26814	743.2	Mooga Sandstone	<0.1	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
-27.88952	150.28571	802.1	Mooga Sandstone	<0.1	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
-27.72224	150.35107	522.73	Mooga Sandstone	<0.1	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
-27.73603	150.3096	645.5	Mooga Sandstone	<0.1	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
-27.77055	150.29915	642.5	Mooga Sandstone	<0.1	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
-27.62183	150.32379	436.47	Mooga Sandstone	<0.1	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
-28.10855	150.48013	272.5	Mooga Sandstone	<0.1	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
-28.09348	150.48383	266.7	Mooga Sandstone	<0.1	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
-27.739561	150.166630	732	Mooga Sandstone	<5	<5		<5	<1	<1	<5	<5	<5	<5
-27.763202	150.067891	811	Mooga Sandstone	<5	<5		<5	<1	<1	<5	<5	<5	<5
-27.920319	149.714753	984	Mooga Sandstone	<5	<5		<5	<1	<1	<5	<5	<5	<5
-28.147975	149.675988	1323.1	Mooga Sandstone	<5	<5		<5	<1	<1	<5	<5	<5	<5
-27.61462	150.08210	780.29	Mooga Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-27.62515	150.15533	701	Mooga Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-27.42803	150.20969	609.6	Mooga Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-27.30085	150.25905	410.8	Mooga Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-27.5305	150.20219	728	Mooga Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-27.5305	150.20219	728	Mooga Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-27.57047	149.85201	1047	Mooga Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-27.32934	150.16608	548.6	Mooga Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-28.30648	150.28629	1247	Hutton Sandstone	<0.1	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
-26.996708	150.849592	727.6	Hutton Sandstone	<5	<5		<5	<1	<1	<5	<5	<5	<5
-26.996708	150.849592	727.6	Hutton Sandstone	<5	<5		<5	<1	<1	<5	<5	<5	<5
-26.565730	150.729527	172	Hutton Sandstone	<5	<5		<5	<1	<1	<5	<5	<5	<5
-26.531090	150.733952	155	Hutton Sandstone	<5	<5		<5	<1	<1	<5	<5	<5	<5
-26.595224	150.722260	40	Hutton Sandstone	<5	<5		<5	<1	<1	<5	<5	<5	<5
-27.199443	150.590278	246	Hutton Sandstone	<5	<5		<5	<1	<1	<5	<5	<5	<5
-26.549722	150.763891	240	Hutton Sandstone	<5	<5		<5	<1	<1	<5	<5	<5	<5
-28.490132	150.417824	756	Hutton Sandstone	<5	<5		<5	<1	<1	<5	<5	<5	<5
-28.528836	150.314654	1031.6	Hutton Sandstone	<5	<5		<5	<1	<1	<5	<5	<5	<5
-27.674954	150.872004	914	Hutton Sandstone	<5	<5		<5	<1	<1	<5	<5	<5	<5
-26.06422	149.02917	220	Hutton Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-26.08525	148.9696	136	Hutton Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-26.00205	149.44104	427	Hutton Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-25.99607	149.30992	204	Hutton Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-25.98061	149.34673	221	Hutton Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-25.85374	149.34074	305	Hutton Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-26.29982	150.18268	422	Hutton Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-26.15858	149.0974	329	Hutton Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-25.93223	149.40669	296	Hutton Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-25.63296	149.76134	240	Hutton Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-25.51113	149.72897	274	Hutton Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-25.39592	149.76805	24.4	Hutton Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-25.54716	149.38191	285	Hutton Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-25.67007	149.58881	464	Hutton Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-25.83217	149.79073	499	Hutton Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-27.733860	150.106108	821.4	Bungil Formation	<5	<5		<5	<1	<1	<5	<5	<5	<5
-26.05461	150.09824	945	Precipice Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-25.55885	149.43571	381	Precipice Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-26.12259	149.95959	1149	Precipice Sandstone	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-26.04273	149.31187	360	Injune Creek Group	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-26.12733	149.27512	547	Injune Creek Group	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-26.05953236	149.9738832	580	Walloon Coal Measures	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-26.12446	149.14238	464	Walloon Coal Measures	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-26.13112	149.20021	380	Eurombah Formation	<0.10	<0.10	<0.2	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1
-28.13936	150.37395	273.4	Kumbarilla Beds	<0.1	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
-27.730710	150.926427	88.4	Kumbarilla Beds	<5	<5		<5	<1	<1	<5	<5	<5	<5

Table 29: Concentrations of halogenated compounds in waters from the Bowen and Surat basins. Concentrations are in µg/L. Source: Feitz et al. 2014.

Latitude	Longitutde	Total depth (m)	Stratigraphy	Vinyl Acetate	2-Butanone (MEK)	4-Methyl-2-pentanone (MIBK)	2-Hexanone (MBK)	Methyl t-butyl ether	Hexachlorobutadiene	1.2.3-Trichloropropane	Pentachloroethane	1.2-Dibromo-3-chloropropane	1.1.2.2-Tetrachloroethane	trans-1.4.-Dichloro-2-butene	cis-1.4.-Dichloro-2-butene
-27.99278	150.00948	1290	Gubberamunda Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-28.43664	150.30852	679.7	Gubberamunda Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-28.16288	150.25992	822.9	Gubberamunda Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-27.71839	150.36981	767.6	Gubberamunda Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-27.71839	150.36981	767.6	Gubberamunda Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-28.00104	150.16122	1266	Gubberamunda Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-27.84651	149.49654	1386	Gubberamunda Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-27.87448	149.49352	2591	Gubberamunda Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-27.63362	149.60791	1355	Gubberamunda Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-27.3235	149.88503	1122	Gubberamunda Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-27.31893	149.76184	1210	Gubberamunda Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-27.66323	150.55312	737.6	Gubberamunda Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-27.42737	150.39252	738	Gubberamunda Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-28.03758	150.01965	1006.5	Mooga Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-28.3978	150.16003	682.14	Mooga Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-27.87649	150.25952	771.8	Mooga Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-27.84495	150.28867	716.7	Mooga Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-27.84495	150.28867	716.7	Mooga Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-27.41539	150.26814	743.2	Mooga Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-27.88952	150.28571	802.1	Mooga Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-27.72224	150.35107	522.73	Mooga Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-27.73603	150.3096	645.5	Mooga Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-27.77055	150.29915	642.5	Mooga Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-27.62183	150.32379	436.47	Mooga Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-28.10855	150.48013	272.5	Mooga Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-28.09348	150.48383	266.7	Mooga Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-27.739561	150.166630	732	Mooga Sandstone	<5	<5	<5	<5		<1	<5		<5	<5		
-27.763202	150.067891	811	Mooga Sandstone	<5	<5	<5	<5		<1	<5		<5	<5		
-27.920319	149.714753	984	Mooga Sandstone	<5	<5	<5	<5		<1	<5		<5	<5		
-28.147975	149.675988	1323.1	Mooga Sandstone	<5	<5	<5	<5		<1	<5		<5	<5		
-27.61462	150.08210	780.29	Mooga Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-27.62515	150.15533	701	Mooga Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-27.57047	149.85201	1047	Mooga Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-27.42803	150.20969	609.6	Mooga Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-27.30085	150.25905	410.8	Mooga Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-27.5305	150.20219	728	Mooga Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-27.5305	150.20219	728	Mooga Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-27.32934	150.16608	548.6	Mooga Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-28.30648	150.28629	1247	Hutton Sandstone	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5
-26.996708	150.849592	727.6	Hutton Sandstone	<5	<5	<5	<5		<1	<5		<5	<5		
-26.996708	150.849592	727.6	Hutton Sandstone	<5	<5	<5	<5		<1	<5		<5	<5		
-26.565730	150.729527	172	Hutton Sandstone	<5	<5	<5	<5		<1	<5		<5	<5		
-26.531090	150.733952	155	Hutton Sandstone	<5	<5	<5	<5		<1	<5		<5	<5		
-26.595224	150.722260	40	Hutton Sandstone	<5	<5	<5	<5		<1	<5		<5	<5		
-27.199443	150.590278	246	Hutton Sandstone	<5	<5	<5	<5		<1	<5		<5	<5		
-26.549722	150.763891	240	Hutton Sandstone	<5	<5	<5	<5		<1	<5		<5	<5		
-28.490132	150.417824	756	Hutton Sandstone	<5	<5	<5	<5		<1	<5		<5	<5		
-28.528836	150.314654	1031.6	Hutton Sandstone	<5	<5	<5	<5		<1	<5		<5	<5		
-27.674954	150.872004	914	Hutton Sandstone	<5	<5	<5	<5		<1	<5		<5	<5		
-26.06422	149.02917	220	Hutton Sandstone					<0.1	<0.05						
-26.08525	148.9696	136	Hutton Sandstone					<0.1	<0.05						
-26.00205	149.44104	427	Hutton Sandstone					<0.1	<0.05						
-25.99607	149.30992	204	Hutton Sandstone					<0.1	<0.05						
-25.98061	149.34673	221	Hutton Sandstone					<0.1	<0.05						
-25.85374	149.34074	305	Hutton Sandstone					<0.1	<0.05						
-26.29982	150.18268	422	Hutton Sandstone					<0.1	<0.05						
-26.15858	149.0974	329	Hutton Sandstone					<0.1	<0.05						
-25.93223	149.40669	296	Hutton Sandstone					<0.1	<0.05						
-25.63296	149.76134	240	Hutton Sandstone					<0.1	<0.05						
-25.39592	149.76805	24.4	Hutton Sandstone					<0.1	<0.05						
-25.54716	149.38191	285	Hutton Sandstone					<0.1	<0.05						
-25.67007	149.58881	464	Hutton Sandstone					<0.1	<0.05						
-25.83217	149.79073	499	Hutton Sandstone					<0.1	<0.05						
-27.733860	150.106108	821.4	Bungil Formation	<5	<5	<5	<5		<1	<5		<5	<5		
-26.05461	150.09824	945	Precipice Sandstone					<0.1	<0.05						
-25.55885	149.43571	381	Precipice Sandstone					<0.1	<0.05						
-26.12259	149.95959	1149	Precipice Sandstone					<0.1	<0.05						
-26.04273	149.31187	360	Injune Creek Group					<0.1	<0.05						
-26.12733	149.27512	547	Injune Creek Group					<0.1	<0.05						
-26.059532	149.97388	580	Walloon Coal Measures					<0.1	<0.05						
-26.12446	149.14238	464	Walloon Coal Measures					<0.1	<0.05						
-26.13112	149.20021	380	Eurombah Formation					<0.1	<0.05						
-27.730710	150.926427	88.4	Kumbarilla Beds	<5	<5	<5	<5		<1	<5		<5	<5		
-28.13936	150.37395	273.4	Kumbarilla Beds	<50	<50	<50	<50	<0.1	<0.05	<5	<5	<5	<5	<5	<5

Table 30: Concentrations of halogenated compounds in waters from the Bowen and Surat basins. Concentrations are in µg/L. Source: Feitz et al. 2014.

-27.99278	150.00948	1290	Gubberamunda Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-28.43664	150.30852	679.7	Gubberamunda Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-28.16288	150.25992	822.9	Gubberamunda Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.71839	150.36981	767.6	Gubberamunda Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.71839	150.36981	767.6	Gubberamunda Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-28.00104	150.16122	1266	Gubberamunda Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.84651	149.49654	1386	Gubberamunda Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.87448	149.49352	2591	Gubberamunda Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.63362	149.60791	1355	Gubberamunda Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.3235	149.88503	1122	Gubberamunda Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.31893	149.76184	1210	Gubberamunda Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.66323	150.55312	737.6	Gubberamunda Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.42737	150.39252	738	Gubberamunda Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-28.03758	150.01965	1006.5	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-28.3978	150.16003	682.14	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.87649	150.25952	771.8	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.84495	150.28867	716.7	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.84495	150.28867	716.7	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.41539	150.26814	743.2	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.88952	150.28571	802.1	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.72224	150.35107	522.73	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.73603	150.3096	645.5	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.77055	150.29915	642.5	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.62183	150.32379	436.47	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-28.10855	150.48013	272.5	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-28.09348	150.48383	266.7	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.739561	150.166630	732	Mooga Sandstone		<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.763202	150.067891	811	Mooga Sandstone		<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.920319	149.714753	984	Mooga Sandstone		<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-28.147975	149.675988	1323.1	Mooga Sandstone		<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.61462	150.08210	780.29	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.62515	150.15533	701	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.57047	149.85201	1047	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.42803	150.20969	609.6	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.30085	150.25905	410.8	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.5305	150.20219	728	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.5305	150.20219	728	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.32934	150.16608	548.6	Mooga Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-28.30648	150.28629	1247	Hutton Sandstone	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-26.996708	150.849592	727.6	Hutton Sandstone		<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-26.996708	150.849592	727.6	Hutton Sandstone		<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-26.565730	150.729527	172	Hutton Sandstone		<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-26.531090	150.733952	155	Hutton Sandstone		<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-26.595224	150.722260	40	Hutton Sandstone		<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.199443	150.590278	246	Hutton Sandstone		<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-26.549722	150.763891	240	Hutton Sandstone		<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-28.490132	150.417824	756	Hutton Sandstone		<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-28.528836	150.314654	1031.6	Hutton Sandstone		<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.674954	150.872004	914	Hutton Sandstone		<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.733860	150.106108	821.4	Bungil Formation		<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-27.730710	150.926427	88.4	Kumbarilla Beds		<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
-28.13936	150.37395	273.4	Kumbarilla Beds	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5

5 Brief review of organic hydrochemistry of groundwater associated with non-Australian coals

5.1 Europe

A search for coal-associated hydrocarbon contaminants in European groundwater led to the discovery of scholarly articles relating to Balkan endemic nephropathy (BEN). BEN is a chronic kidney disease that some (e.g. Feder et al. 1991, 2002) have linked to organic contaminants derived from lignite coal deposits that have leached into drinking water supplies. The disease is geographically confined to countries of the Balkan Peninsula. Aqueous leaching experiments examining BEN to coal-associated contaminants have been discussed in section 3.6. However, it should be stressed that other non-coal associated causes have also been hypothesised for the disease (see Maharaj et al. 2014 and references therein).

5.2 USA

Hydrochemical studies of waters associated with the coalbed methane (CBM) industry in the US have focused on the inorganic chemistry. The Produced Waters database (http://energy.cr.usgs.gov/prov/prodwat/index.htm) provides tens of thousands of analyses of inorganic constituents from produced waters from the various CBM producing states. Although it is recognised that dissolved organic substances may also be present in some CBM produced waters, these substances are neither well documented nor researched (Committee on Management and Effects of Coalbed Methane Development and Produced Water in the Western United States, 2010).

There is little information on Carboniferous coals. However, more detailed chemical studies are available on shallower Cainozoic coals. The major studies looking at organic chemistry of waters associated with coals have been undertaken in the Powder River Basin, Wyoming (Orem et al., 2007) and in Louisiana (Bunnell et al., 2003; 2006). The coals in the Powder River Basin are Cainozoic age lignite and subbituminous coals, and Palaeogene low rank (lignite) in Louisiana. These coals are much younger than the Carboniferous-Permian coals that are the subject of this literature review and they have substantially different geological and hydrogeological attributes. The water chemistry data is shown here as general information, and is not presented as being representative or typical of Permian coals.

Orem et al. (2007) analysed organic compounds in produced water samples from CBM wells in the Powder River Basin, Wyoming, as part of a larger study on the potential health and environmental effects of organic compounds derived from coals. Samples were analysed using gas chromatography–mass spectrometry (GC-MS) analysis and individual organic compounds in the sample chromatograms were identified by comparison of mass spectral features to libraries of mass spectral data (NIST98 and Wiley 7). Only a fraction of the total number of peaks in each chromatogram were identified. The identified organic compounds (sorted by compound class), the wells they were identified in and their concentrations are presented in Table 31. The compounds identified in the GC-MS total ion current (TIC) chromatographs include: PAHs and functional derivatives of PAHs (Figure 10), benzene derivatives, biphenyls, aromatic amines, heterocyclic aromatic NSO compounds, and various polar non-aromatic compounds (n-alkanes, fatty acids, ethers, cyclic aliphatic compounds and others).

PAHs and their functional derivatives were found to be the most frequently occurring compounds. The major groups of PAHs identified include: naphthalene and derivatives, fluorene and derivatives, indene and derivatives, anthracene and derivatives, phenanthrene and derivatives, and pyrene and derivatives. The probable source of PAHs in produced waters from CBM wells was concluded to be leaching from sub-bituminous coal, based on similarities between the spectrum of PAHs present in the produced water and those typically present in coal (Orem et al., 2007). Concentrations of total PAHs ranged up to 23 µg/L, with concentrations of individual compounds ranging from <0.01 to 18 µg/L. As expected, the lower molecular weight PAHs were highest in both number of compounds and concentrations due to greater solubility in the aqueous phase.

Derivatives of phenols and biphenyls were also found in the Powder River samples with concentrations of up to 16 µg/L. These compound classes are widely recognised in coal and Orem et al. (2007) attribute their presence most likely due to alteration of lignin biopolymer during coalification.

Orem et al., 2007 found a large number of aromatic NSOs in the Powder River samples, including derivatives of quinolone, pyranine, pyridine, benzothiozole, dibenzothiophene. Concentrations >14 µg/L were detected. These compounds were previously identified in groundwater associated with low rank coals (Orem et al., 1999) and were therefore concluded to be the result of leaching of coal.

Numerous phthalates were also detected in the Powder River samples, however, phthalates do not occur in nature, and their presence is most likely attributed to PVC in well adhesives, valves or fittings (Orem et al., 2007). Concentrations ranged up to 19 µg/L. Volatile organic compounds have also been analysed in produced water from the Powder River Basin (Jackson and Reddy 2007; 2010).

The presence of long-chain saturated hydrocarbons (e.g. docosane, cyclodocosane, hexacosane, heptacosane) at concentrations >1 µg/L was unexpected by the authors due to the low solubility of these compounds in aqueous solution. However, enhanced solubility may have occurred through binding to colloidal matter (Orem et al., 2007).

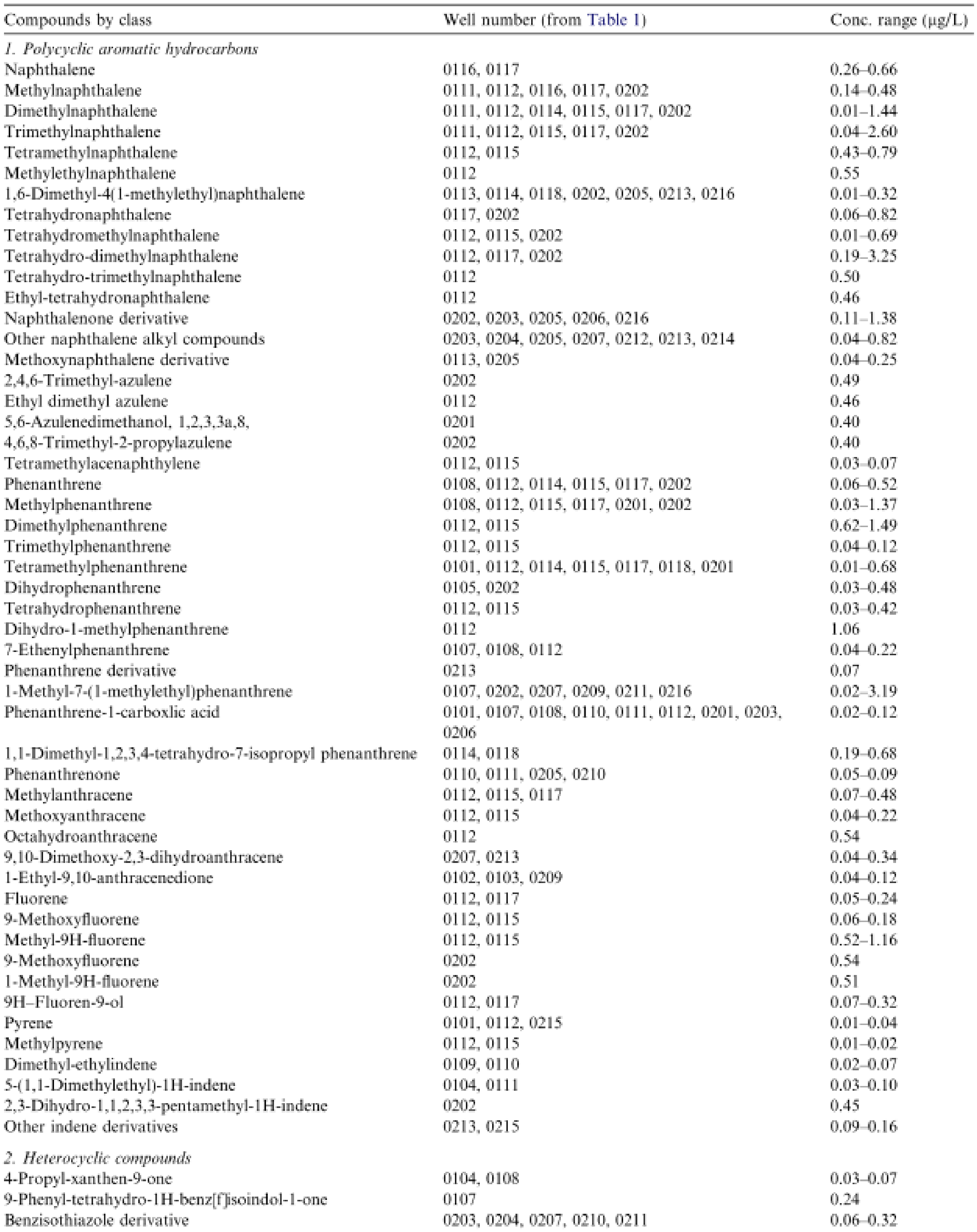
In 2015, the US Interior Department unveiled new fraccing rules related to protecting water supplies (http://www.usatoday.com/story/news/nation/2015/03/20/obama-interior-department-fracking-rules-sally-jewell/25101133/).

The following points are among those new rules:

- "Provisions for ensuring the protection of groundwater supplies by requiring a validation of well integrity and strong cement barriers between the wellbore and water zones through which the wellbore passes;
- "Increased transparency by requiring companies to publicly disclose chemicals used in hydraulic fracturing to the Bureau of Land Management through the website FracFocus, within 30 days of completing fracturing operations;
- "Higher standards for interim storage of recovered waste fluids from hydraulic fracturing to mitigate risks to air, water and wildlife,
- "Measures to lower the risk of cross-well contamination with chemicals and fluids used in the fracturing operation, by requiring companies to submit more detailed information on the geology, depth, and location of pre-existing wells to afford the Bureau of Land Management an opportunity to better evaluate and manage unique site characteristics."

Recently, some attention has also been devoted to the hydrocarbon contamination of groundwater arising from surface spills associated with hydraulic fracturing operations in general and not just CSG activity. Gross et al. (2013) performed a search for publically available data regarding groundwater contamination from spills at US drilling sites. The authors selected the Colorado Oil and Gas Conservation Commission (COGCC) database for this analysis. They pointed out that the majority of spills were in Weld County, Colorado, which has the highest density of wells that used hydraulic fracturing for completion. It was noted that from July 2010 to July 2011, 77 reported surface spills impacted the groundwater in that county. Gross et al. (2013) noted that for groundwater samples taken both within the spill excavation area and on the first reported date of sampling, the BTEX measurements exceeded National Drinking Water maximum contaminant levels. Nevertheless, it was noted that remediate action was effective in reducing BTEX levels.

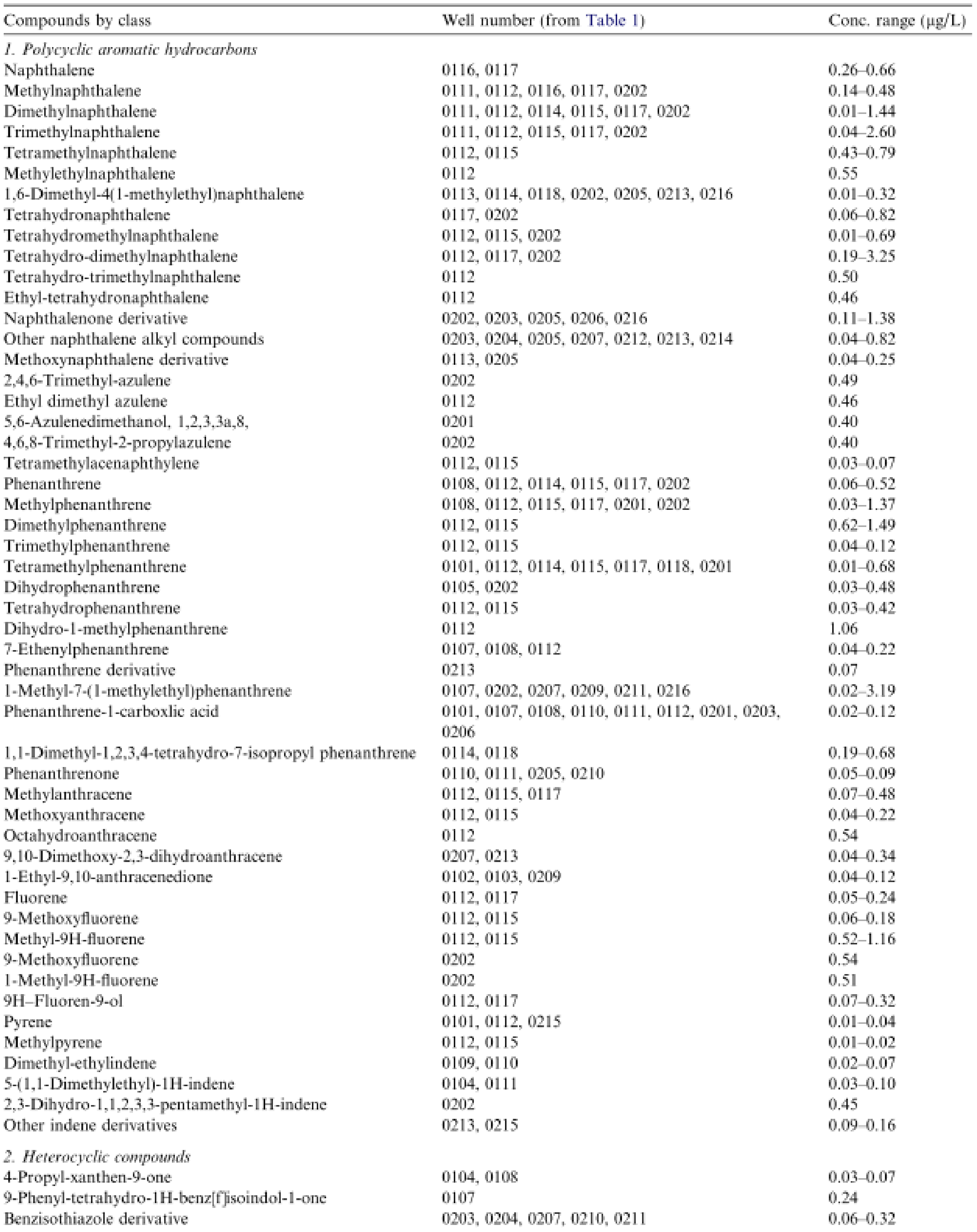
Table 31: Selected compounds identified in produced water samples from 2001 and 2002 samples collected from CBM wells in the Powder River Basin, Wyoming, and their concentration range in µg/L. Source: Orem et al. (2007).



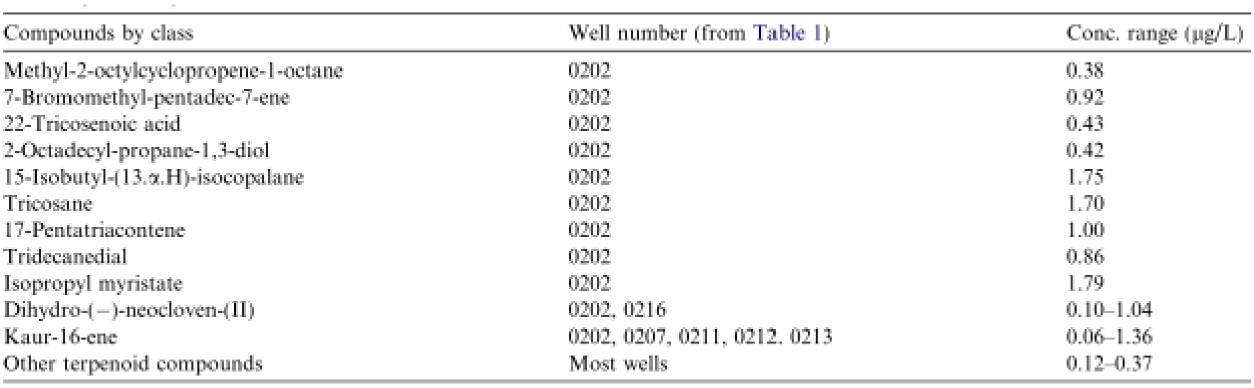
Compounds by class	Well number (from Table 1)	Conc. range (µg/L)
1. Polycyclic aromatic hydrocarbons		
Naphthalene	0116, 0117	0.26–0.66
Methylnaphthalene	0111, 0112, 0116, 0117, 0202	0.14–0.48
Dimethylnaphthalene	0111, 0112, 0114, 0115, 0117, 0202	0.01–1.44
Trimethylnaphthalene	0111, 0112, 0115, 0117, 0202	0.04–2.60
Tetramethylnaphthalene	0112, 0115	0.43–0.79
Methylethylnaphthalene	0112	0.55
1,6-Dimethyl-4(1-methylethyl)naphthalene	0113, 0114, 0118, 0202, 0205, 0213, 0216	0.01–0.32
Tetrahydronaphthalene	0117, 0202	0.06–0.82
Tetrahydromethylnaphthalene	0112, 0115, 0202	0.01–0.69
Tetrahydro-dimethylnaphthalene	0112, 0117, 0202	0.19–3.25
Tetrahydro-trimethylnaphthalene	0112	0.50
Ethyl-tetrahydronaphthalene	0112	0.46
Naphthalenone derivative	0202, 0203, 0205, 0206, 0216	0.11–1.38
Other naphthalene alkyl compounds	0203, 0204, 0205, 0207, 0212, 0213, 0214	0.04–0.82
Methoxynaphthalene derivative	0113, 0205	0.04–0.25
2,4,6-Trimethyl-azulene	0202	0.49
Ethyl dimethyl azulene	0112	0.46
5,6-Azulenedimethanol, 1,2,3,3a,8,	0201	0.40
4,6,8-Trimethyl-2-propylazulene	0202	0.40
Tetramethylacenaphthylene	0112, 0115	0.03–0.07
Phenanthrene	0108, 0112, 0114, 0115, 0117, 0202	0.06–0.52
Methylphenanthrene	0108, 0112, 0115, 0117, 0201, 0202	0.03–1.37
Dimethylphenanthrene	0112, 0115	0.62–1.49
Trimethylphenanthrene	0112, 0115	0.04–0.12
Tetramethylphenanthrene	0101, 0112, 0114, 0115, 0117, 0118, 0201	0.01–0.68
Dihydrophenanthrene	0105, 0202	0.03–0.48
Tetrahydrophenanthrene	0112, 0115	0.03–0.42
Dihydro-1-methylphenanthrene	0112	1.06
7-Ethenylphenanthrene	0107, 0108, 0112	0.04–0.22
Phenanthrene derivative	0213	0.07
1-Methyl-7-(1-methylethyl)phenanthrene	0107, 0202, 0207, 0209, 0211, 0216	0.02–3.19
Phenanthrene-1-carboxlic acid	0101, 0107, 0108, 0110, 0111, 0112, 0201, 0203, 0206	0.02–0.12
1,1-Dimethyl-1,2,3,4-tetrahydro-7-isopropyl phenanthrene	0114, 0118	0.19–0.68
Phenanthrenone	0110, 0111, 0205, 0210	0.05–0.09
Methylanthracene	0112, 0115, 0117	0.07–0.48
Methoxyanthracene	0112, 0115	0.04–0.22
Octahydroanthracene	0112	0.54
9,10-Dimethoxy-2,3-dihydroanthracene	0207, 0213	0.04–0.34
1-Ethyl-9,10-anthracenedione	0102, 0103, 0209	0.04–0.12
Fluorene	0112, 0117	0.05–0.24
9-Methoxyfluorene	0112, 0115	0.06–0.18
Methyl-9H-fluorene	0112, 0115	0.52–1.16
9-Methoxyfluorene	0202	0.54
1-Methyl-9H-fluorene	0202	0.51
9H–Fluoren-9-ol	0112, 0117	0.07–0.32
Pyrene	0101, 0112, 0215	0.01–0.04
Methylpyrene	0112, 0115	0.01–0.02
Dimethyl-ethylindene	0109, 0110	0.02–0.07
5-(1,1-Dimethylethyl)-1H-indene	0104, 0111	0.03–0.10
2,3-Dihydro-1,1,2,3,3-pentamethyl-1H-indene	0202	0.45
Other indene derivatives	0213, 0215	0.09–0.16
2. Heterocyclic compounds		
4-Propyl-xanthen-9-one	0104, 0108	0.03–0.07
9-Phenyl-tetrahydro-1H-benz[f]isoindol-1-one	0107	0.24
Benzisothiazole derivative	0203, 0204, 0207, 0210, 0211	0.06–0.32

Compounds by class	Well number (from Table 1)	Conc. range (μg/L)
Benzothiazole	0116, 0117	0.51–14.27
2-(Methylthio)-benzothiazole	0111, 0116, 0117	0.05–0.54
2-Mercaptobenzothiazole	0116	0.89
2(3H)-Benzothiazolone	0116, 0209	0.04–3.90
Quinolo-furazan derivative	0116	0.82
Pyreno[4,5-c]furan	0202	1.83
Methyl-2-quinolinecarboxylic acid	0117	6.65
Drometrizole	0117	0.91
3,4-Dihydro-1,9(2H,10H)acridinedione	0118, 0210, 0216, 0218	0.02–1.35
Caffeine	0201, 0208, 0211, 0212	0.09–0.50
1-Allyl-3-methylindole-2-carbaldehyde	0202	0.49
3-(Hexahydro-1H-azepin-1-yl)-1,1-dioxide-1,2-benzisothiazole	0202	0.66
1-Allyl-3-methylindole-2-carbaldehyde	0202	1.49
2-Ethylhexyl diphenyl phosphate (Octicizer)	0211, 0212, 0214, 0215, 0216, 0218	0.10–0.75
Other heterocyclics	Most wells	Up to 17.87
3. Aromatic amines		
Dioctyldiphenylamine	0101, 0103, 0107, 0108, 0110, 0111	0.03–0.18
Bis-(octylphenyl)-amine	0112, 0117	0.05–0.19
Diphenylamine	0116, 0211	0.04–3.73
2-Methyl-*N*-phenyl-benzenamine	0116, 0117	0.41–3.53
Other benzenamines	0206, 0209, 0201,0212	0.06–0.25
1,4-[13C]-1,2,3,4-Tetrahydro-5-naphthaleneamine	0201	0.33
4. Phenols		
Nonyl-phenol	0203, 0210, 0212, 0217, 0218	0.09–7.91
Dimethylphenol	0116	1.38
4-(1-Methyl-phenylethyl)-phenol	0116	1.18
2,6-Bis(dimethylethyl)-phenol	0116	0.31
4,4′-(1-Methylethylidene)bis-phenol	Most wells	Up to 16.17
p-Tert-butylphenol	0203, 0213	0.07–0.19
Other alkyl phenols	Most wells	Up to 5.89
5. Other aromatics		
Benzenemethanol	0117	0.33
Other benzene alkyl compounds	0203, 0205, 0206, 0207, 0209, 0211, 0216, 0218	0.02–0.62
Ethyl phenylmethyl benzene	0111	0.10
Dimethyl phthalate	0203, 0213, 0216,	0.11–0.28
Dibutyl phthalate	Most wells	Up to 1.27
Di-*n*-octyl phthalate	0209, 0215, 0216	0.58–4.63
Benzyl butyl phthalate	0204, 0209, 0212, 0214, 0216, 0.218	0.04–0.33
Diethyl phthalate	Most wells	Up to 14.90
Didecyl phthalate	Most wells	Up to 7.23
Other phthalates	Most wells	Up to 18.68
Triphenyl phosphate	0206, 0207, 0212	0.07–0.21
Di-tetra-butyl-4-hydroxbenzaldehyde	0108, 0206	0.16–0.53
Biphenyl	0112, 0117	0.16–0.30
Methyl-biphenyl	0112, 0117	0.15–1.00
Dimethyl-biphenyl	0112, 0115	0.07–2.01
Propane-diphenyl	0109, 0111, 0114	0.03–0.22
1-(2-Hydroxy-5-methylphenyl)-2-hexen-1-one	0111	0.29
Diphenylmethane	0112, 0115	0.01–0.43
2,3′,5-Trimethyldiphenylmethane	0209, 0215	0.04–0.05
4,4-Diacetyldiphenylmethane	0117	0.37
1-1Methylenebis(4-methyl)-benzene	0112, 0201	0.09–0.11

Compounds by class	Well number (from Table 1)	Conc. range (μg/L)
9-Phenyl-tetrahydro-1H-benz[f]isoindol-1-one	0107	0.24
Trimethoxy-benzaldehyde	0112	0.39
Methyl-(2,5-dimethoxyphenol)-methanoate	0112	0.31
4-Hydroxy-3-methoxy-benzaldehyde	0217	4.31
3,5-Di-tetra-butyl-4-hydroxybenzaldehyde	0116	0.42
Methyl(Z)-3,3-diphenyl-4-hexenoate	0202	2.00
3-(4-Methoxyphenyl)-2-ethylhexylester-2-propenoic acid	0112, 0202	0.01–2.78
3-(4-Methoxyphenyl)-2-propenoic acid	Most wells	0.06–0.16
Other aromatic compounds	Most wells	0.01–0.42
6. Non-aromatic compounds		
2,6-Bis(dimethylethyl)-2,5-cyclohexadiene-1,4-dione	0109, 0111, 0112, 0114, 0202	0.04–0.28
2,5-Cyclohexadiene-1,4-dione	0104, 0105, 0110, 0113, 0203	0.01–0.08
8-Isopropyl-2,5-dimethyl-terralin	0112	0.36
n-Hexadecanoic acid	0201, 0202	0.63–2.56
Phosphoric acid, tributyl ester	0201, 0203, 0210, 0217	0.10–18.96
2a,7a-(Epoxymethano)-2H-cyclobutyl	0201	0.33
Dodecanoic acid	Most 2001 wells, 0201, 0202, 0208	1.33–1.70
Tetradecanoic acid	0201, 0208	0.15–0.54
Bis(2-ethylhexyl)-hexanedioic acid	0201, 0208	0.13–0.70
1,2-Di-but-2-enyl-cyclohexanone	0201	0.09
2-[2-[4-(1,1,3,3-Tetramethylbutyl)phenoxy]ethoxy]-ethanol	Most 2001 wells, 0201, 0204, 0206, 0207, 0211, 0212	0.08–1.34
2-(2-Butoxyethoxy)-ethanol	0202	0.45
Butanoic acid, butyl ester	0202	0.44
Tricyclo[4.4.0.0(3,9)]decane	0202	0.26
Dimethyl-tetracyclo[5.2.1.0(2,6)-0(3,5)]decane	0202	0.27
7-Tetradecyne	0202	0.38
Tetradecane	0202	0.54
8-Hexadecyne	0202	0.28
Pentadecanoic acid	0202	0.84
2,6,10-Trimethyl-dodecane	0202	0.96
2-Methyl-8-propyl-dodecane	0202	0.52
1,2-Di-but-2-enyl-cyclohexane	0202	0.77
4-(4-Ethylcyclohexyl)-cyclohexene	0202	1.66
1-Butyl-2-ethyloctahydro-4,7-epoxy	0202	0.90
2-Methyl-nonadecane	0202	2.58
2-Dodecen-1-yl(−)succinic anhydride	0202	1.16
1-Nonadecene	0202	2.15
1,7,11-Trimethylcyclotetradecane	0202	1.06
Ethyl-cyclodocosane	0202	1.54
1-Docosene	0202	2.33
Tetracosane	0202	1.86
1-Hexacosene	0202	2.04
Docosane	0202	1.94
7-Bromomethyl-pentadec-7-ene	0202	2.77
Hexacosane	0202	1.73
2,6,10,14-Tetramethyl-hexadecane	0202	1.65
1-Chloro-octadecane	0202	2.12
Heptacosane	0202	0.95
(Z)-9-Tricosene	0202	0.98
Sterane	0202	0.51
Cholesterol	0208	0.26
Squalene	Most wells	Up to 0.24
Pentacosane	0202	1.54
Cyclotriacontane	0202	1.08
28-Nor-17.α.(H)-hopane	0202	1.26
Ethyl-cyclodocosane	0202	0.65
28-Nor-17.α.(H)-hopane	0202	0.84
1,7,11-Trimethyl-cyclotetradecane	0202	0.47



Compounds by class	Well number (from Table 1)	Conc. range (μg/L)
1. Polycyclic aromatic hydrocarbons		
Naphthalene	0116, 0117	0.26–0.66
Methylnaphthalene	0111, 0112, 0116, 0117, 0202	0.14–0.48
Dimethylnaphthalene	0111, 0112, 0114, 0115, 0117, 0202	0.01–1.44
Trimethylnaphthalene	0111, 0112, 0115, 0117, 0202	0.04–2.60
Tetramethylnaphthalene	0112, 0115	0.43–0.79
Methylethylnaphthalene	0112	0.55
1,6-Dimethyl-4(1-methylethyl)naphthalene	0113, 0114, 0118, 0202, 0205, 0213, 0216	0.01–0.32
Tetrahydronaphthalene	0117, 0202	0.06–0.82
Tetrahydromethylnaphthalene	0112, 0115, 0202	0.01–0.69
Tetrahydro-dimethylnaphthalene	0112, 0117, 0202	0.19–3.25
Tetrahydro-trimethylnaphthalene	0112	0.50
Ethyl-tetrahydronaphthalene	0112	0.46
Naphthalenone derivative	0202, 0203, 0205, 0206, 0216	0.11–1.38
Other naphthalene alkyl compounds	0203, 0204, 0205, 0207, 0212, 0213, 0214	0.04–0.82
Methoxynaphthalene derivative	0113, 0205	0.04–0.25
2,4,6-Trimethyl-azulene	0202	0.49
Ethyl dimethyl azulene	0112	0.46
5,6-Azulenedimethanol, 1,2,3,3a,8,	0201	0.40
4,6,8-Trimethyl-2-propylazulene	0202	0.40
Tetramethylacenaphthylene	0112, 0115	0.03–0.07
Phenanthrene	0108, 0112, 0114, 0115, 0117, 0202	0.06–0.52
Methylphenanthrene	0108, 0112, 0115, 0117, 0201, 0202	0.03–1.37
Dimethylphenanthrene	0112, 0115	0.62–1.49
Trimethylphenanthrene	0112, 0115	0.04–0.12
Tetramethylphenanthrene	0101, 0112, 0114, 0115, 0117, 0118, 0201	0.01–0.68
Dihydrophenanthrene	0105, 0202	0.03–0.48
Tetrahydrophenanthrene	0112, 0115	0.03–0.42
Dihydro-1-methylphenanthrene	0112	1.06
7-Ethenylphenanthrene	0107, 0108, 0112	0.04–0.22
Phenanthrene derivative	0213	0.07
1-Methyl-7-(1-methylethyl)phenanthrene	0107, 0202, 0207, 0209, 0211, 0216	0.02–3.19
Phenanthrene-1-carboxlic acid	0101, 0107, 0108, 0110, 0111, 0112, 0201, 0203, 0206	0.02–0.12
1,1-Dimethyl-1,2,3,4-tetrahydro-7-isopropyl phenanthrene	0114, 0118	0.19–0.68
Phenanthrenone	0110, 0111, 0205, 0210	0.05–0.09
Methylanthracene	0112, 0115, 0117	0.07–0.48
Methoxyanthracene	0112, 0115	0.04–0.22
Octahydroanthracene	0112	0.54
9,10-Dimethoxy-2,3-dihydroanthracene	0207, 0213	0.04–0.34
1-Ethyl-9,10-anthracenedione	0102, 0103, 0209	0.04–0.12
Fluorene	0112, 0117	0.05–0.24
9-Methoxyfluorene	0112, 0115	0.06–0.18
Methyl-9H-fluorene	0112, 0115	0.52–1.16
9-Methoxyfluorene	0202	0.54
1-Methyl-9H-fluorene	0202	0.51
9H–Fluoren-9-ol	0112, 0117	0.07–0.32
Pyrene	0101, 0112, 0215	0.01–0.04
Methylpyrene	0112, 0115	0.01–0.02
Dimethyl-ethylindene	0109, 0110	0.02–0.07
5-(1,1-Dimethylethyl)-1H-indene	0104, 0111	0.03–0.10
2,3-Dihydro-1,1,2,3,3-pentamethyl-1H-indene	0202	0.45
Other indene derivatives	0213, 0215	0.09–0.16
2. Heterocyclic compounds		
4-Propyl-xanthen-9-one	0104, 0108	0.03–0.07
9-Phenyl-tetrahydro-1H-benz[f]isoindol-1-one	0107	0.24
Benzisothiazole derivative	0203, 0204, 0207, 0210, 0211	0.06–0.32



Compounds by class	Well number (from Table 1)	Conc. range (μg/L)
Methyl-2-octylcyclopropene-1-octane	0202	0.38
7-Bromomethyl-pentadec-7-ene	0202	0.92
22-Tricosenoic acid	0202	0.43
2-Octadecyl-propane-1,3-diol	0202	0.42
15-Isobutyl-(13.α.H)-isocopalane	0202	1.75
Tricosane	0202	1.70
17-Pentatriacontene	0202	1.00
Tridecanedial	0202	0.86
Isopropyl myristate	0202	1.79
Dihydro-(−)-neocloven-(II)	0202, 0216	0.10–1.04
Kaur-16-ene	0202, 0207, 0211, 0212. 0213	0.06–1.36
Other terpenoid compounds	Most wells	0.12–0.37

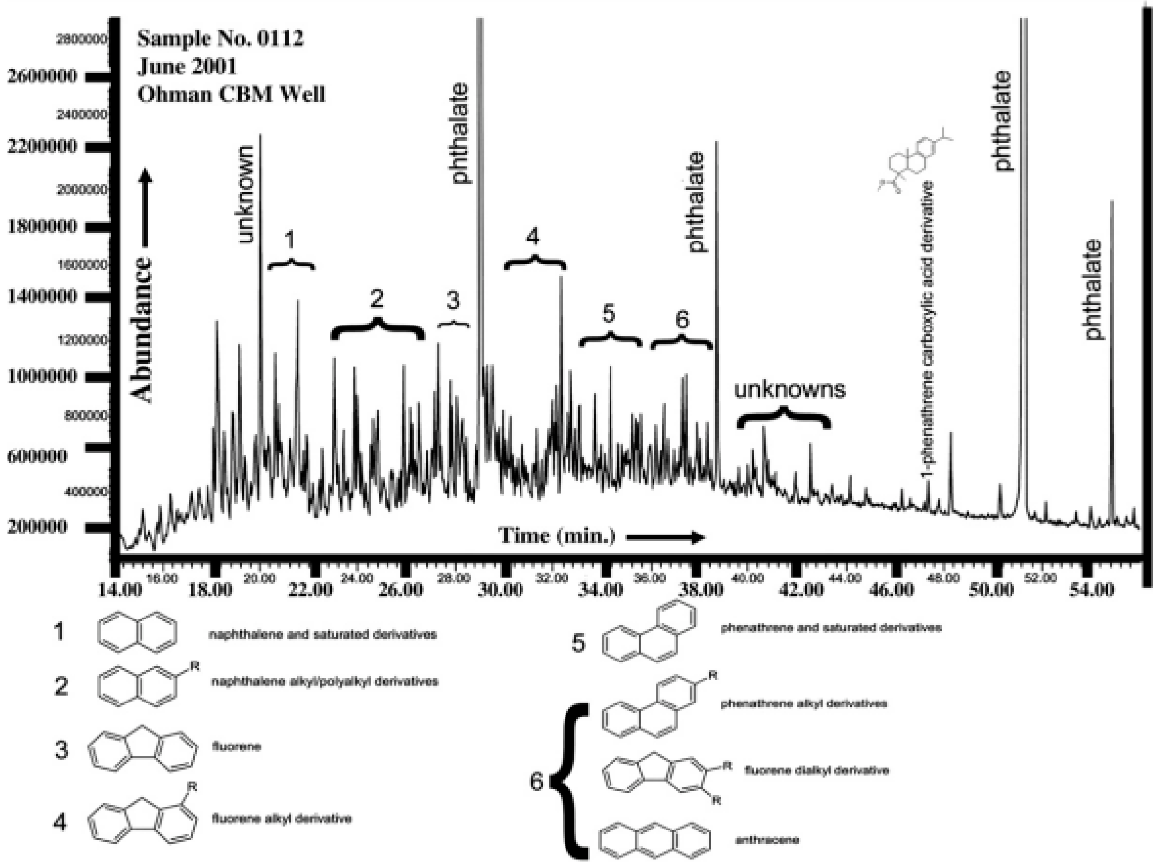


Figure 10: GC-MS TIC chromatogram of a dichloromethane (DCM) extract of produced water from well 0112, showing identified polycyclic aromatic hydrocarbons (Orem et al., 2007).

5.3 New Zealand coal provinces

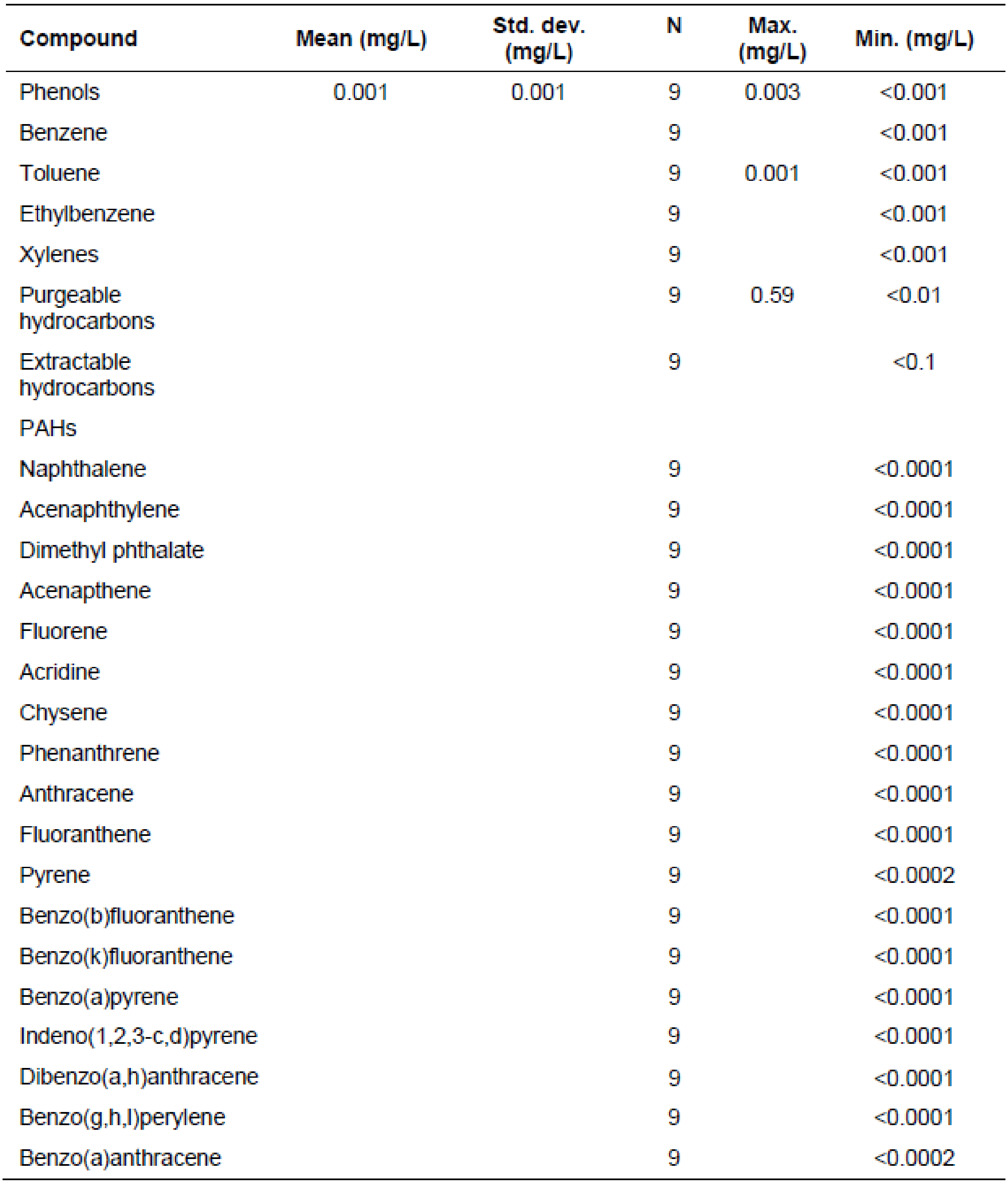
A study of the organic chemical composition of groundwater from the Maramarua coalfield in the north island of New Zealand was undertaken by Taulis and Milke (2007). The Palaeogene coals in the area are subbituminous with low ash and sulphur contents. Although the study focused on mainly inorganic constituents, total petroleum hydrocarbons were also analysed. The reported TPH concentrations were as follows: C7-C9 (<0.03 mg/L), C10-C14 (<0.05 mg/l), C15-C36 (<0.1 mg/L), and total hydrocarbons (<0.2 mg/L).

5.4 Canadian coal provinces

A study of drinking water samples collected from water supply wells and lakes in the Sydney Basin, Nova Scotia, Canada was undertaken by Goodarzi and Mukhopadhyay (2000). Three water samples had elevated concentrations of various PAHs compared to detection limit. All samples were collected from the Upper Carboniferous Sydney Mines Formation and the South Bar Formation. There are 12 distinct coal seams within these formations, and all coals are of bituminous rank, with the majority of them being high to medium volatile bituminous. The authors attributed the presence of PAHs to the leaching of coal during the early depositional phase.

The Alberta Geological Survey, with support from the Alberta Energy Research Institute, has created a public domain database of high quality chemical analyses of groundwater from water supply wells known or strongly suspected to be completed in coal seams. The samples were collected in 2002 from three coal-bearing geological intervals in the Alberta Basin: the Cainozoic Paskapoo Formation, Cretaceous Scollard Formation, and the Late Cretaceous Horseshoe Canyon Formation. Inorganic and organic hydrochemistry, and isotope data for these formations are published in Lemay and Konhauser (2006). Organic chemistry results are summarised in Table 32.

Table 32: Organic chemistry results for Scollard and Paskapoo Formations. Concentrations are in mg/L. Source: Lemay and Konhauser (2006).



Compound	Mean (mg/L)	Std. dev. (mg/L)	N	Max. (mg/L)	Min. (mg/L)
Phenols	0.001	0.001	9	0.003	<0.001
Benzene			9		<0.001
Toluene			9	0.001	<0.001
Ethylbenzene			9		<0.001
Xylenes			9		<0.001
Purgeable hydrocarbons			9	0.59	<0.01
Extractable hydrocarbons			9		<0.1
PAHs					
Naphthalene			9		<0.0001
Acenaphthylene			9		<0.0001
Dimethyl phthalate			9		<0.0001
Acenapthene			9		<0.0001
Fluorene			9		<0.0001
Acridine			9		<0.0001
Chysene			9		<0.0001
Phenanthrene			9		<0.0001
Anthracene			9		<0.0001
Fluoranthene			9		<0.0001
Pyrene			9		<0.0002
Benzo(b)fluoranthene			9		<0.0001
Benzo(k)fluoranthene			9		<0.0001
Benzo(a)pyrene			9		<0.0001
Indeno(1,2,3-c,d)pyrene			9		<0.0001
Dibenzo(a,h)anthracene			9		<0.0001
Benzo(g,h,I)perylene			9		<0.0001
Benzo(a)anthracene			9		<0.0002

6 Conclusion

Water soluble organic compounds such as BTEX, phenols and polyaromatic hydrocarbons have been encountered in groundwaters in Australian basins. In most cases, they were detected at low concentrations, below the detection limit or below the LOR. In many cases the origin of these organic components is unclear. Some of the detected compounds, such as halogenated phenols have no natural origin from coal. They may indicate contamination from other sources either before collection of the sample or during collection and/or analysis. Other compounds that may be encountered in CSG operations, such as BTEX and PAH, may be derived from coal. Despite the aromatic nature of coals, reports on BTEX and other organics associated with CSG are sparse. The results of this review indicate that there is a need for further baseline monitoring and evidence-based research within the Bowen and Surat basins and elsewhere to adequately identify the origin of many of the organic components and assess any potential environmental impacts.

7 Recommendations

On the basis of the literature review undertaken here three preliminary recommendations can be made:

- There should be an emphasis on the identification and establishment of natural background concentrations of organic compounds in water associated with Australian coal basins. This should also include a systematic study of the relationship of organics in water with coal type, rank and microbial processes.
- In addition to baseline data, periodic monitoring of organic compound concentrations throughout the production life of a gas well would assist in building a suitable database to better understanding the occurrence and distribution of these compounds in deep groundwater systems throughout the CSG production cycle.
- Effort should be devoted to fingerprinting of aromatic compounds in coals and how these translate into fingerprints leached into groundwater. This may offer a way to trace organics in future studies and to better differentiate natural and anthropogenic compounds.

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