Klohn Crippen Berger
65 years of service

CSG Compliance Unit

Department of Natural Resources and Mines

Potential effects of free gas on bore water supply from CSG development

Final Report

Canada's Best Managed Companies Platinum member

ISO 9001
ISO 14001
OHSAS 18001

D10058A01

March 2016

Klohn Crippen Berger
65 years of service

March 11, 2016

CSG Compliance Unit
Department of Natural Resources and Mines
61 Mary Street
Brisbane
QLD 4000

Mr. David Free
Chief Hydrogeologist, Groundwater Investigation & Assessment

Dear Mr. Free:

Report on potential effects of free gas on bore water supply from CSG development

Klohn Crippen Berger (KCB) is pleased to provide the CSG Compliance Unit (CSGCU), Department of Natural Resources and Mines (DNRM) with this report on the potential effects of free gas on bore water supply from CSG development in the Surat Basin.

I trust this report meets your requirements. Thank you for the opportunity for involvement with this project.

Yours truly,

KLOHN CRIPPEN BERGER LTD.

Sanjeev Pandey
Senior Hydrogeologist

160311R Final Report.docx
D10058A01

EXECUTIVE SUMMARY

Context

Klohn Crippen Berger Ltd (KCB) has prepared this report for the Coal Seam Gas Compliance Unit (CSGCU) of the Queensland Department of Natural Resources and Mines (DNRM). The report is an overview of potential effects of free gas on bore water supply from CSG development in the Surat Basin.

Impacts of CSG development on groundwater in Queensland are managed through a regulatory framework which, amongst other things, requires 'make-good' of water bores that are likely to be impacted. A water level decline of more than 5 m for consolidated aquifers and 2 m for unconsolidated aquifers is used to define impact areas for each aquifer within which water bores tapping the aquifer are considered potentially impacted bores.

A bore assessment of potentially impacted bores is required by the tenure holders, which determines whether make-good measures are required. CSGCU is receiving complaints from bore owners about the free gas in water bores and the impacts the free gas has on the capacity of water bore to supply water. To address this, the CSGCU commissioned KCB to compile a summary of scientific background about the potential effects that free gas can have on a bore's capacity to supply water in the context of CSG development in the Surat Basin.

Approach

The review presented in this report is a desktop assessment based on a focused literature review and application of scientific principles.

CSG is produced by depressurising the Walloon Coal Measures in the Surat Basin. Once the free gas is available in the formation (source), it is then available to migrate to CSG production wells or as a 'stray' or 'fugitive' gas away from the CSG wells (cause). Some of the free gas may end up in water wells and could potentially affect pump infrastructure and water supply (effect). The review and report structure, therefore, follows this source, cause and effect sequence.

There is a general lack of reported studies about the impacts of free gas on water bores. Methane gas presenting at water supply bores is a common problem faced in many sedimentary basins in the USA, Canada and more recently in the Surat Basin where the basins are exploited for CSG (or coalbed methane), tight gas or conventional gas. Primary focus of these studies has been on establishing the source of such gases – i.e. whether the free gas is thermogenic (originating mainly from coal or CSG) or biogenic (non-CSG sources derived from biological decomposition).

Source of free gas (Source)

In the context of CSG development, the free gas is primarily composed of methane. Methane in water bores could be either from biogenic sources (non-CSG) or from thermogenic sources such as CSG. Depressurisation of coal seams is the main process by which the CSG is intentionally released and commercially captured. Similar processes also occur at a smaller scale during extraction of water from water bores causing unintentional depressurisation and release of free gas at smaller scale. Many such instances have been recorded in the Surat Basin.

During CSG production, as the target coal formation is depressurised, methane transfers from the coal surface to the dissolved phase in groundwater. With decrease in pressure, the free gas is also released because the solubility of gas is lower at lower pressure. At this stage the reservoir is saturated for gas and methane is present as a dissolved gas in groundwater, and as free gas within the pores of the rock formation - a two phase flow occurrence.

Potential migration of free gas to water bore (Cause)

Once free gas is formed, it is available to migrate. Groundwater (containing some dissolved gases) flows from high pressure to lower pressure, but free gas flow is driven by two factors: pressure difference (or pressure gradient); and buoyancy force.

Pressure gradient drives gas from high pressure to low pressure if a continuous free gas path is available. At the same time buoyancy force allows free gas to rise upward through the formation because gas is lighter than groundwater. Buoyancy force will lift the gas to surface unless the upward movement of gas is stopped by physical barrier of low permeability geological formations.

Pathways are the route or conduit through which free gas moves from one part of the aquifer to another, or to the surface and water bores. Natural pathways for free gas migration include vertical and sub-vertical fractures, geological faults and high vertical permeability units. Anthropogenic pathways include wells, water bores and exploration holes.

Because of the buoyancy, gas bubbles can escape along bedding planes away from the gas filed in an up-dip direction where pressure gradient is low or negligible. Conceptually free gas can also migrate to water bores that are situated at large distances up-dip of the producing CSG well in formations above the CSG target formations. Gas migration to water bores can occur through existing wells, water bores and exploration holes that are improperly constructed or maintained (bores with compromised integrity) or through water bores that access water from the formations to which gas has migrated to. A number of investigations in USA and Canada have established bores and wells as pathways for gas migration to water bores, and to the ground surface.

In most instances CSG-induced free gas in water bores is likely to correspond to areas where decline in water levels from CSG development has occurred or likely to occur. Conceptually there are instances where free gas in water bores may occur despite there being no decline in water level in that bore. This may be in the CSG target formations as well as in overlying formations around the CSG development areas which may or may not be affected by water level decline. This may also be along the margins of the CSG development areas in up-dip direction. A number of cases of water level rises in bores are recorded in the Surat Basin which correspond to intermittent release of free gas from the bores.

Impacts on bores water supply (Effect)

Free gas, particularly methane, in a water bore is more than just nuisance. It directly affects the bore's capacity to provide water supply for the intended purpose unless, where possible, remedial actions are taken. A bore's capacity to supply water can be affected in the following ways:

- Free gas hampers pumping operations and damages pumps and infrastructure, potentially resulting in costly operations and replacements. Damages occur through gas locks, cavitation and overheating.

- Free gas in the formation around a water bore provides a resistance to flow of water (i.e. reduces the water permeability) to the bore and reduces bore's designed capacity or bore yield.
- Free gas affects water quality in bores by creating turbid water, sediment movement and potentially leading to formation of gases such as hydrogen sulfide.
- Free gas contains methane which can burn and can be explosive – posing difficulties in running and maintenance of bore and leading to bore abandonment in extreme cases.

Conclusions

The focus of this review is on the possibility that, if free gas from CSG development does migrate to a water bore than, how it can impact on a bore's capacity to supply water. The two fundamental questions in this context are:

1. could there be free gas when there is no decline in water level in that bore from CSG development; and
2. could the presence of free gas affect the capacity of that bore to supply water?

An assessment of literature and application of scientific principles suggests that conceptually, simple answer to each of these questions is 'yes'. Free gas from CSG development can occur in water bores that do not experience a water level decline from CSG development. Presence of free gas in a water bore also directly and indirectly affects its capacity to supply water, unless remedial actions are taken.

The conclusions are largely based on conceptual understanding drawn from scientific principles and some related examples. More specific assessments and investigations of some representative water bores where free gas is reported, or is likely to occur, will provide greater insight into the matter.

TABLE OF CONTENTS

EXECUTIVE SUMMARY I

1 INTRODUCTION 6
- 1.1 Background 6
- 1.2 Objective and Scope 6
- 1.3 Approach and Report Structure 7
- 1.4 Information and Data Sources 7
- 1.5 Contextual Terminology 8

2 SOURCES AND PATHWAYS FOR GAS MIGRATION TO WATER BORES 9
- 2.1 General 9
- 2.2 Availability of Free Gas 9
- 2.3 Migration of Free Gas 9
- 2.4 Gas Pathways to Water Bores 12
- 2.5 Relationship between the Water Levels in Bores and Free Gas Migration 13

3 IMPACTS ON BORES' CAPACITY TO SUPPLY WATER 15
- 3.1 General 15
- 3.2 Damage to Pumps and Bore Infrastructure 15
  - 3.2.1 Background 15
  - 3.2.2 Types of Damage from Free Gas 16
- 3.3 Reduction in Water Availability 18
- 3.4 Impact on Water Quality 18
- 3.5 Impact on General Safety 19

4 RELATED CASE STUDIES 20
- 4.1 General 20
- 4.2 Surat Basin, Queensland 20
- 4.3 Northeastern Pennsylvania, USA 20
- 4.4 San Juan and Raton Basins Colorado, USA 21
- 4.5 New York State, USA 21
- 4.6 Alberta, Canada 22

5 CONCLUSIONS 23
- 5.1 General 23
- 5.2 Free Gas vs Water Level 23
- 5.3 Impacts on Water Bores 24
- 5.4 Overall Conclusion 24

6 CLOSING 25

REFERENCES 26

TABLE OF CONTENTS
(continued)

List of Figures

Figure 1. Schematic of potential gas migration (reproduced from APLNG, 2010). 11
Figure 2: Schematic representation of CSG pathways via bores and faults (Mallants & Raiber, 2016). Pathway (1) refers to gas migration into water bores via corroded bore casing while pathway (2) refers to gas flow through fractures/degraded bore seals 13
Figure 3: Example of cavitation damage in a pump impeller (Source: www.waterworld.com) 17

1 INTRODUCTION

Klohn Crippen Berger Ltd (KCB) was commissioned to provide a report to the Coal Seam Gas Compliance Unit (CSGCU) of the Queensland Department of Natural Resources and Mines (DNRM), about potential effects of free gas on bore water supply from CSG development in the Surat Basin.

This report is prepared in accordance with the scope and agreed contract conditions under the Standing Offer Arrangement DSITIAD01.

1.1 Background

Impacts of CSG development on groundwater in Queensland are managed through a regulatory framework which, amongst other things, requires 'make-good' of water bores that are likely to be impacted. A cumulative assessment and management framework is also in place whereby extensive development areas are established as cumulative management areas (CMAs). Queensland's Office of Groundwater Impact Assessment (OGIA) publishes an Underground Water Impact Report that provides an assessment of cumulative impacts and identifies water bores that could be potentially impacted. A drawdown of more than 5 m for consolidated aquifers and 2 m for unconsolidated aquifers is used to define impact areas for each aquifer within which water bores tapping the aquifer are considered potentially impacted bores. Individual tenure holders are eventually responsible for assessing those bores (bore assessment) and follow-up make good arrangements, if needed. Implementation of the framework is facilitated by the CSGCU.

A bore assessment of potentially impacted bores is required to establish whether the bore has an impaired capacity or is likely to start having an impaired capacity in the future as a result of CSG development. The bore assessment determines whether make-good measures are required. There are also provisions for the regulator to direct bore assessment in areas outside the predicted impact area if the regulator believes that a bore's water supply could be negatively impacted.

The fundamental premise for make-good arrangement is the 'impaired capacity'. Under the framework, a bore is impaired if:

- there is a decline in the water level of the aquifer at the location of the bore because of the exercise of underground water rights; and
- because of the decline, the bore can no longer provide a reasonable quantity or quality of water for its authorised use or purpose.

The majority of bore complaints received by CSGCU involve issues relating to free gas in water bores and the impacts the free gas had been having on the capacity of water bore to supply water. Some ambiguity has also emerged in terms of the extent to which the make-good arrangements in the legislation deals with the free gas issues. To address this, the CSGCU has commissioned KCB to compile a brief scientific background report about the potential effects that free gas can have on a bore's capacity to supply water in the context of CSG development in the Surat Basin.

1.2 Objective and Scope

The key objective of the project is to provide scientific background regarding how free gas in a water bore could potentially affect the capacity of the bore to supply water.

More specifically the scope includes: a rapid review of relevant documents; focused discussions with the CSGCU; a literature survey of reported cases of affected bores from free gas; conceptual understanding of free gas movement in a reservoir; and synthesis of collected information with reporting.

The scope of this assessment does not include: field investigations; analysis of data; analysis of policy or legislative framework; and assessment of potential areas or bores that could be affected by free gas.

1.3 Approach and Report Structure

The review presented here is a desktop assessment based on a focused literature review[1] and application of scientific principles.

CSG is produced by depressurising the Walloon Coal Measures in the Surat Basin. Once the free gas is available in the formation (source), it is then available to migrate to CSG production wells or as a 'stray' or 'fugitive' gas away from the CSG wells (cause). Some of the free gas may end up in water bores and could potentially affect the pump infrastructure and water supplies (effect).

The report structure follows this source, cause and effect sequence. Chapter 2 of the report provides an overview of the conceptual understanding of gas migration and potential pathways (source and cause). Chapter 3 provides technical background about the potential effect that free gas can have on water bores (effect). Chapter 4 presents a summary of some relevant case studies. Conclusions of the assessment are provided in Chapter 5.

The report is deliberately written for a broader target audience. Therefore, as far as possible, complex technical terms and details are omitted to the extent possible.

1.4 Information and Data Sources

In general there is a lack of reported studies about the impacts of free gas on water bores. CSG and other unconventional petroleum and gas development is at a relatively mature stage in America, Canada and has evolved rapidly in Australia. In general, theoretical understanding of the genesis and migration of CSG, together with some assessment of groundwater impacts, is well reported in scientific literature. The primary focus of most studies and reporting relating to fugitive gas has been on establishing the source of such gases – i.e. whether the fugitive gas is thermogenic (originating mainly from coal or CSG) or biogenic (non-CSG sources derived from biological decomposition).

As part of the review, we have not been able to cite any specific study about the impact of free gas on a bore's capacity to supply water. Therefore, the assessment presented here has drawn mainly from basic scientific principles relating to movement of free gas in the sub-surface and operations of water pumps, supplemented with related examples in reported literature and focused discussions with industry representatives.

[1] The literature review is focused on readily available publicly reported studies and secondary references instead of review and analysis of complaints and outcomes that may be recorded in various databases by government and private agencies. It is believed that, to a larger extent, publicly reported studies have already captured the primary search of such databases and their analysis.

CSIRO undertook a two stage literature review for the CSGCU in 2014 and 2015 [(Mallants & Raiber, 2016) (Walker & Mallants, 2014)] to support decision making for investigating complaints about gas in water bores. One of the focuses of the CSIRO work was on sampling and analysis for identifying the source of methane and a decision support system to classify potential risks to bore. The report has drawn heavily from this work where relevant.

1.5 Contextual Terminology

For easy referencing, some of the common terms and the context in which they are referred in the report are as below.

‘Bore’ is a reference to water bore.

‘Well’ is a reference to CSG production or exploration well.

‘Bores with compromised integrity’ is a reference to wells, water bores and exploration holes that have their integrity compromised in terms of isolation of fluids from one formation to another or from ground surface. This could be due to inappropriate construction or poor maintenance of wells and bores.

‘Free gas’ is a reference to gas derived from CSG operations as a result of depressurisation of coal seams in the Surat Basin, which is the Walloon Coal Measures[2]. Methane is the largest component of this free gas. Unless specified, a reference to ‘gas’ is also a reference to free gas.

‘Fugitive or stray gas’ is a reference to gas that is generated from CSG depressurisation but is not captured by CSG wells during production or testing.

‘Dissolved gas’ is a reference to gas dissolved in groundwater. Dissolved gas can become free gas depending upon a number of factors – most important of these factors is the pressure. A drop in pressure causes dissolved gas to become free gas.

‘Pathways’ is a reference to fractures, joints, high permeability zones and faults that exists in a geological formation and which can or may facilitate gas movement.

‘Target formation’ is a reference to coal seam bearing formations that are directly targeted for CSG development.

‘Formation’ is a reference to a geological formation which hydrogeologically may be an aquifer or aquitard.

‘Gas field’ is a reference to a group of CSG wells in close proximity that are used for commercial CSG production.

‘Gas reservoir’ is a reference to a pool of CSG in a gas field contained, typically, in a sub-surface target formation – such as the Walloon Coal Measures.

[2] Free gas can also originate from non-CSG operations, such as the lowering of pressure by bores or pressure changes in aquifers from climatic variations. However, in the context of this report a reference to free gas is the free gas generated from CSG operations, unless specified otherwise.

2 SOURCES AND PATHWAYS FOR GAS MIGRATION TO WATER BORES

2.1 General

This chapter provides a conceptual overview of how CSG is freed up or produced from the formations and the factors that affects its migration once it is available as free gas. It is only a conceptual overview to provide a context in terms of source and cause for free gas to describe the free gas effect on water bores in Chapter 3. Detailed technical discussion on the matter is available from other researchers and studies such as by Walker & Mallants (2014), Gorody (2012), Baldwin & Thoms (2014), Worley Parsons (2009) and Moore (2012).

2.2 Availability of Free Gas

Methane is the predominant constituent of CSG in the Surat and Bowen basins. Methane can be present as dissolved gas and free gas depending on the methane solubility, the formation pressure and temperature. In the context of the Surat Basin, the solubility and the pressure are the two key factors. At high pressure more gas is dissolved in water (i.e. soluble) and as the pressure decreases, the solubility also decreases releasing free gas from water. At ground surface methane solubility is very low at about 25 - 32mg/L (Gorody, 2012). Typically with every increment in water depth of 10 m, another 25 mg/L of methane can be dissolved in water.

During CSG production, as the target coal formation is depressurised, methane transfers from the adsorbed phase (i.e. gas which is attached to coal surface) to the dissolved phase in groundwater. With further decrease in pressure, the free gas is released (i.e. exsolves) because the solubility of gas is lower at lower pressure. This process is also referred to as 'degassing' in common terminology. At this stage the reservoir is saturated and methane is typically present as a dissolved gas in groundwater, and as free gas within the pores of the rock formation (hence two phase flow or dual-phase flow). Continuing pumping of groundwater will lead to even lower pressure in the formation and will facilitate release of more free gas. The free gas is then captured by the CSG wells.

At a smaller scale, a similar process can also happen in and around a water supply bore in target formations (Walker & Mallants, 2014). As the water is pumped from a water supply bore, the pressure around the water bore drops and gas can be released from the water. Many such instances are reported in the Surat Basin prior to CSG development going back 100 years from CSG formations as well as from other formations (CSIRO, 2014). However, compared to the scale of depressurisation in a CSG reservoir, the relative pressure drop in a water supply bore is typically much smaller and laterally less extensive.

2.3 Migration of Free Gas

Once free gas is available, it is able to migrate. Groundwater and dissolved gases move from high pressure to lower pressure (advection process). However, free gas flow is driven by two factors: pressure difference (or pressure gradient) through advection process; and buoyancy force.

Pressure gradient drives gas from high pressure to low pressure – similar to groundwater flow if a continuous free gas pathway is available. The higher the pressure gradient, the greater the driving force. At the same time buoyancy forces tend to make the gas rise upward through the formation because gas is lighter than groundwater. Buoyancy force will lift the gas to surface unless the upward movement of gas is stopped by physical barriers of low permeability geological formations, impermeable structures, or the overlying formation pressure.

In the vicinity of a producing CSG well, the two forces may work against each other (buoyancy in upward direction and pressure gradient along a downward sub-vertical direction). The relative strengths of these forces control whether the gas is captured by a CSG well (or a pumping bore) or escapes away through permeable zones including fractures, bedding planes or other conduits as fugitive gas.

In relation to gas migration, conceptually there are three broad zones – starting from CSG wells to the edge of a gas field.

1. Closer to a CSG wells – the primary driving force is through the very steep pressure gradient that exist in this zone toward the wells at a steep downward angle. Due to high pressure gradient, the driving force from form this pressure gradient easily overcomes the upward buoyancy force and as a result nearly all adjacent free gas is captured by the wells.

2. Between the CSG wells and the margins of the gas field - the pressure gradient gradually decreases away from the CSG wells and the buoyancy force starts to dominate. In this zone any bore or well open to the target formation will provide a pathway for gas to move up vertically.

3. Towards the margins of the gas field - the pressure gradient is minimal and, if the gas has desorbed, the buoyancy forces may dominate. This can drive the gas vertically and laterally away from the gas filed if a pathway exists (fugitive gas). Fractures or high permeability zones along a low dipping geological formation can easily provide such a pathway in the up-dip direction, e.g. the formations of the Surat Basin (Worley Parsons, 2013).

A good schematic of gas movement in relation to a CSG production field is presented in Figure 1 (APLNG, No date).

Specific estimates of how far the fugitive gas can migrate to surface or water bores from a CSG well or well field are in the Surat Basin. Such distances will depend on a multitude of complex factors driven primarily by the variability in geological formations, geological structures and pressure regime. Baldwin and Thomson (2014) have estimated that methane would probably travel no further than 10-15 km from a CSG well via buoyancy in the case of an upward geological dip. On this basis, Mallants & Raiber (2015) suggested 10 km as the distance beyond which the risk to water bores from CSG development will be minimal in the Surat Basin.

Blyth (2007), in investigating a complaint of increased methane in a water bore in Alberta from a nearby CSG development, assessed the potential of gas migration to overlying aquifer – specifically an estimate of downward groundwater flow velocity that is needed to stop a gas bubble rising upward due to buoyancy force. The assessment implied that for a bubble of 0.1 mm radius, a downward groundwater flow velocity of 1,800 m/day will be required to stop the bubble rising up - a nearly impractical scenario to occur in natural groundwater systems. This also suggests that downward groundwater flow movement through a formation does little to stop the upward rise of gas.

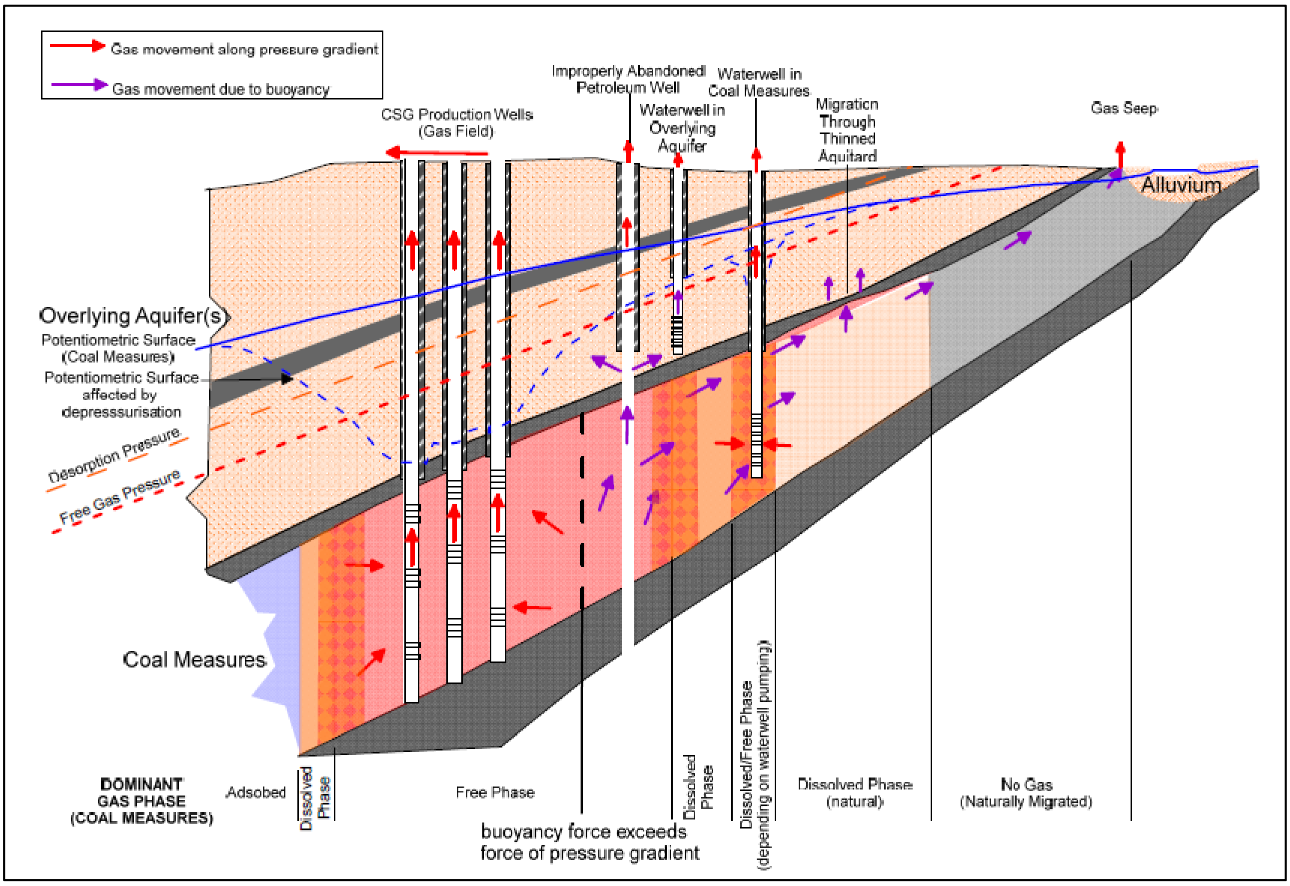

Figure 1. Schematic of potential gas migration (reproduced from APLNG, 2010).

Migration of gas under the buoyancy forces is not continuous and rather happens in pulses. Pulsed migration is a dynamic process of free gas movement through air pathways which intermittently open and close in response to subtle changes in pressure regime which may be triggered by climatic variations, recharge events and other factors in confined parts of the aquifers. Baldwin and Thomson (2014) reports that natural climate variability may significantly influence free gas migration via rising and falling water tables, release of free gas at springs, and trapping of gas by capillary forces. Once the source of gas pressure is mitigated, maximum headspace gas concentration also rapidly declines in a series of pulses. Due to this, free gas that finds its way to the surface or bores, also tends to be variable in concentrations and in intermittent occurrence (Gorody, 2012), (Baldwin & Thomson, 2014).

Another factor that affects the movements of gases in subsurface is shutting the CSG wells on and off. If CSG wells are shut off for a period of time during production or testing then the primary driver for the gas movement is the buoyancy force. Some gas is dissolved back again in the water, due to rebuild-up of pressure. However, a significant amount of gas from the reservoir can still potentially move away in up-dip direction and find its way to surface through various pathways in areas away from gas fields.

Presence of two phases (gas and water) in a subsurface environment, combined with upward movement of free gas, can also potentially replace the water upward in some circumstances resulting in a rise in water levels and associated expulsion out a mixture of water and gas from the bore at the surface. This is likely to happen in a low pressure environment where a water column is lifted and promotes artesian like flow (Walker & Mallants, 2014). It is worth noting that the water level in such instances is not the water level from a formation saturated with groundwater as is commonly referred, but rather represents pressure from a formation with two phases. A number of cases of rises in water level are reported by Origin Energy on the eastern margins of their Orana gas field in the Surat Basin where water levels have risen by more than 30 m in some instances (pers. comm. CSGCU).

2.4 Gas Pathways to Water Bores

Pathways are the route or conduit through which free gas moves from one part of the geological formation to another. As discussed in the previous section, there is a continuum between the CSG wells and the margins of the gas field in terms of the relative dominance of forces that drive the free gas. Whether the gas migrates to surface or not, depends upon the availability of pathways, their angle and distance from source.

Natural pathways for free gas migration include vertical and sub-vertical fractures, geological faults and high permeability bedding plains or zones in geological formations. Anthropogenic pathways include wells, water bores and exploration holes that have their integrity compromised in terms of isolation from one formation to another or from ground surface. This could be due to inappropriate construction or poor maintenance of wells and bores. If gas moves into other formations, properly constructed bores and wells in that formation may also provide a pathway for gas to migrate to surface.

Mallants and Raiber (2015) and Baldwin and Thomson (2014) note that the natural pathways can be tortuous depending on the horizontal and vertical permeability of the formations it passes through, plus the dipping nature of the strata, as well as sudden changes in permeability that create conduits (e.g. zone of fractured rock including bores with compromised integrity) or barriers (e.g. faults). Up-dip migration via the more permeable beds of the Walloon Coal Measures and Springbok Sandstone is a likely natural pathway (Baldwin & Thomson, 2014).

A simplistic analysis of movement of gases suggests that gas bubbles can escape along the low dipping formation bedding planes away from the field in an up-dip direction where pressure gradient is low or negligible. Highly inclined fractures can also provide a vertical pathway (Walker & Mallants, 2014). Gas will preferentially invade the largest pore spaces that have the lowest threshold capillary pressures (Walker and Mallants, 2014). Permeable horizontal bedding planes can often have a large pore network allowing for free gas to migrate both laterally and vertically due to buoyancy (Walker and Mallants, 2014).

Mallants and Raiber (2015) present a conceptual model for gas migration between a CSG well and a domestic water bore. This conceptual model shows that gas can migrate to water bores that are situated at large distances up-dip of the producing CSG well. This gas flow is not part of a groundwater flow system and is purely controlled by the forces of buoyancy. The conceptual model also shows that gas can flow to both the CSG well and water bore as a result of groundwater depressurization.

Existing wells, water bores and exploration holes can provide unintentional openings through the cement grouts, casing walls, screens across multiple formations or open holes. Such openings not only provide pathways to groundwater but also provide pathway to vertical movement of free gas from one formation to another or from subsurface to surface. Mallants & Raiber (2015) have presented a schematic of preferential pathways through bores with compromised integrity and faults (Figure 2).

Several investigations in the USA and Canada have established bores and wells as pathways for gas migration to water bores and to the ground surface. In the San Juan Basin where CSG development has been occurring since 1990, investigations on complaints about the methane in water bores have established that existing wells and bores with compromised integrity have provided a pathway to CSG into water bores in some cases (Baldwin & Thomson, 2014). In Pennsylvania, contamination to water bores from shale gas development is reported. A study to assess the source of the gas established that shale gas may have found its way to drinking water supply bores through faulty and inadequate casing and well design and imperfections in cement casings (Jackson, et al., 2013).

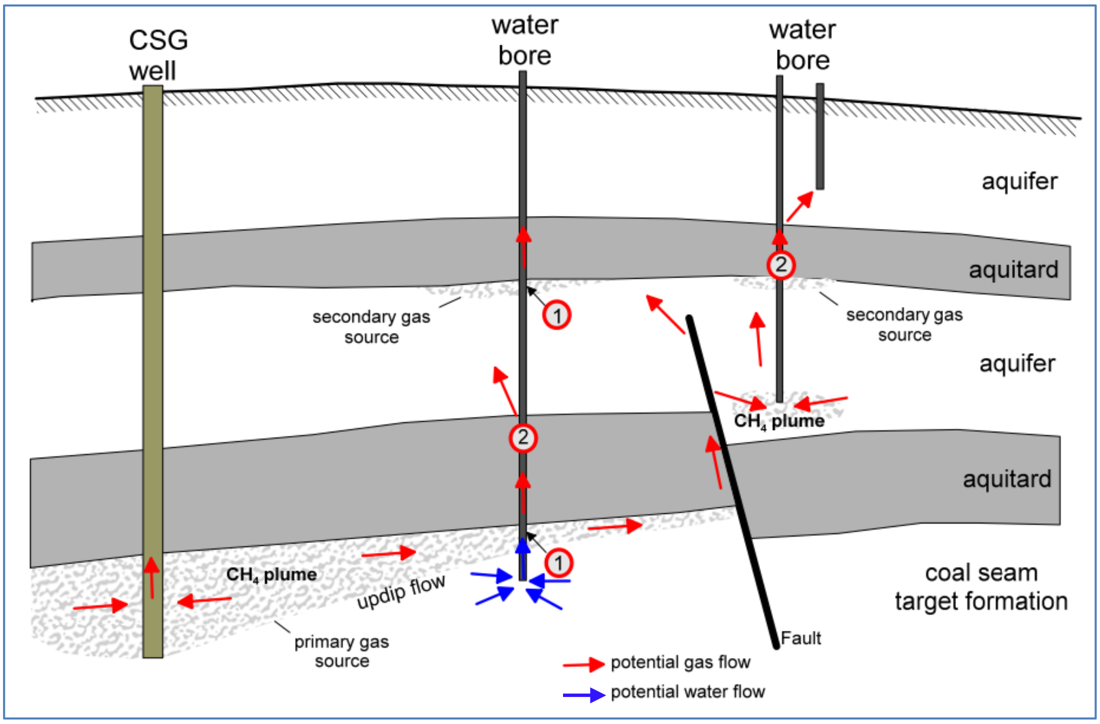

Figure 2: Schematic representation of CSG pathways via bores and faults (Mallants & Raiber, 2016). Pathway (1) refers to gas migration into water bores via corroded bore casing while pathway (2) refers to gas flow through fractures/degraded bore seals

2.5 Relationship between the Water Levels in Bores and Free Gas Migration

Groundwater only moves from one formation to another if there is a hydraulic gradient and a pathway for flow. In contrast, due to buoyancy the free gas can move through the same pathways to the other formations (or to the surface) regardless of the hydraulic gradient. This also implies that free gas can potentially move to water bores that do not experience water level decline.

In the context of CSG development, a hydraulic gradient towards the CSG wells is created due to depressurisation of the coal seams. If a pathway to flow is available between the formations above and below the target formation (i.e. groundwater connectivity), then groundwater will flow towards the target formations. This movement of water may create a decline in water level in surrounding formations. Free gas can also exploit the same pathways to vertically move to overlying formations due to buoyancy, and potentially end up in water bores that are tapping formations through which gas is migrating.

A relationship between the CSG induced decline in water level in bores and migration of free gas to same bores may or may not exist. Conceptually there are four circumstances where free gas in a bore may not relate to CSG induced water level decline:

1. The pathways, particularly provided by the bores with compromised integrity, can often be small and in a regional context may not materially affect groundwater flow across the formations, and hence there may be no CSG induced water level decline in the surrounding formations. However, the same pathways can lead to vertical movement of significant free gas into water bores. This will result in free gas in water bores that do not experience water level decline, particularly in shallower formations that may otherwise be hydraulically disconnected from the target formations.

2. In circumstances where CSG production is stopped or suspended for a period of time, there will be little or no hydraulic gradient and, as a result, little or no effect on water levels in water bores in overlying formations. At the same time since the free gas is now available and only controlled by buoyancy, it can move into overlying formations and into water bores through pathways.

3. As discussed in section 2.3, free gas can also cause a rise in water level from time-to-time. In that instance, free gas may occur in water bores that record rise in water levels as observed in the Surat Basin.

4. In areas away from the CSG development, free gas can potentially migrate up-dip (section 2.3). These up-dip areas can be beyond the areas that may experience CSG induced water level decline and, therefore, in these circumstances free gas may also migrate to a water bore where there is no CSG induced decline in water levels.

The possibilities raised above are on a conceptual basis alone. Further work may be needed to establish the relationship in the Surat Basin through quantitative analysis and case investigations. Mallants & Raiber (2015) used a distance of 10 km from the CSG wells beyond which risk of free gas in a water bore is considered minimal in the Surat Basin.

A number of water bores up-dip of Orana fields have reported water level rise. These are flagged for decommissioning by Origin Energy as they are deemed unsuitable for water supply (pers. comm CSGCU).

Migration of free gas in Wallumbilla town water supply bore from conventional oil and gas development, provides a suitable case in this context. Information provided by CSGCU suggests that Wallumbilla town water supply bore in the Gubberamunda formation recorded an increase in free gas with pumping. Follow-up investigations revealed that the gas originated from a deeper conventional oil and gas target and found its way through a poorly abandoned gas well about 50m away despite there being no decline in water level from the oil and gas activities.

3 IMPACTS ON BORES' CAPACITY TO SUPPLY WATER

3.1 General

There is an abundance of literature available on methane being present in water supply aquifers overlying the CSG and unconventional gas target formations such as in Northern Pennsylvania, Alberta and San Juan Basin in USA. Numerous complaints of gas in water bores and water supplies are reported worldwide. In almost all of these cases the complaints are primarily driven by safety concerns and gas contamination to groundwater supplies. As a result, investigations and studies have also typically focussed on the sources of the reported gas and mechanisms by which the gas may have migrated to the water supply bores and reticulation systems. There is limited literature in the public domain about the actual impacts of gas on water bores. The literature that is available is typically water well factsheets and articles produced by water resource managers or pump manufacturers about general statements of problems and how to deal with the methane or air once it has made its way to a water bore.

Our review of the available information suggests that there are a number of ways free gas can affect a bore's capacity to supply water. Presence of free gas in a water bore is more than just nuisance. It directly affects the bore's capacity to provide water supply for intended purpose unless, where possible, remedial actions are taken.

There are four broad categories of the ways free gas can affect a bore's capacity to supply water:

- damage to pumps and infrastructure that could reduce the pumping capacity if unattended;
- reduction in the water bore yield due to presence of gas in and around the vicinity of the bore;
- changes in water quality that could make the water unsuitable for intended use; and,
- health and safety issues that could prohibit normal access and maintenance to affected water bores.

3.2 Damage to Pumps and Bore Infrastructure

3.2.1 Background

There are two broad types of pumps commonly used in water bores:

- rotodynamic pumps such as the centrifugal pumps; and,
- positive displacement pumps such as the piston pumps.

Centrifugal pumps are most widely used in agriculture while for small water supplies (typically less than 2 litres per second), positive displacement pumps are often used.

Centrifugal pumps have a rotating impeller which gives energy to the water. The speed and size of the impeller determines the pressure and the rate of water flow into the pump. There are many types of centrifugal pumps but most common for water bores are the electro-submersible pumps (ESP). They are called submersible pumps because the pump assembly is submerged below the water level. The two key components are the pump impellers and the motor. The motor and pump are in the one unit. Motor is kept underneath the pump intake and the impellers.

A typical submersible pump is suspended on a head piece using a rising main pipe. The motor requires continuous flow of water past the unit for cooling, which is generally achieved by placing the unit above the water entrance to the bore. The electrical supply cables are strapped to the outer wall of the rising main and continue down the well to the motor.

Progressive cavity pumps (PCP) are positive displacement pumps with two key components: a moving single helical steel rotor and a stationary double-threaded helical elastomer stator. The PCPs have an ability to handle solids and viscous fluids together and are useful for many industrial applications, with common applications in countries like Canada and Venezuela. The pump has only one moving part downhole and no valves. The pump does not gas lock but can overheat in handling gas (Simpson , et al., 2003). About a 50-50 mix of gas and liquid can be pumped with no damage to the motor. PCPs are commonly used for extracting commercial CSG production in the Surat Basin (Dunn, 2015).

3.2.2 Types of Damage from Free Gas

Submersible pumps do not operate well when free gas is present. Free gas may be in the water bore prior to pumping. Free gas may also be generated due to agitation from pumping if there is dissolved gas in the water. Estimates of the level of free gas that a submersible pump can tolerate without significant damage, are available in literature. A submersible pumps tolerance to gas is usually no more than 10-20 per cent gas volume fraction (Herl & Eudey, 2009). Typically at low pressures, a submersible can tolerate 10-15 per cent gas but can tolerate more free gas if the pressure is higher (Simpson , et al., 2003). Modifications to pumps and operating procedures can assist in managing the problem, although the success rate may be 50 per cent (Alberta Agriculture and Rural Development, 2006): drilling holes in the submersible pump impellers to release the air bubbles; moving the pump check valve from the top of the pump to 1.5 - 3 m above the pump; and installing a shroud around the pump to divert gas bubbles past the pump intake.

There are four main types of damage that can occur to a pump and water bore if there is free gas in water bores: gas locks; cavitation; over-heating; and blow-outs. Each type of damage will severely affect a bore’s capacity to supply water if remedial actions are not taken. Of these, the most common damage to submersible pumps is from gas locks and cavitation.

Gas locks

A gas lock is essentially a priming problem for the pump, whereby free gas released from solution gets between the pump valves and restricts the ability of water to enter or leave the pump. The pump becomes locked and pumping rates reduce dramatically. Gas locking has been reported in large methane-producing reservoirs in Central Alberta (Alberta Agriculture and Rural Development, 2006), (Alberta Government, 2011), central Queensland (Walker & Mallants, 2014) and the United States of America. In a typical gas lock situation, the pump will be operating normally, then quit pumping while the motor keeps running. As a result there is often a sharp increase in motor winding temperature and a sharp decrease in load on the motor (Herl & Eudey, 2009). If the temperature spike is not detected and steps are not taken to remediate immediately, the pump can be destroyed.

Pump Cavitation

Cavitation is generally regarded as the most common problems with pumps. Cavitation is the formation and collapse of gas/air-filled cavities in the pumped fluid whereby there is insufficient head at the point of pump suction. As the bubble implode, they exert force on metal surfaces causing severe pitting and physical and mechanical damage to the pump components including impellers (Sterrett, 2007). An example of damage from cavitation is shown in Figure 3 .

Figure 3: Example of cavitation damage in a pump impeller (Source: www.waterworld.com)

When pump cavitation is left unresolved, it may cause (Industrial Static Control, 2015):

- Breakdown of pump housing.
- Damage to the impeller.
- Too much vibration, resulting in untimely seal and bearing breakdown.
- Excess energy consumption.
- Low water flow or pressure.

The frequencies recorded of cavitation 'hammering' are from 1,000 cycles per second up to 25,000 cycles per second and the resulting damage is generally termed 'pitting'. The noise (commonly referred to as the sound of sand and gravel moving through the pump, or rumbling) heard outside the pump during cavitation, is caused by the collapse of the vapour bubbles. Only about 75 per cent of cavitation creates pump noise but the material damage is always there (LaBour Pumps, no date).

In the Surat Basin it is reported that bore pumps had to be replaced due to the motors burning out as a result of cavitation when the dissolved gas comes out of solution as a result of pressure changes (Harris, et al., 2012)[3].

Overheating

Cooling of the submersible pumps depends on the water circulating around the motor during pumping. In the event that large quantities of gas pass the motor, the heat transfer from the motor

[3] Indirectly referenced from Walker & Mallants (2014)

to the water will be dramatically reduced, potentially causing overheating and motor damage (Simpson , et al., 2003).

Blow-outs

In extreme cases, build-up of pressure from free gas in a bore may dislodge the entire bore casing and pump (Walker & Mallants, 2014). The term 'blow-out' is also used for sudden expulsion of water and gas from a bore. Such cases of blow-outs in the Chinchilla area of the Surat Basin are reported and investigated by the CSGCU (ABC Australia, 2014).

3.3 Reduction in Water Availability

As free gas becomes more prominent in the aquifer immediately surrounding a water bore, pore spaces are filled with gas which cause additional resistance to water flow. This effectively reduces the permeability to water – referred to as reduction in relative permeability. Laboratory permeameter experiments have demonstrated that methane gas can reduce permeability by up to 25 per cent after only five months of methane arrival (de Lozada, 1994). For this reason, even if a suitable gas-compliant pumping system is installed in the water bore, the bore yields may diminish as free gas progressively blocks pore space by methane bubbles replacing water in the pore spaces.

Gorody (2012) notes an empirical observations regarding some complaints about the water supply bores whereby there has been a perceived decline in water bore yields before the onset of documented free gas invasion in the bores. He has attributed this to a drop in relative permeability.

Reduction in water availability due to a reduction in relative permeability, is in addition to any other reduction caused by a decline in water levels in an aquifer due to CSG development.

As discussed in section 2.3, intermittent gas migration into a water bore has the potential to create water level rises and fluctuations that would create surges within the water bore. Excessive surges in water level can potentially cause some formation collapse, particularly in an open hole, and thus also reduce bore capacity to supply water.

3.4 Impact on Water Quality

According to Walker and Mallants (2014) gas bubbling can also impact the water quality in at least two ways:

- First, bubbles cause sediments that accumulate at the bottom of water bores to move through the water column, which in turn leads to water that becomes coloured, turbid, slimy, and smelly.
- Secondly, in certain circumstances, it can lead to the conversion of dissolved sulfate into odoriferous, noxious, and toxic sulfides.

Hydrogen sulfide can lead to problems of odour, toxicity, and corrosion of casings and pipes (Moore, 2012 in Walker and Mallants, 2014). Bubbling of methane through the water column of a domestic water bore will displace oxygen in the bore and promote anoxic (oxygen-poor) conditions. If sulphate-bearing waters become anoxic as a result of the contamination, then the bore is at risk for entraining dissolved hydrogen sulphide (Worley Parsons, 2013).

3.5 Impact on General Safety

Methane, carbon dioxide and nitrogen are all odourless gases. Methane will burn, can be explosive and must be vented to the outside because it poses a safety hazard. The lower explosive limit (LEL) is the minimum amount of a gas in the air that can cause an explosion. This limit is 5 per cent for methane. A gas concentration of 10 per cent or more of the LEL in a confined space is considered to be a safety hazard. For methane, this limit works out to be over 5,000 ppm (Alberta Agriculture and Rural Development, 2006). Mallants and Raiber (2015) states that methane can be explosive at concentrations of 50,000 ppm to 150,000 ppm in air. Methane is an asphyxiant at a concentration of over 50% in air.

Hydrogen sulfide has a characteristic rotten egg smell. The gas can cause some health risks such as worry, anxiety and resentment from the smell. Real human impacts from hydrogen sulphide are not likely until air levels reach at least 2ppm for 30 minutes or more (Government of Western Australia, 2009).

Safety issues may not directly impact on a bore's capacity to supply water but certainly pose difficulties in running and maintenance of the bore as the safety issues can limit access. In extreme cases bores may have to be completely abandoned for safety reasons.

4 RELATED CASE STUDIES

4.1 General

As previously noted in this report, there is a general lack of reported studies about the impacts of free gas on water bores. Methane gas presenting at water supply bores is a common problem faced in many sedimentary basins in the USA, Canada and more recently in the Surat Basin where the basins are exploited for CSG (or coalbed methane), tight gas or conventional gas. There is a lot of literature cataloguing the presence of methane in water supply bores, however, very few studies/reports make mention of the actual impacts to individual bores. There are a number of water fact sheets about the practical measures that can be taken by bore owners once their bores are impacted by methane gas or air. Again, little information is presented on the actual impact on bore water supplies other than a generic mention of gas locking of submersible pumps, pump cavitation, and impacts to water quality.

Some of the related examples from CSG and unconventional gas development in relation to gas migration and water bore problems are summarised below.

4.2 Surat Basin, Queensland

CSIRO undertook a two stage literature review for the CSGCU in 2014 and 2015 [(Mallants & Raiber, 2016) (Walker & Mallants, 2014)] to support decision making for investigating complaints about the increase in gas in water bores. The key focus of the CSIRO work was on sampling and analysis for identifying the source of methane and a decision support system to classify potential risks to bores. They presented a thorough review of historical media reports which describe gas in bores prior to CSG development. They also summarised state reports which describe gas blow-outs and occurrences of gas in bores since the 1960's.

Seepage of gas in Condamine River has been widely reported in media that triggered a number of investigations. Most recent investigations by Norwest (2014) to identify the source did not definitively conclude the main source and the primary mechanism of free gas migration, but it did conclude that free gas had migrated from a distal source and that a number of different natural (buoyancy up-dip in the basin via fracture zones, faults) and anthropogenic mechanisms (open exploration holes, multi-aquifer water wells, production wells with ineffective casing and seals) could plausibly explain the occurrence of methane in the river away from CSG development areas.

A high level of gas content has been historically reported around Wallumbilla, Surat and Tara by DNRM in formations above and below the CSG target prior to CSG development. Wallumbilla town bore in a shallower formation, above a much deeper conventional oil and gas reservoir, experienced free gas that found its way through a poorly abandoned gas well about 50m away, although groundwater levels in the aquifer were not directly impacted from the oil and gas development. As a result the operator of the oil and gas well provided an alternate water bore (pers comm CSGCU).

4.3 Northeastern Pennsylvania, USA

Commercial oil production started in Pennsylvania in 1859. Over the last 150 years hundreds of thousands of gas and oil wells have been drilled in Pennsylvania (DEP, 2009). The Department of

Environmental Protection – Bureau of Oil and Gas Management has published an inventory of stray gas cases. That publication lists over 60 sites that have been impacted in terms of water bores, streams, and infrastructure, with many deemed to be a direct result of gas migration from a nearby oil and gas well. Examples of impacts to water bores include minor explosions, damage to water bore pumps, changes in water quality, and sudden increase in gas concentrations (B F Environmental Consultants, 2012).

The development of the Marcellus Shale has increased the potential for methane gas migration. In Pennsylvania, between 2008 and 2011, there were two major cases of reported free gas migration into groundwater, each affecting more than 15 drinking-water bores, with both cases linked to faulty casing of production gas wells that provided a pathway to migration into formations where water bores were located (Considine, et al., 2012).

141 drinking water bores across northeastern Pennsylvania were also assessed separately (Jackson, et al., 2013). Methane was detected in 82% of drinking water samples, with average concentrations six times higher for homes within one km (1 km) of natural gas wells. The source was attributed to shale gas and contamination in the pathways to water bores was postulated to be through faulty and inadequate casing and well design and imperfections in cement casings.

In contrast to the earlier findings (Considine, et al., 2012), (Jackson, et al., 2013), later studies showed that methane is found everywhere in shallow groundwater sampled from 1701 water bores across the area, with higher concentrations best correlated with topographic and hydrogeological controls rather than shale-gas extraction at greater depths. Methane gases in the shallow subsurface have been observed for over 200 years, with several dozen instances of flammable effervescing springs and water bores dating back to the 1700s (Molofsky, et al., 2013).

4.4 San Juan and Raton Basins Colorado, USA

A summary of gas seepage complaints and investigations from CSG development in the San Juan Basin is provided by Baldwin and Thoms (2014). Since the early 1990s, various government agencies and the industry have undertaken extensive investigations to address complaints about the methane occurrence in water bores. Similar to elsewhere, the investigations focused on establishing the source and concluded that in most cases methane contamination in groundwater occurred from naturally occurring methane in the aquifers in which the water bores were completed and was not the result of CSG development. Investigations also revealed that old oil and gas wells and improperly plugged and abandoned wells provided conduits for methane migration from the coal seams into overlying formations and water bores.

From the reported literature, we could not site specific examples of impacts of free gas on water bores capacity to supply water. The complaints seem to be focused on safety and gas contamination issues. However, it is implied from the reported investigations that wells and bores with compromised integrity have provided a pathway to CSG into water bores in some cases.

4.5 New York State, USA

U.S. Geological Survey (USGS) study found that nine per cent of wells sampled in New York had methane concentrations above the recommended level of 10 mg/L, and of those wells most were screened in shale bedrock or in unconsolidated sediments overlying black shale bedrock (Kappel &

Nystrom, 2012). Other investigations (Heising & Tia-Marie, 2013) noted strong correlation between methane occurrence in groundwater bores and their hydrogeological setting. Methane in bores was predominantly thermogenic, likely as a result of close vertical proximity to underlying methane-bearing saline groundwater and possibly as a result of enhanced bedrock fracture permeability beneath valleys that provides an avenue for upward gas migration.

4.6 Alberta, Canada

Dissolved gases in water bores are a common occurrence in Alberta. The major gases in bores are methane, carbon dioxide, nitrogen and hydrogen sulfide (Alberta Agriculture and Rural Development, 2006). Gas locking of submersible and jet pumps is a common issue in Alberta and the most favoured method to deal with the gas is to divert some of the produced water back down the water bore. Typically one third of the bore water is diverted back down the hole as a means of maintaining a suction pressure and avoiding gas locking. Pressure tanks also require some modification. Gases will build until they fill the tank, escape into water lines and spurt from the taps when they are opened. A deep bore air volume control will enable the release of excess gas from the pressure tank.

5 CONCLUSIONS

5.1 General

In the context of CSG development, the free gas primarily contains methane. Methane in water bores could be either from biogenic sources (non-CSG) or from thermogenic sources such as CSG. Depressurisation of coal seams is the main process by which CSG is intentionally released and commercially captured. Similar processes also occur at a smaller scale during extraction of water from water bores causing unintentional depressurisation and release of free gas at smaller scale. Many such instances have been recorded in the Surat Basin.

There are a large number of worldwide reported cases of free gas in water bores and reticulation systems where CSG and unconventional gas is produced commercially. Investigations have generally concluded that in most cases the free gas is from naturally occurring sources and not from CSG development. In some instances free gas is found to make its way to water bores through openings provided by inappropriate well and bore construction and maintenance. However, the focus of this report is not on the source of free gas. It instead focuses on if free gas from CSG development migrates to a water bore and how this impacts on a bore's capacity to supply water. The two fundamental questions in this context are:

1. could there be free gas when there is no decline in water level in that bore from CSG development; and
2. could the presence of free gas affect the capacity of that bore to supply water?

An assessment of literature and the application of scientific principles suggests that conceptually, the simple answer to each of these questions is 'yes'. A summary of the basis for this conclusion is provided in the following sections.

5.2 Free Gas vs Water Level

Migration of free gas from CSG development is driven by pressure gradient towards production wells and, at the same time, vertically and laterally under the buoyancy force through pathways like fractures, faults and bores. Migration of free gas to water bores is very complex, occurs in pulses and depends upon a number of factors relating to the pressure changes and geological variability. The movement and timing is much more difficult to predict than groundwater flow.

As detailed in section 2.5, in most instances CSG-induced free gas in water bores tapping the CSG target formations or the overlying formations, is likely to correspond to areas where declines in water levels as a result of CSG development has occurred or likely to occur. However, there are instances where free gas in water bores may occur despite there being no decline in water level in that bore. This may occur in the formations that are targeted for CSG as well as in overlying formations in the CSG production areas which may or may not be affected by water level decline. Free gas may occur along the margins of the CSG development areas in an up-dip direction. A number of cases of water level rises in bores are also recorded in the Surat Basin which correspond to intermittent release of free gas from the bores.

5.3 Impacts on Water Bores

Presence of free gas in a water bore is more than just nuisance. It directly affects the bore's capacity to provide water supply for the intended purpose unless, where possible, remedial actions are taken. A bores' capacity to supply water can be affected in the following ways:

- Free gas hampers ***pumping operations and damage pumps*** and infrastructure potentially resulting in costly operations and replacements. Damages to electrical submersible pumps occur through gas locks, cavitation and overheating. Pumps may have to be replaced with different types, such as the positive cavity pumps (PCPs) or may require modifications to operate satisfactorily. Remedial options may not always be feasible.
- Free gas in the formation around a water bore provides a resistance to flow of water to the bore and reduces the formation's effective permeability to water. This in turn results in a ***decline in a bore's designed capacity*** or yield (i.e. the amount of water that the bore is capable of providing in a given period of time).
- ***Quality of water*** in a bore is also affected by the presence of gas. It causes sediments to accumulate at the bottom of water bores to move through the water column. In certain circumstances, it can lead to the production of some toxins.
- Free gas contains methane, carbon dioxide and nitrogen which are all odourless gases. Methane can burn, can be explosive and must be vented to the outside because it poses a ***safety hazard***. Safety issues pose difficulties in running and maintenance of bore.

5.4 Overall Conclusion

The review presented in this report suggests that free gas from CSG development can occur in water bores that do not experience a water level decline from CSG development. Presence of free gas in a water bore also directly and indirectly affects its capacity to supply water, unless remedial actions are taken.

The conclusions presented in this report are largely based on a conceptual understanding drawn from scientific principles and some related examples. More specific assessments and investigations of some representative water bores where free gas is reported, or is likely to occur, will provide greater insight into the matter.

6 CLOSING

This report is an instrument of service of Klohn Crippen Berger Ltd. The report has been prepared for the exclusive use of CGCU for the specific application to the potential effects of free gas on bore water supply from CSG development in the Surat Basin. The report's contents may not be relied upon by any other party without the express written permission of Klohn Crippen Berger. In this report, Klohn Crippen Berger has endeavoured to comply with generally-accepted professional practice common to the local area. Klohn Crippen Berger makes no warranty, express or implied.

KLOHN CRIPPEN BERGER LTD.

Sanjeev Pandey
Senior Hydrogeologist

REFERENCES

ABC Australia, 2014. Queensland's CSG compliance unit investigating bore 'blow out' on the Western Downs. Online available at: http://www.abc.net.au/news/2014-11-24/bore--blow-out-investigation/5914126

Alberta Agriculture and Rural Development, 2006. Dissolved Gases in Well Water. Agri-Facts Factsheet Agdex 716 (D18). Alberta Government.

Alberta Government, 2011. Gas in Your Water Well. Factsheet.

APLNG, No date. Natural Gas and Water Bores. APLNG Project Fact Sheet.

B F Environmental Consultants, 2012. Methane Gas Migration and your Water Well: A Pennsylvania Perspective: Fact Sheet.

Baldwin, D. & Thomson, J., 2014. Condamine River Seep Investigations: Technical Report. Norwest Corporation for Origin Energy.

Blyth, A., 2007. Singer Water Well - Complaint Review. Alberta Environment.

Considine, T., Watson, R., Considine, N. & Martin, J., 2012. Environmental impacts during Marcellus Shale gas drilling: cause, impacts, and remedies. Shale Resources and Society Institute Report. State University of New York at Buffalo.

CSIRO, 2014. Methane in Water Bores. Fact Sheet.

de Lozada, D.D., Vandevivere, P., Baveye, P., and Zinder, S., 1994. Decrease to the hydraulic conductivity of sand columns by Methanosarcina barkeri.. World Journal of Microbiology and Biotechnology. pp. Volume 10, pp 325-333.

Dunn, L., 2015. Progressive Cavity Pumping System- Overview with a focus on Coal Seam Gas Applications. Weatherford presentation to Society of Petroleum Engineers, Brisbane, March 9 2015.

Gorody, A. W., 2012. Factors affecting the variability of stray gas concentration and composition in groundwater. Environmental Geosciences. V 19, No 1, pp 17-31.

Government of Western Australia, 2009. Environmental Health Guide: Hydrogen Sulphide and Public Health.

Harris, K., Morris, R. & Pointon, V., 2012. The presence of methane in Great Artesian Basin aquifers of the Surat Basin.

Heising, P. M. & Tia-Marie, S., 2013. Occurrence of Methane in Groundwater of South-Central New York State, 2012—Systematic Evaluation of a Glaciated Region by Hydrogeologic Setting. USGS.

Herl, S. & Eudey, D., 2009. Electric submersible pumps fine-tuned for gassy wells. E&P Global Exploration and Production News, Hart Energy Publishing, Texas, USA, August.

Industrial Static Control, 2015. Understanding the problem of cavitation in water pumps. Online available at: http://industrialstaticcontrol.com/2015/04/23/understanding-the-problem-of-cavitation-in-water-pumps

Jackson, R. B. et al., 2013. Increase stray gas abundance in a subset of drinking water wells near Marcellus shale gas extraction. Proceedings of the National Academy of Sciences, Jul 13.pp. Vol 110; No 28; pp 11250-11255.

Kappel, W. M. & Nystrom, E. A., 2012. Dissolved Methane in New York Groundwater, 1999—2011. USGS.

LaBour Pumps, no date. Entrained Air in Centrifugal Pumps.

Mallants, D. & Raiber, M., 2016. Decision Support System for Investigating Gas in Water Bores and Links to Coal Seam Gas Development. CSIRO for QLD Department of Natural Resource and Mines.

Molofsky, L. J. et al., 2013. Evaluation of Methane Sources in Groundwater in North-eastern Pennsylvania. Groundwater. pp. Volume 51, Issue 3, pp 333-349.

Moore, T., 2012. Coal bed methane: a review. International Journal of Coal Geology. pp. 101: 36-81.

Simpson, D. A., Lea, L. F. & Cox, J. C., 2003. Coal be methane production.

Sterrett, R. J., 2007. Groundwater and Wells. Third Edition. Johnson Screens, a Weatherford Company.

Walker, G. R. & Mallants, D., 2014. Methodologies for Investigating Gas in Water Bores and Links to Coal Seam Gas Development. CSIRO for QLD Department of Natural Resource and Mines.

Worley Parsons, 2009. Potential for Gas Migration Due to Coalbed Methane. Alberta Environment.

Worley Parsons, 2013. Groundwater risks associated with coal seam gas development in the Surat and southern Bowen basins. Final report. Department of Natural Resources and Mines.