11 REVISED SITE CONCEPTUAL MODEL

11.1 INTRODUCTION

In this type of study, as described in Section 5, it is important to continue to monitor and collect appropriate data to test and verify that initial explanations continue to be supported by subsequent data. Therefore, any conceptual model should always be considered subject to revision, based on new data.

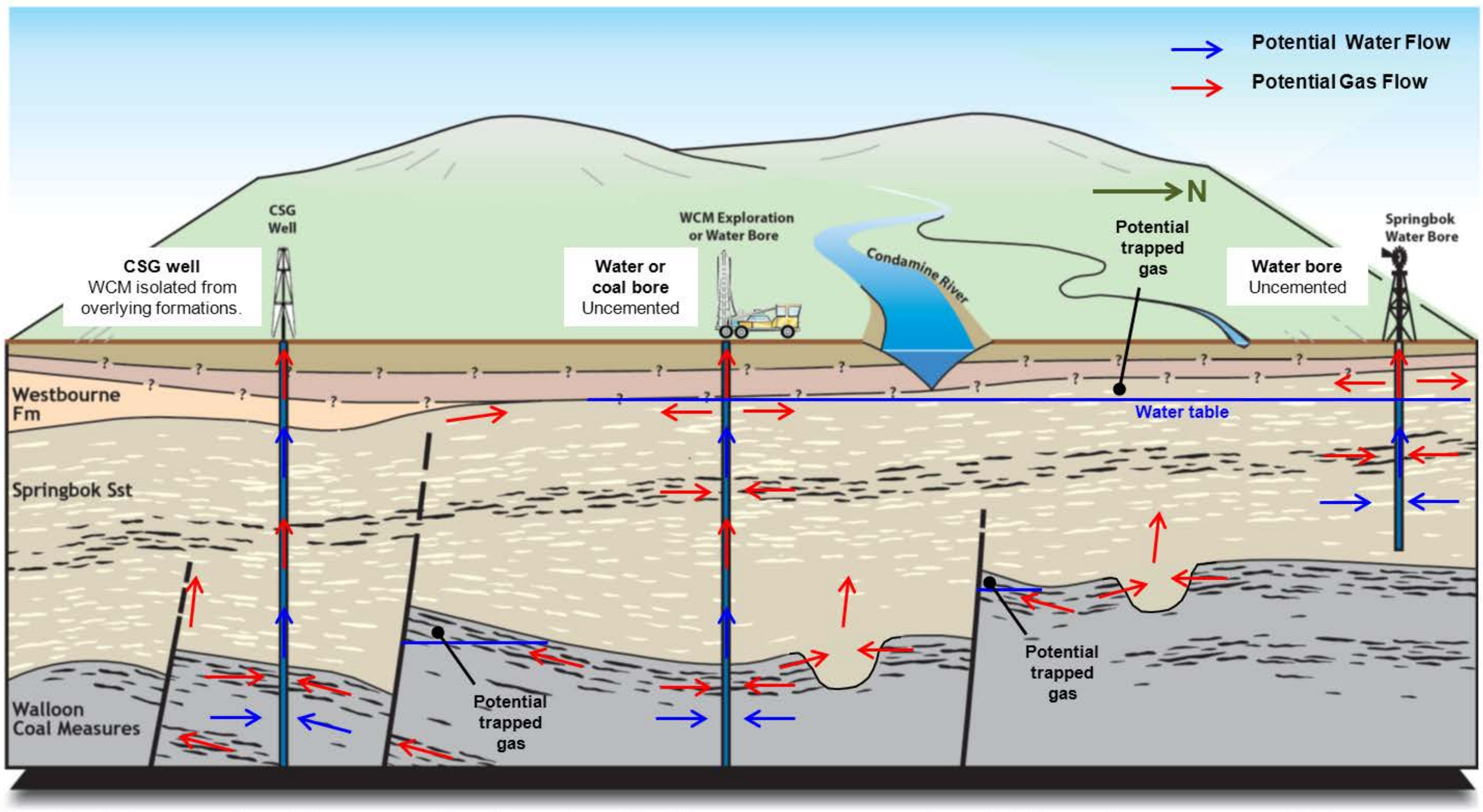
During the first two phases of the Condamine River gas seep investigation, the initial site conceptual model, comprising the geologic and hydrogeologic framework for the study area, was enlarged and revised to include hypotheses regarding gas sources, mechanisms, and pathways developed from the results of the work conducted, including:

- Primary sources
- Pathways
- Primary release mechanisms
- Secondary trapping or storage
- Secondary release mechanisms

11.2 GENERAL DESCRIPTION OF REVISED CONCEPTUAL SITE MODEL

Figure 11-1 is based on Figure 5-1, and illustrates many of the features of the revised conceptual model for the Condamine River gas seeps. For simplicity, it identifies several, but not all, of the potential sources, mechanisms, and gas flow pathways. The figure is not intended to show that all the displayed sources, mechanism, and pathways are operating, but just to illustrate some of the credible possibilities. However, it is quite possible that more than one mechanism, or the interplay between multiple mechanisms (cumulatively or sequentially), operates in this complex system.

The figure indicates that the primary gas sources are the coals in the WCM and/or the Springbok Sandstone. Initially the methane gas in the coals is in a sorbed state due to water pressure. Under certain circumstances and following fundamental laws of nature (gas diffusion and fluid flow), gas will desorb from the coals and diffuse through the coal matrix or “micro-pores” to the coal cleats, which provide the chief pathway for gas and fluid movement through the coal. Gas desorbed from the coals in earlier times (through any of the mechanisms described below) would have migrated upward by buoyancy (through coal cleats, permeable sandstones in contact with the coals, and/or fractures or faults), and thus become subject to secondary trapping by physical or other barriers. Such trapped gas could account for some of the documented historical blowouts that have occurred during drilling certain “gassy” water bores in the area.



Not to scale. Conceptual only. Pathways are potential, not proven. This is a gross simplification of a complex system. For full explanation, see text.

FIGURE 11-1

REVISED SITE CONCEPTUAL MODEL – SOURCES AND PATHWAYS

The primary gas release mechanism in the revised conceptual model is depressurization releasing sorbed methane from coals. Depressurization could be due to a combination of water extraction, migration and/or natural water pressure changes. Water extraction includes: (1) water extraction from producing CSG wells, and (2) water extraction from water bores. Water migration includes: (1) water migrating from deeper to shallower formations via abandoned coal exploration, petroleum, CSG, and water bores; (2) water migrating from deeper to shallower formations via water bores completed in multiple formations; (3) water migrating from deeper to shallower formations via natural faults or fractures. Natural water pressure changes include the results of variations in natural recharge and discharge, due for example to floods and droughts.

The rate of depressurization could be very rapid or could take place over decades or longer, depending on the depressurization method, the rate of water removal, and the hydraulic properties of the affected formations (e.g., permeability, porosity, and storage coefficient). Regardless, the key point is the eventual reduction of water pressures to below the critical desorption pressure for specific coals. This is not a simple point in time, however, because within a formation the critical desorption pressure will vary depending on reservoir characteristics (coal thickness, coal density, reservoir pressure) and other factors for each coal, depressurization would result in differing gas release rates at different times.

Superimposed on these depressurization mechanisms are a number of natural factors and processes: (1) desorption during drought and low- or zero-recharge conditions that lower reservoir pressure, to re-adsorption during high rainfall, flooding, and related high-recharge conditions that increase reservoir pressure; (2) time lags in the expression of recharge at the water table; (3) rises and falls in the water table and corresponding reduction or increase in the thickness of the unsaturated zone; (4) changes in gas solubility in response to pressure and temperature changes; (5) trapping of free gas by structures or facies changes (possibly subtle geologic variations); (6) trapping of free gas in pore throats by capillary forces; and (7) changes in gas bubble size in response to pressure changes. One or a combination of these factors could cause secondary trapping or secondary release from trapping, further affecting the timing and location of gas release and migration.

The effects of depressurization can spread in two ways: (1) propagation of reduced pressure caused for example by a producing CSG well, to coals not in the vicinity of the well, and releasing gas that is not captured by that well, and (2) desorption of gas relatively close to a producing CSG well, with the gas migrating generally updip due to buoyancy. In the first case, the effect can spread in all directions from the well, assuming isotropic conditions, at a rate controlled by the reservoir properties but independent of the dip angle. In the second case, the effect spreads generally updip (with some transverse dispersion) at a rate governed by the geologic dip and the reservoir properties. In both of these examples, the cause of depressurization is CSG production, but as noted above there are many other potential causes of depressurization.

The conceptual model includes a number of potential desorbed ("free") gas pathways to the Condamine River, including: (1) from subcropping coals in the Springbok Sandstone directly into the Condamine River, (2) from the WCM to the Condamine River via the Springbok Sandstone (e.g. where the erosional base of the Springbok cuts into the WCM and permeable sandstones are in contact with WCM coals) and/or faults and fractures, (3) from the WCM or Springbok Sandstone coals to the Condamine River via water bores, (4) from the WCM or Springbok Sandstone coals to the Condamine River via abandoned coal exploration, petroleum, and water bores, and/or from the WCM or Springbok Sandstone coals to the Condamine River via CSG wells in which isolation of the formations is not complete.

The components of the conceptual model are described in more detail below.

11.3 Sources

In this report, "Source" refers to the combination of (1) the method of methane generation, and (2) the initial location (depth and/or geologic formation), from which the free methane that discharges from the observed gas seeps originated. It includes coals where sorbed methane desorbs to the free gas phase due to depressurization, but it does not include locations where free gas is temporarily trapped during its migration. Potential sources included:

- "Swamp" gas produced by biogenic acetoclastic reactions.
- WCM coal seam gas produced by biogenic CO_2 reduction.
- Springbok Sandstone coal seam gas produced by biogenic CO_2 reduction.
- A combination of gas sources.

As discussed in Section 7.3 the isotopic character of the gas at the seeps is different from "swamp" gas and similar to the biogenic gas from the coals of the WCM and the Springbok Sandstone. At this time the stable isotope data do not provide a way to differentiate between WCM and Springbok Sandstone methane

11.4 Pathways

In this report, "Pathways" refers to the routes that may be taken by the methane from its source to the gas seeps including routes taken by free gas from locations where it has been temporarily trapped. Free gas will rise vertically through water due to buoyancy, with a route modified by the vertical and lateral permeabilities of the formations through which it rises, or by the presence of permeability modifiers such as conduits or barriers. Potential pathways for methane gas migration include:

- Methane may be flowing directly from coals or other lithologies in the Springbok Sandstone that subcrop or outcrop under the Condamine River.
- Methane may be flowing out of coals that are located beneath, but do not directly subcrop/outcrop under the Condamine River, and migrating updip due to buoyancy.

- Methane may be flowing directly from coals through naturally occurring fractures or faults that extend from the Springbok Sandstone and/or the WCM to the bottom of the Condamine River.
- Methane may be flowing directly from coals in the Springbok Sandstone and/or WCM through man-made conduits (water bores, petroleum bores, coal exploration bores, and inappropriately completed CSG wells), entering the groundwater, and discharging into the Condamine River. Flow though man-made conduits could be related to improperly abandoned (i.e., not properly plugged to ensure isolation of gas bearing zones from aquifers) bores, or imperfectly cemented and sealed well annuluses.
- Methane that has not been captured by producing CSG wells and water bores may be migrating updip by buoyancy and flowing out of coals in the WCM through naturally occurring fractures or faults that extend up to the bottom of the Condamine River.
- Erosion within Condamine River flood events may have removed a low-permeability layer (such as the thick clayey soils or consolidated conglomerate of the older alluvium described in Section 4.1) and uncovered coals, other bedrock, or fractures or faults that contain methane, thereby providing a pathway for methane migration into the Condamine River.

Several of the potential pathways listed above rely in part on gas flowing through fractures and faults. Seismic surveys conducted by Origin (see Section 4.1) have identified inferred faults in the area of investigation; however, it should be noted that faults can enhance and/or reduce permeability[75]. They are not necessarily permeable conduits for gas flow, but can be low-permeability barriers to migration (such as in fault-bounded "gas traps"). Therefore, the presence of faults and fractures does not guarantee that they are conduits for gas migration. Additional data, including pressure monitoring, soil gas surveys, and geologic mapping, are needed to determine whether faults and fractures are barriers or conduits – or possibly both in different locations or formations.

11.5 MECHANISMS

In this report, "Mechanism" refers to the physical and chemical changes and processes that may cause gas to migrate from its source, move along a pathway, and emerge at the gas seeps. Both anthropogenic and natural mechanisms (short- and long-term) may occur and need to be considered; different mechanisms may be working together; and additional investigation and monitoring may identify other factors that are contributing to gas seepage.

[75] McKillop, M. D., O. Dixon, and J. Hodgkinson. 2011. A new interpretation and model of the Moonie-Goondiwindi and Burunga-Leichardt fault systems in Queensland. Queensland Geological Record 2011/01. Geological Survey of Queensland.

11.5.1 Anthropogenic mechanisms

Potential anthropogenic mechanisms for production of free gas include:

- Depressurization of the WCM by CSG production wells, allowing methane to desorb. Desorption may occur beneath the seeps, or at an offset and down-dip location. Desorbed gas could have been captured by the CSG well, or migrated via other pathways such as faults, or updip due to buoyancy through higher permeability beds such as coal or sandstone.

- Free gas released via the above mechanism could become secondarily trapped within the Springbok Sandstone.

- Depressurization of coals in the Springbok Sandstone and/or WCM by water bore pumping, allowing methane to desorb (e.g. at least one water bore within the area of investigation that is used for agricultural purposes has an allocation of 240 Ml/yr for water from the WCM and the underlying Hutton Sandstone). Desorbed gas could have migrated via the water bore itself, or other opportunistic pathways such as faults and higher permeability beds (e.g., coal and sandstones).

- Drilling of coal exploration boreholes and inappropriate abandonment may have resulted in connecting the Springbok Sandstone and the WCM, and depressurisation of deeper units (which would have had a higher initial reservoir pressure). Gas could have migrated between units via open bores.

- Depressurization of coals in the Springbok Sandstone and/or WCM by coal exploration bores that were allowed to flow water and gas, or due to their subsequent conversion to water bores, allowing methane to desorb. Desorbed gas could have migrated via the coal exploration bore itself, or via other opportunistic pathways such as faults or fractures.

11.5.2 Short-term natural mechanisms

Other natural mechanisms related to hydrostatic pressure changes in the shallow geology due to flooding events include:

- Methane desorbed from shallow coal seams in the Springbok Sandstone and/or the WCM during low hydrostatic pressure periods (e.g., extended low rainfall and recharge conditions) could have become secondarily trapped as free gas in overlying unsaturated formations because of permeability and/or structural traps. Subsequently, trapped gas could have been displaced due to recharge from high rainfall periods.
- Desorbed methane in temporary traps could have been dissolved in groundwater as the water table rose following high rainfall periods. The dissolved gas would then have migrated with the groundwater. During subsequent dry periods, as the water table falls and hydrostatic pressure decreases, gas solubility (which is directly related to pressure) would decrease and methane would come out of solution. This gas could

have migrated upwards and discharged to the river. The solubility of pure methane in water at a temperature of 20° C and a pressure of 1 atmosphere (atm) is 23.7 mg/L. The solubility increases linearly at 23.7 mg/L per atm.

A variation of the above scenario is that groundwater containing dissolved gas may discharge into natural springs in the river bed, with methane coming out of solution due to the lower pressure at the point of discharge, i.e. a simultaneous discharge of water and gas.

- Desorbed methane trapped as free gas in overlying unsaturated formations could be displaced upwards and/or up-dip as the water table rises in response to high recharge periods.
- Desorbed methane in temporary traps could have been retained in traps due to a large bubble size, held in the pore throats of the formation matrix by capillary forces. Higher water pressures due to a rising water table in response to high recharge periods, would have compressed free gas, reduced bubble size and hence capillary forces, and allowed the gas to migrate upwards.
- Naturally rising gas could have been trapped by lower permeability alluvium underlying the Condamine River channel. Channel bottom scouring and erosion, or rearrangement of existing bottom sediments, during high rainfall periods, could have removed the lower permeability material, allowing the gas to migrate upwards.
- Nutrient- and bacteria-rich floodwaters could have infiltrated and recharged shallow coals, triggering production of biogenic methane.
- Hydraulic loading by flooding could have activated movement along existing faults and fractures, allowing methane to migrate upwards via a fault conduit.

Potential natural mechanisms that are related to other short-term physical or chemical changes in the environment include:

- The solubility of gas is dependent on pressure, as noted above. The pressure at any point in a water column is dependent on the depth below the water surface, plus the atmospheric pressure acting on that surface. Therefore daily, frontal, or other changes in barometric pressure would be expected to cause variations in methane solubility. If the water is already close to saturation with dissolved methane, barometric pressure reduction would result in exsolved gas migrating upwards.
- Seismic activity may have reactivated, opened up, or extended faults or fractures, allowing methane to migrate upwards via a fault conduit.

11.5.3 Long-term natural mechanisms

Potential natural mechanisms that are related to long-term physical changes in the environment include:

- Long-term land surface erosion reducing hydrostatic heads in the coal seams; thereby reducing their maximum sorption capacity.

- Long-term climate changes affecting groundwater levels, reducing hydrostatic heads in the coal seams; thereby reducing their maximum sorption capacity.

Long-term land surface and climate change mechanisms are potential "natural depressurization" mechanisms that would generally take place over long time periods. It is not likely that they would trigger a sudden increase in seepage, but could be responsible for coals in the Springbok Sandstone and WCM being at or near full saturation with respect to methane, such that a small pressure reduction would result in gas desorbing. These mechanisms are based on CSG theory and gas sorbed on the internal coal surfaces has been found to generally follow a formula known as the Langmuir equation[76], which describes how the sorption capacity of coals increases with higher pressures and vice versa.

[76] Langmuir, I. 1916. *The constitution and fundamental properties of solids and liquids. part i. solids. Journal of the American Chemical Society* **38** (11): 2221–2295.

11.6 CONCEPTUAL MODEL REVIEW

At the end of the first two phases of the study, the conceptual model components described above (i.e., hypotheses regarding sources, pathways, and mechanisms) were either rejected based on contrary data, or retained for further investigation. This is summarized in the following subsections (10.6.1 to 10.6.3).

11.6.1 Sources

Potential sources of the methane discharging from the observed seeps:

Potential Source	Comments	Hypothesis Retained/rejected
"Swamp" (shallow-sourced biogenic acetoclastic) gas	The seep gas samples analysed to date do not match the isotopic character of "swamp" gas.	Rejected
WCM coal seam gas	The seep gas samples analysed to date match the isotopic character of WCM gas.	Retained
Springbok Sandstone coal seam gas	The seep gas samples analysed to date match the isotopic character of Springbok Sandstone gas.	Retained
Combination of gas sources	The isotopic characters of gas samples attributed to the WCM and Springbok Sandstone are similar, so either or both formations could be a source. In addition, water and coal exploration bores may be completed in or open to both the WCM and Springbok Sandstone, thereby connecting two potential sources and there is uncertainty about what formation the wells are completed in. Faults could connect two or more formations. This in turn depends on the hydrogeologic nature of the faulting, i.e. permeable or sealing.	Retained

11.6.2 Pathways

Potential pathways for methane gas migration:

Pathway	Comments	Hypothesis Retained/rejected
Methane may be flowing directly from coals or other lithologies in the Springbok Sandstone that subcrop or outcrop under the Condamine River.	What are thought to be coals in the Springbok Sandstone have been found in the Condamine River valley (Figure 3-1 location #10).	Retained
Methane may be flowing out of coals or other lithologies that are located beneath, but do not directly subcrop/outcrop under the Condamine River.	The WCM dip at an angle of approximately 1 degree. Updip migration is possible due to the buoyancy of gas in water.	Retained
Methane may be flowing directly from coals through naturally occurring fractures or faults that extend from the Springbok Sandstone and/or the WCM to the bottom of the Condamine River.	This pathway depends on the vertical extent of the potential fractures/faults, which has not yet been confirmed (either by seismic analysis or by structural/stratigraphic drilling). It also depends on the hydrogeologic nature of the faulting, i.e. permeable or sealing.	Retained
Methane may be flowing directly from coals in the Springbok Sandstone and/or WCM through man-made conduits (water bores, coal exploration bores, and CSG wells), entering the groundwater, and discharging into the Condamine River. Flow though man-made conduits could be related to improperly abandoned (i.e., not properly plugged to ensure isolation of gas bearing zones from aquifers) bores, or imperfectly cemented and sealed well annuluses.	There are numerous potential man-made conduits of a wide variety of ages, based on both documented and anecdotal information.	Retained
Methane that has not been captured by producing CSG wells may be migrating (1) updip by buoyancy and (2) through naturally occurring fractures or faults that extend up to the bottom of the Condamine River.	As described above, the WCM dip at an angle of approximately 1 degree. Upward migration is possible at that dip angle, due to the buoyancy of gas in water. However, this is a dual pathway that depends on the vertical extent of the potential fractures/faults, which has not yet been confirmed (either by seismic analysis or by structural/stratigraphic drilling).	Retained
Recent erosion by major Condamine River flood events may have removed a low-permeability layer (such as the thick clayey soils or consolidated conglomerate of the older alluvium described in Section 4.1) and uncovered coals, other lithologies, or fractures or faults that contain methane, thereby providing a pathway for methane migration into the Condamine River.	Low-permeability layers have been identified (consolidated conglomerate and black clayey soils). Before the construction of the Chinchilla Weir in 1973, Lumsden (1966) indicated that the Condamine River had cut down into older alluvium and bedrock. Therefore, in places the erosion of this layer took place long before the 2012 gas seep observations. Post-seep reconnaissance mapping along the River showed that there does not appear to be a geographic correlation between areas where the conglomerate is cut by the River, and the observed seeps.	Retained

11.6.3 Mechanisms

Potential mechanisms for production of free gas have to take into account the timing of the four seeps – the observation that the Rock Hole seep had been in existence for at least several decades, whereas the three other seeps (Pump Hole, Fenceline, and Camping Ground) may not have been observed prior to 2012, or may have recently increased flow rates. Potential mechanisms also have to take into account the ongoing nature of the gas seeps since early 2012, and be compatible with the cumulative volume that has been discharged to date. Regarding timing, CSG exploration and production from tenements in this area did not start until January 2004, when production began in Origin's Talinga Field. Production at QGC's Argyle Pilot began in November 2004 and production from the main area of the Argyle Field began in August 2007. All types of depressurization (plus regional hydrostatic head reduction) potentially liberate desorbed methane. Therefore, one, all, or a combination of the retained mechanisms below, that feature different types of pressure reduction, could be operating in conjunction.

Mechanism (Anthropogenic)	Comments	Hypothesis Retained/rejected
Depressurization of coals in the Springbok Sandstone by water bore pumping, allowing methane to desorb. Desorbed gas could have migrated via the water bore itself, or other opportunistic pathways such as faults and up dip via higher-permeability beds (e.g., coal or sandstone).	Water bore usage, and production of gas at water bores, have been documented, pre-dating CSG production by decades. The Orana 8 pressure data indicates that WCM groundwater was initially normally pressured i.e. could be in equilibrium with surface water levels. Pressure data from monitoring wells in the alluvium, Springbok Sandstone, and WCM should be used to determine vertical gradients.	Retained
Drilling of coal exploration boreholes and inappropriate abandonment may have resulted in interconnection of the Springbok Sandstone and the WCM, and depressurisation of deeper units (which would have had a higher initial pressure). Gas could have migrated between units via the open bore.	Drilling of coal exploration bores, and inappropriate abandonment in some cases, have all been documented, generally pre-dating CSG production by decades	Retained
Depressurization of coals in the WCM by coal exploration bores that were allowed to flow water and gas, or due to their subsequent conversion to water bores, allowing methane to desorb.	Flowing coal exploration bores, conversion of coal exploration bores for water use, and production of gas at water bores, have all been documented, generally pre-dating CSG production by decades.	Retained
Depressurization of the WCM by CSG production wells, allowing methane to desorb.	CSG exploration and production from tenements in this area began in January 2004, when production began in Origin's Talinga Field. Production at QGC's Argyle Pilot began in November 2004 and production from the main area of the Argyle Field began in August 2007.	Retained
Mechanism (Short-term natural – flood related)	**Comments**	**Hypothesis Retained/rejected**
Desorbed methane trapped in permeability and/or structural traps, displaced due to recharge from high rainfall periods.	Requires further assessment.	Retained
Desorbed methane, in temporary traps, dissolved in groundwater, and released due to pressure changes.	Requires further assessment.	Retained
Desorbed methane, in temporary traps, dissolved in groundwater, and released at springs.	Requires further assessment.	Retained
Desorbed methane, in temporary traps, displaced due to rising water tables.	Requires further assessment.	Retained
Desorbed methane, trapped in small pores, released due to pressure increases causing bubbles to shrink and overcome capillary forces.	Requires further assessment.	Retained
Desorbed methane, trapped below low-permeability alluvium, released when alluvium is eroded.	Installation of monitoring wells will help evaluate this mechanism.	Retained
Nutrients and bacteria in floodwaters could have triggered production of biogenic methane.	This would depend on the rate of infiltration of recharge. Installation of monitoring wells will help evaluate this mechanism. However, stable isotope results for gas samples collected from the seeps do not support this hypothesis.	Rejected
Hydraulic loading by flooding could have activated movement along existing faults and fractures, allowing methane to migrate upwards via a fault conduit.	Requires further assessment.	Retained
Mechanism (Short-term natural – other)	**Comments**	**Hypothesis Retained/rejected**
Barometric pressure effects	Unlikely to account for sustained gas seeps, but may influence variations in seepage rates.	Rejected
Seismic activity reactivating or otherwise increasing fault zone permeability.	Current seismic data do not support this hypothesis; however, the sensitivity (minimum detectable magnitude) of the Geoscience Australia seismic monitoring network for the area may be a limiting factor. This should be reassessed in Phase 3.	Retained

Mechanism (Long-term natural)	Comments	Hypothesis Retained/rejected
Long-term land surface erosion reducing hydrostatic heads in the coal seams, reducing their maximum sorption capacity.	Unlikely that this would trigger a sudden increase in seepage, but could be responsible for coals being at or near full saturation, such that a small pressure reduction would result in gas desorbing.	Rejected
Long-term climate changes affecting groundwater levels, reducing hydrostatic heads in the coal seams, and reducing their maximum sorption capacity.	Unlikely that this would trigger a sudden increase in seepage, but could be responsible for coals being at or near full saturation, such that a small pressure reduction would result in gas desorbing.	Rejected

11.7 Summary

The site conceptual model includes numerous credible hypothetical sources, pathways, and mechanisms – it is indeed possible that there are multiple factors involved in the phenomenon of surface seeps. Currently, there is a wide range of possibilities for the observations of the seeps in early 2012 and the ongoing gas discharge, and neither CSG-related or natural mechanisms, nor natural or anthropogenic pathways, can be ruled out. As scientific data are obtained that verify or eliminate individual hypotheses from consideration, the conceptual model has been and will be updated and refined. Although the "swamp" origin of the gas (biogenic gas produced by acetoclastic reactions) and some mechanisms were rejected in Phase 1 and Phase 2 of this investigation, many other hypotheses will require further technical investigation and evaluation and field activities before they can be verified or eliminated.