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Review Article

Coal seam gas associated water production in Queensland: Actual vs predicted

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ABSTRACT

Coal Seam Gas (CSG) development in Queensland is currently going through a transition from less than 300 billion cubic feet/year (~315 PetaJoules/year (PJ/yr)) for domestic consumption to ~1400 bcf/yr (nearly 1500 PJ/yr) by about 2019 driven by additional Liquid Natural Gas (LNG) export contracts. Prior to this ramp up in production, industry, government and academia have been forecasting not only gas but associated water production (produced water) for the various purposes of financial investment decisions and field development planning, prudent governance and regulatory planning, and estimation of potential environmental impacts for planning management, monitoring and mitigation strategies. During the course of resource development, prediction methodologies and model sophistication has varied greatly as more data becomes available and uncertainty is reduced. In Queensland, now that all 6 LNG trains are running and at various stages of ramping up to full production, there is a substantial and growing data inventory to history match numerical models and improve forward forecasting.

We review the historical forecasting of CSG water production in Queensland leading up to the development and operation of CSG to LNG export, and compare that to the current actual produced volumes now that the projects have come on stream. The latest available measured produced water from CSG development (December 2016) equates to ~60.5Giga Litres/year (GL/yr) with combined operator forecasts defining a peak projected to occur for about 10 years at 70–80 GL/yr. When this is converted to cumulative water volumes over the life of the industry (based on combined operator forecasts), just over 1700 GL of water is expected to ultimately be produced. Current estimates of water and salt production in Queensland are about 25% of those made by government and academia prior to the expansion of CSG to LNG export and ~70% of the 2010–11 industry estimates. We show that this discrepancy can be attributable to a combination of the following factors:

1. Gas industry conservatism (over-estimation) driven by the bias to reduce project risk and achieve gas delivery targets;
2. Government conservatism driven by a bias for prudent forecasting i.e. to assure that a credible worst case can still be managed within the regulatory framework;
3. Academia conservatism driven by a bias for understanding worse case scenarios of environmental impact;
4. The use of numerical models for basin scale impact assessment that do not take account of near-well multiphase flow characteristics of saturation and relative permeability; and
5. A systemic underestimation of the cumulative effects on depressurization of the coal resource where one operator's asset requires less water production to reach target reservoir pressures due to neighbouring operator production. This is mainly because each operator only has access to its own development plans.

1. Introduction

Coal seam gas (CSG), also known as coal bed methane (CBM), is natural gas that is adsorbed into the matrix of coal and held in place by weak chemical bonds (e.g. Van der Waals), which are determined by the microstructure, mineralogy and organic content of the coal (Brunauer et al., 1940). The methane may be thermogenic (formed by heat and pressure) or biogenic (formed by microbial action) in origin, or a mix of both, and it may have been generated in-situ or migrated into the coal from elsewhere. The gas is predominantly dry (i.e. mainly

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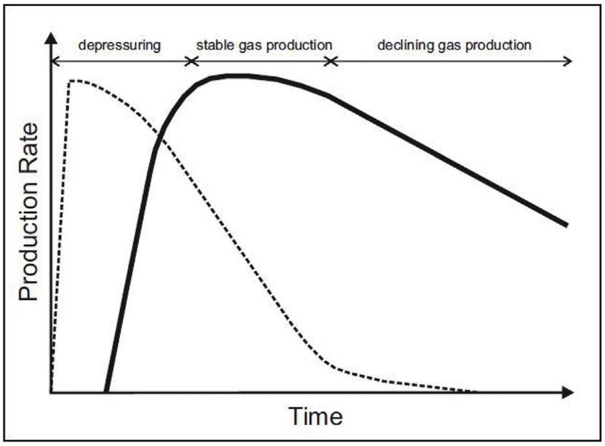

Fig. 1. A generic coal bed methane production profile with initial water production (dashed) followed by gas production (solid) after (Underschultz, 2016).

methane with low abundance of higher order hydrocarbons such as ethane, propane etc.). The cleat system of the coal typically has a high water saturation (the % of water relative to methane within the cleat porosity), although there are some CBM reservoirs that initially have high gas saturation in the cleat system before production starts (e.g. SW Virginia (Zuber, 1998) and Alberta (Bastian et al., 2005; Clarkson, 2009)). To produce the gas via a wellbore in the case of high water saturation, formation water is first produced from the cleat system thereby reducing the formation fluid pressure within the cleats. The resulting pressure gradient induced between the coal matrix and the cleats creates a sufficient hydraulic driving force to overcome the Van der Waals forces holding the gas adsorbed into the coal matrix, and the coal matrix begins to degas. Depending on the details of the coal reservoir, wells may be constructed as either vertical or horizontal, either with or without stimulation (Towler et al., 2016). A generic production curve is shown in Fig. 1 and indicates that initial water production tails off as gas production ramps up. The detailed shape of actual production curves can vary significantly from basin to basin and even from well to well within a single asset. Despite this uncertainty prior to commercial development CSG acreage, industry, government and academia forecast gas and associated water production for the various purposes of financial investment decisions and field development planning, prudent governance and regulatory planning, and estimation of potential environmental impacts for planning management, monitoring and mitigation strategies.

1.1. History of CBM and CSG development

Extraction of methane from coal was originally motivated by the desire to lower risks to miners in the gas rich coals of the US Appalachian Basin. In the process, the economic value of the gas itself was recognised and CBM production developed as an energy source in its own right. This happened first in the US where it was initially incentivised by a tax credit (Underschultz, 2016). In Canada, CBM has been produced in small volumes since 2000 but production began to expand in the mid 2000's when the Henry hub gas price went over $5/GJ U.S. (www.iea.org/ugforum/ugd/) making this gas resource economical. By the mid to late 2000's the commerciality of shale gas on the back of improved horizontal drilling and stimulation techniques began to displace CBM. CBM production in the U.S. peaked in 2008 at about 2000 bcf/yr (~2100 PJ/yr) and has declined ever since (Underschultz, 2016).

In January 2015, Australia began exporting CSG as liquefied natural gas (LNG) to Asian and other markets (Towler et al., 2016). This event represented the first time that CSG or any other ‘unconventional gas’ has been developed for the purpose of liquefied export. An overview of

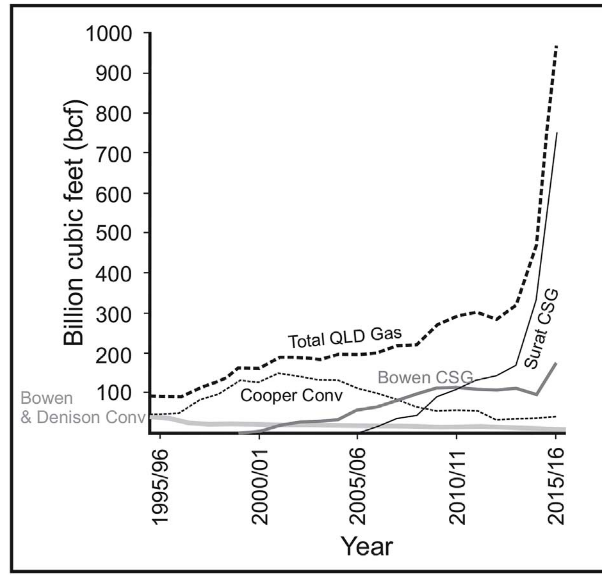

Fig. 2. Queensland conventional and coal seam gas production (modified from Queensland Government, Petroleum and gas statistics, DNRM, 2017). Note that 1.0 bcf equals ~1.05 PJ and ~0.0208 Million Tonnes (MT).

this development is provided by Towler et al. (2016). In Queensland, CSG exploration started in the 1980's with only about 30 wells drilled for this purpose by 1990. The first commercial CSG production occurred from Permian coals of the Bowen Basin in 1990's (DNRM, 2017) which was sold into the domestic gas market. This was followed in late 2010 - early 2011 by a CSG development ramp up to supply LNG for export. Fig. 2 shows the historical gas production in Queensland (Australia), the state in which most CSG gas has been developed. While conventional gas production, particularly in the Cooper Basin has declined since 2002, CSG development has more than replaced this loss with total gas production continuing to rise.

Stratigraphically, the majority of CSG reserves in Queensland come from the Jurassic aged Walloon Coal Measures in the Surat Basin with smaller volumes of gas being produced from various Permian age reservoir zones in the underlying Bowen Basin (Fig. 3), the most important of which are the Baralaba Coal Measures and the Bandanna Formation. Fig. 3 shows the hydrostratigraphic nomenclature where high permeability strata correspond to major aquifers in the Great Artesian Basin that both overly and underlay the coal measures.

1.2. Challenges of CSG development

The shift to unconventional gas has not been without its challenges (Moore, 2012). Concerns about the long term impact of gas development on the environment and particularly groundwater and surface water resources have been paramount. The potential impacts include: 1) reduction in water levels in aquifer systems adjacent to CSG reservoirs (DNRM, 2013; Moore et al., 2015) and stratigraphy depicted in Fig. 3; 2) risk of leaks and spills from surface saline water storage facilities (Davies et al., 2015; Khan and Kordek, 2014; U.S. EPA, 2015); and 3) where CSG produced water is treated for beneficial use, concerns about the handling and storage of brine or salt (Davies et al., 2015; Dean and D'Hautefeuille, 2012). The extent and degree of concern in all of these cases is at least partly related to the forecast annual volume of produced water expected as a result of CSG development. Uncertainty in forecasting produced water (and gas) volumes at the start of large resource projects is high (KCB, 2012; Keir et al., 2013; Moore et al., 2015; USQ, 2011; Vink et al., 2008) and when the public or media refer to these reports they often do not quote or account for the uncertainty. Forecasts in the early stages of the resource development cycle are required to plan infrastructure, understand environmental risks and

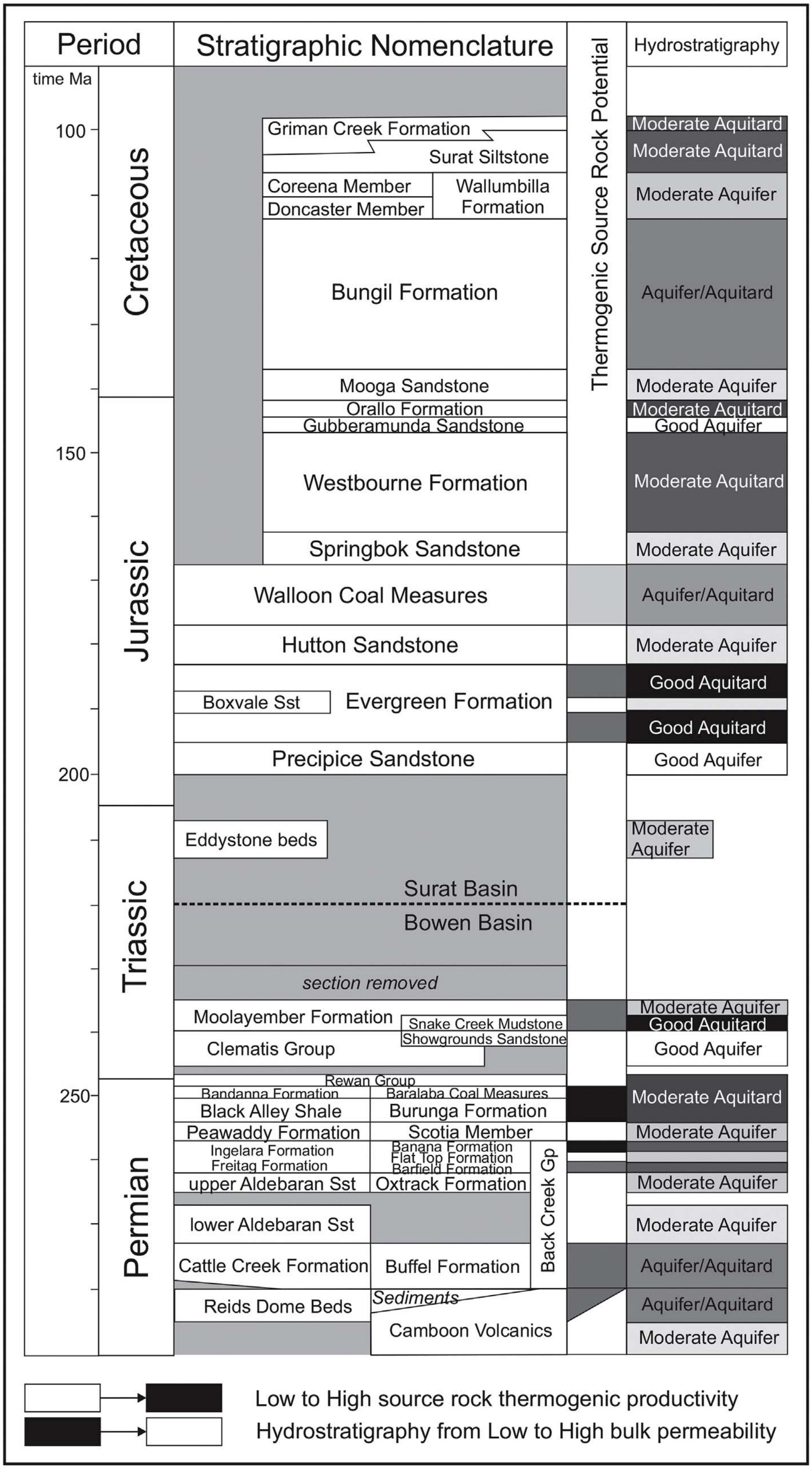

Fig. 3. Stratigraphic nomenclature of the Bowen and Surat basins with indications of source rock and hydro-stratigraphic significance of aquifers and aquitards. Modified from Shaw et al. (2000) and Korsch et al. (1998).

design monitoring, mitigation and water management strategies. Thus, there is a real environmental, social and economic need to not only improve forecast accuracy but also to understand and account for sources of uncertainty in produced water estimates.

In this paper we review the historical forecasting of CSG water production in Queensland leading up to the development and operation of CSG to LNG export. We compare these early estimates to actual produced volumes to date and we examine how new forward estimates benefit from history matching against production. Finally, we assess the sources of uncertainty in water production forecasts so that this can guide improved future assessments.

2. Current CSG water production and forward forecast

CSG production in Queensland has ramped up with all six of the LNG trains now running (although not all yet running to capacity). The recent water and gas production data from across the Queensland CSG assets can be used to history match and calibrate reservoir and groundwater flow models. These history matched models can then be used to forecast future production. Underschultz et al. (2016) examined both proprietary company data and public domain data for gas and associated water production submitted to the state government regulator, and also interviewed industry technology experts with the four main CSG operators in Queensland (Australia Pacific LNG, Santos GLNG, Shell operated Queensland Gas Company (QGC) venture & Arrow Energy) to obtain their current forward gas and associated water production forecasts that had been history matched against production to date. They took data from each of the four operators and aggregated the values to a single industry wide forecast in order to compare and contrast with earlier published pre-LNG production estimates. Each operator has its own internal methodology to forecast future production, but Underschultz at al. (2016) simply utilised the forecast from each company in an aggregated form. The aggregated water production values are presented in Fig. 4 and Fig. 5 as historical (actual) and forecast produced water in units of GL/year and cumulative GL over time respectively. It can be seen that the bulk of the produced water comes from the Surat Basin. History-matched production models at that time (2016) predict a peak in annual produced water to be ~85 GL with an "average peak" of ~80 GL from 2015 to 2025 (10 years) after which water production rates rapidly decrease (Fig. 4). In terms of cumulative produced water (Fig. 5), history matched forecasting would suggest that the total industry wide volume will be just over 1700 GL by ~2065.

3. Historic forecasts of Surat and Bowen Basin CSG water

In the lead up to commercial LNG export there were a number of studies conducted for government (KCB, 2012; Vink et al., 2008), industry through their Environmental Impact Statement reports (e.g.

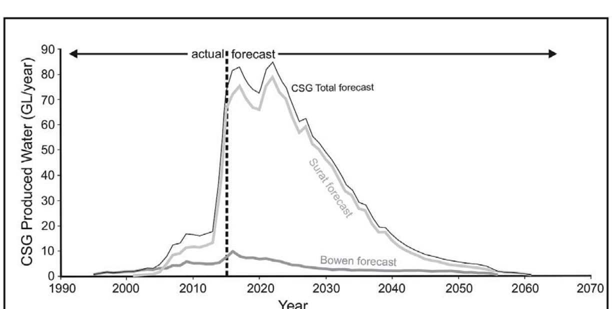

Fig. 4. Actual (left of dashed line) and current forecast (right of dashed line) CSG produced water for the Surat and Bowen basins. Total (Surat and Bowen basins combined) produced water (actual and industry forecast) is shown as the solid and dashed red lines. Data is displayed as GL/year production over time (Underschultz et al., 2016).

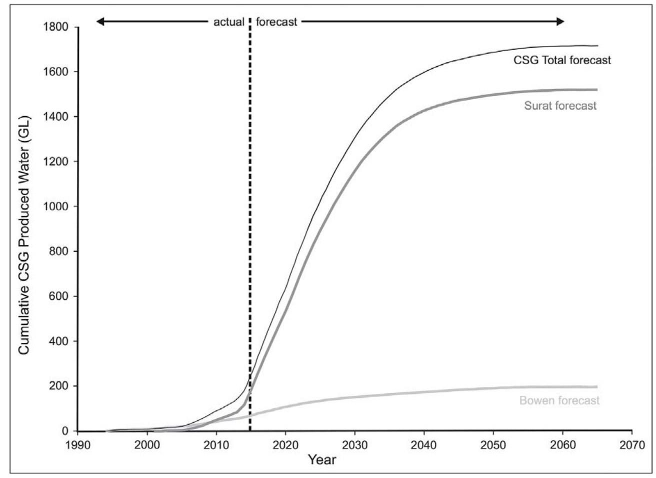

Fig. 5. Actual (left of dashed line) and forecast (right of dashed line) CSG produced water for the Surat and Bowen basins. Total (Surat and Bowen basins combined) produced water (actual and forecast) is shown in the solid black curve. Data is displayed as cumulative GL production over time (Underschultz et al., 2016).

APLNG, 2010), and by research organisations (USQ, 2011; Keir et al., 2013; Moore et al., 2015) on forecasting the volume and quality of water that the CSG industry was likely to produce. Early forecasts made by the government and research organisations had to rely on publically available or government held data that often had not been collected for the purpose of assessing risks of CSG development activity (e.g. Vink et al., 2008) or on estimates made public by the CSG operators. For example, information in the government groundwater database on both water levels and quality was "biased" to productive aquifers with very little information on the hydraulic properties of the coal seams and aquitards (Vink et al., 2008). In addition, where data did exist for the coal seams it was restricted to the shallow subcrop areas where water bores had been installed for agricultural production. These areas are not representative of the wider CSG resource hydraulic properties that occur to greater depth. Historical water production forecasts made for/by government and independent researchers (including Underschultz et al., 2016) are compared with the industry estimates in Fig. 6. The earliest estimates, shown as the two thick grey lines (Vink et al., 2008) represent water production forecasts assuming 28 (solid thick grey line) and 40 Million Tonnes per annum (MT/a) (dashed thick grey line) CSG industry development scenarios. The solid thin black line represents total water production forecast based on the combined four main

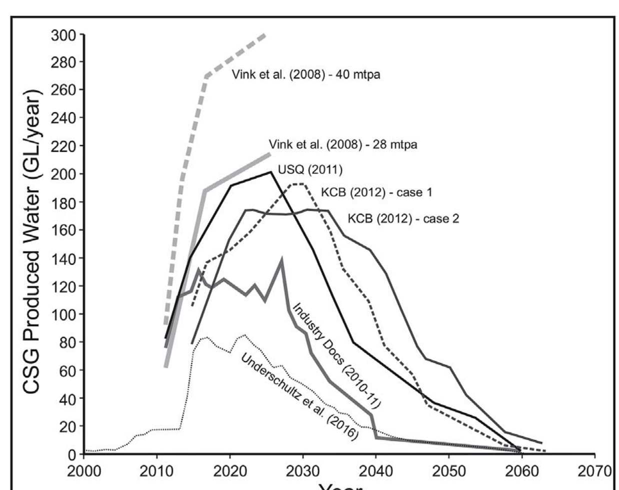

Fig. 6. Combined historical CSG produced water forecasts, modified from KCB (2012) with Underschultz et al. (2016) data added.

individual CSG company (QGC, APLNG, Santos and Arrow) models in 2011 (USQ, 2011). Water production forecasts for two CSG industry development scenarios (KCB, 2012) include the thin dark grey dashed line (case 1) for predicted water production based on a development scenario defined by company supplied data supplemented with information available through EIS reports. KCB (2012) also considered a slower rate of development (case 2) based on the depth to coal and geographical constraints such as the location of towns and transport corridors. Case 2 is therefore a delayed version of case 1, and results in water production represented by the thin dark grey solid line (Fig. 6). It should be noted that both development scenarios assume the operation of 8 LNG trains rather than the 6 that were constructed and KCB (2012) note that there is significant uncertainty in the industry expansion scenarios. The solid dark grey thick line represents the total industry estimates of water production, which was compiled from individual company EIS reports dated between March 2010 and April 2011 (KCB, 2012). Finally, the most recent forecasts made by industry (4 main operators) and calibrated to actual production data (up to the end of 2015) is aggregated and represented by the lowermost thin dashed curve (Underschultz et al., 2016).

Most of the early forecasts assumed a range of gas production scenarios anywhere from 15 to nearly 70 MT/a depending on assumptions regarding how many LNG trains (max = 8) were ultimately to be developed (KCB, 2012; USQ, 2011; Vink et al., 2008). Water production was then estimated from assumptions around a typical water production profile for a well and the number of wells required for a given gas production scenario. Using aggregated water and gas production figures from the period of domestic gas production and assuming typical production profiles such as shown in Fig. 1, water production profiles varied from ~0.02 to 0.35 Mega Litres/day (ML/day) at the start of production tapering to between 0.0 and 0.05 ML/day after 20 years production (QWC, 2012). KCB (2012) used an algorithm that accounts for interference effects between wells depending on location and sequence of development. There has also been a wide range in the estimated number of CSG production wells that will be required to deliver the volumes of gas in the various development scenarios. Cited forecasts of gas well numbers have historically ranged from ~25,000 to > 40,000 (e.g. Australian Broadcasting Commission, 2011; KCB, 2012), which is in excess of the ~20,000 wells for the Surat and Bowen basins now expected to be developed for production (OGIA, 2016). OGIA (2016) also runs a high development scenario of 31,000 wells which is the maximum number of wells possible under current approvals.

The wide variations described above in the gas production scenarios, water production per well, and the number of wells required, all factored into a large uncertainty in the initial forecast volumes of produced water. At peak production, the early (2008–2011) estimates generally ranged between 120 and 300 GL/yr (KCB, 2012; USQ, 2011; Vink et al., 2008). Most of the estimates had a similar profile, with peak production forecast to occur at about the same time (2025–2030). This is primarily due to the overall assumption of how gas production would ramp up to meet specified LNG sales contract targets. The industry estimates of water production at this time tended to be lower than other estimates with peak production on the order of 120 GL/yr and with a broader and flatter "peak" (Fig. 6; KCB, 2012). The industry estimates were based on numerical groundwater models where each company modelled its own assets and planned development (either using groundwater or reservoir modelling software) and then the individual estimates were simply summed (e.g. USQ, 2011). All of these estimates assumed the same area of tenements would be used for gas production but used different model parameterisations of available data. Because these estimates were completed prior to the time when significant CSG production had occurred (prior to CSG to LNG export) there was very little production data that could be used to history match models. In addition, most of these estimates were made prior to final investment decision on all of the 8 proposed LNG trains and the assumption was that all 8 would proceed. Only six were ultimately constructed.

The history matched forecast of water production that Underschultz et al. (2016) gathered were generally derived using two phase dynamic flow (reservoir models) based on current geological static models. Earlier industry estimates (e.g. USQ, 2011) were typically based on single phase, dynamic hydrogeology-type models. It can be seen from Fig. 6 that there has been an overall decrease in water production forecasts with time (including industry estimates) as more information has become available (reduced uncertainty) about the nature of the CSG resource, its interconnection with the other aquifers and how the gas it likely to be produced. The industry estimates have also been consistently lower than other estimates and once there has been some established production to history-match we see a further reduction in the estimated volume of produced water that will ultimately be produced (less than 1/4 of some of the early research/government estimates and ~70% the 2010–11 industry estimates). When this is converted to cumulative water volumes over the life of the industry the Underschultz et al. (2016) forecast is just over 1700 GL (Fig. 5) compared to the earlier estimates of 2500–5,000GL (KCB, 2012).

Based on this same industry data that Underschultz et al. (2016) used, the Office of Groundwater Impact Assessment, OGIA (2016), used a MODFLOW USG model to forecast water production. They conducted a history match based on the entire data set rather than simply amalgamate the individual company model outputs as done by Underschultz et al. (2016). The key differences in these approaches are firstly the primary use of a groundwater flow model vs a reservoir engineering model for the predictions. Secondly by simply using each companies predicted water production output each company estimate only considers their own assets in isolation, whereas OGIA history matched the data from each company combined as one dataset thereby allowing well interactions across the entire area to be accounted. The OGIA (2016) model predicts a peak of 110 GL/yr with a CSG resource lifetime average water production of 70 GL/yr.

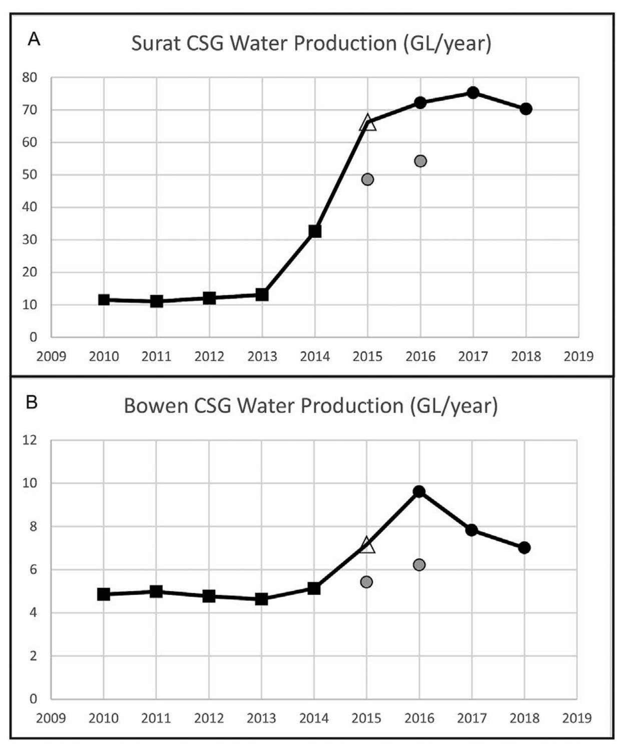

Fig. 7. Zoom in of Underschultz et al. (2016) with black square symbols being actual data and black circle symbols being forecast values. Note that the open triangle symbol is a combination of 6 month actual and 6 months forecast values. Since Underschultz et al. (2016) new data for the period July 2015 to December 2016 is shown by the grey circles. A) is data for the Surat Basin and B) is data for the Bowen Basin.

For this paper we now take the Underschultz et al. (2016) graphs (the lowest publically available water production forecast to date for Queensland CSG development) that were grounded in actual production data to mid-2015 and add another 18 months of new actual production data that has since become available. Fig. 7 zooms in on the time period from 2010 to 2018 and plots the data from Underschultz et al. (2016) which consists of actual data to June 2015 and forecast production post June 2015 and it splits the data for the Bowen and Surat basins into separate graphs. Note that the Underschultz et al. (2016) data point for 2015 is a sum of 6 months actual and 6 months forecast production. The two new points in Fig. 7 for the Surat and Bowen Basin graphs represents the new data for actual production in 2015 and 2016. It can be seen that again the actual produced water values are tracking below the forecast value made only 18 months ago. This could be due to the Underschultz et al. (2016) forecast being based on amalgamating the four main gas operators individual forecasts each of which does not account for cumulative depressurization effects across all operator assets.

3.1. Water quality forecasts

The chemistry of CSG/CBM produced water, like production volume, also varies considerably between coal basins and in some cases within individual gas field assets. The nature of water produced with gas from coal depends on a number of factors including: the depositional environment and the coal type; the permeability of the coal; and the permeability of the formations above and below (Jackson and Myers, 2002).

CSG/CBM waters are typically characterised by total dissolved solids (TDS) between fresh and sea water. The water type tends to be sodium-chloride or sodium-bicarbonate dominated with very low to absent sulfate. Calcium and magnesium concentrations can be elevated giving CSG/CBM water its characteristic hardness (Van Voast, 2003; Kinnon et al., 2010; Baublys et al., 2015; Owen and Cox, 2015). The Healthy Headwaters report (DNRM, 2013) provided a widely cited reference as to what a "typical" CSG produced water chemistry could be expected once the production of CSG to LNG got underway in Australia. It provides a range of major ion concentrations (Table 1). The significance of produced water quality is that this will drive options for the beneficial use of the water, with or without treatment, and will influence the operating challenges associated with surface storage facilities, water treatment plant and storage of the end by-products (brine and salt).

Similarly to the water production forecasts, there is much more data now available on the chemistry of the produced water. A growing water chemistry analyses database for water produced from the coal seams in the Bowen and Surat basins (Hunter et al., 2015) are proving to fit within the previously described global trends. The TDS values of produced water from the Bowen and Surat Basin coals are summarised in Table 2. Whilst the TDS ranges from < 1000 mg/L to over 18,000 mg/L this includes the extreme tails of the distribution. A more representative range is the 20th – 80th percentile of ~8000–9000 mg/L for the Permian aged Bandanna Coal Measures of the Bowen Basin and ~2000–3000 mg/L for the Jurassic aged Walloon Coal Measures of the Surat Basin. Waters from the older and deeper Bandanna Coal Measures with a median salinity of ~8900 mg/L are distinctly more saline than the younger and shallower Walloon Coal Measures with a median salinity of ~2500 mg/L. The grouping of data "CRA-WCM" represents wells completed near to or across the stratigraphic boundary where the Condamine Alluvium (an unconsolidated surficial alluvial aquifer) directly overlies the Walloon Coal Measures. The relatively low TDS (median value of ~400 mg/L) in these waters is due to the shallow depth and possible better hydraulic connection on the geological time scale, to more recent recharge. The trends in TDS more broadly can be related to the relative residence time of water in coal seams (increasing TDS with age) coupled with cation exchange on clays and removal of SO_4 through sulfate reduction. Water quality data for the Bandanna Coal Measures was only collected from CSG wells while data for the WCM has been collected from gas wells and water bores. Comparison of TDS measured in the Walloon Coal Measures from CSG wells and groundwater bores with a screened interval exclusive to the Walloon Coal Measures is shown in Fig. 8. It can be seen that with the exception of a few outliers, the groundwater bores generally have lower TDS. This result is not surprizing given that the purpose of the groundwater bores is to supply water for agriculture.

The statistical variation of major ion concentrations is shown in Table 3 and is complimentary to the TDS data in Table 2. Alternatively, the data can be displayed on a trilinear plot (Piper Diagram) that allows the visualisation of various water types (Fig. 9). The major ions show that the coal seam waters have very low relative proportion of SO_4, are mostly dominated by Na and either Cl or HCO_3. Interestingly, waters from the CRA-WCM tend to have slightly higher proportion of SO_4 and much higher proportion of Ca and Mg relative to Na. The major ion composition of these waters ranges from being very similar to the coal seam waters to a composition that is more representative of surface waters. The TDS of these samples however is similar, being comparatively fresh and not varying concomitantly with a change in composition.

With more data now available for each of the coal reservoirs it becomes obvious that the detailed formation water chemistry is quite specific to each reservoir. The Healthy Headwaters reported CSG produced water characteristics (Table 1) record a range of cation and anion concentrations that encompasses the characteristics of both the Permian and Jurassic coal reservoirs. For example, Table 3 (using the 20th and 80th percentile as a guide) shows that SO_4 is less than 2 mg/L in the Walloon Coal Measures but ranges up to 26 mg/L in the Bandanna Formation. Because of the salinity difference there is also a marked contrast in the Na and Cl concentrations typical for each reservoir. The combination of these characteristic values gives a characteristic ionic chemistry for each reservoir readily distinguishable on a trilinear diagram (Fig. 9).

Some of the variation between earlier and current water quality estimates is due to the nature of data availability. Early estimates were based on information available in the Queensland Government groundwater database that was primarily compiled for groundwater resource planning and was therefore biased towards better quality water. The inclusion of CSG well data in current estimates provides water quality attributes that more accurately reflect water quality to be produced by the industry. Both datasets demonstrate the high variability in water quality in the coal seams across the basin and must be recognised in evaluating beneficial use and environmental risk.

It should be noted that the relative water production volumes from the Bowen and Surat basins (Fig. 5) together the relative salinity characteristics of each reservoir (Table 2), means that the bulk of the produced water is expected to be of the better quality (200–3000 mg/L for the Surat Basin rather than 8000–9000 mg/L for the Bowen Basin). This observation in turn has an impact on estimates of the brine and salt

Table 1
The range of "typical" CSG produced water major ion chemistry (DNRM, 2013).

	Min (mg/L)	Max (mg/L)
TDS	79	11,300
SO_4	0	25
Cl	1	4680
N	< 0.01	7.2
$CaCO_3$	1300	2519
F	0.1	16
Na	36	4280
K	0.1	78
Ca	0.1	59
Mg	0	45
Fe	0	190

Table 2
Statistical values of total dissolved solids (TDS, in mg/L) for Queensland CSG produced water. All the data and subsets for the Permian aged Bandanna Formation, the Jurassic aged Walloon Coal Measures, and the Walloon Coal Measures that occur immediately beneath the unconsolidated surficial alluvial aquifer are provided. The grouping of data "CRA-WCM" represents wells completed near to or across the stratigraphic boundary where the Condamine Alluvium (an unconsolidated surficial alluvial aquifer) directly overlies the Walloon Coal Measures.

	n	Mean	Median	Min	Max	20th percentile	80th percentile	standard deviation
All data	713	2866	2500	101	18154	2100	3300	1626
Bandanna	11	8767	8920	7160	10200	8290	9160	822
WCM	693	2803	2500	101	18154	2100	3200	1442
CRA_WCM	9	494	396	258	894	390	872	226

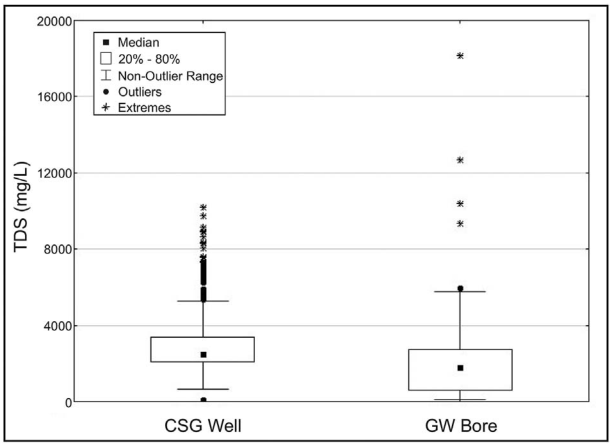

Fig. 8. A box and whisker plot of the total dissolved solids (TDS mg/L) of Walloon Coal Measures water samples categorised by well type. CSG well is a coal seam gas production well and GWDB is a groundwater bore with a screened interval completed in the Walloon Coal Measures.

volumes expected over the life of the industry as a result of water amendment for beneficial use (primarily through reverse osmosis desalination and subsequent brine concentration). KCB (2012) used a simple mass balance approach to convert their forecast of water production and water quality into a rudimentary forecast of total salt production. The cumulative value that they estimated by this approach was between 27 and 50 megatonnes representing their P25 and P75 confidence band with an average value of ∼39 megatonnes. If the Underschultz et al. (2016) forecast is used and the same KCB (2012) approach is implemented, then the volume of salt to be produced for the CSG industry in QLD is 5.5 megatonnes.

4. Predicted cumulative conservatism in forecasting

The Australian experience of forecasting produced water with CSG development is that early in the resource development cycle produced water has been consistently and significantly overestimated. In terms of the potential environmental risks, overestimating water production would present a worst case, which flows through to more conservative (ie highest potential cost) estimates of economic and social risk and has led to the over-design of water treatment facilities.

We investigated the possible sources of this conservatism to determine if an alternative approach could be adopted in future. Since CSG resources are relatively shallow (typically less than 1,000 m) and geographically widespread, they are normally exploited by drilling hundreds of densely spaced wells across a tenement. Variability in gas and water production performance is wide ranging (e.g. Fisk et al., 2010; Lin et al., 2015; QWC, 2012; Sharma et al., 2013). A common approach to prediction of produced water is to take the gas industry's estimate of development wells to be drilled over a given time period and apply an average water production or 'typical' gas-water ratio per well. In other words, most government and academic assessments require gas industry development scenarios as a starting point. When there is more than one industry operator, the development scenarios supplied by each operator are amalgamated to form an overall view of how CBM/CSG development is likely to proceed. However, the uncertainty in the individual operator development scenarios is not normally considered in its entirety. Howell et al. (2014) describe challenges in water production estimates for fields using conventional petroleum industry 'history matching' approaches but for CSG companies with significant, dedicated technical resources and large data sets. However, individual operators are normally not privy to their competitor's development plans and thus they fail to account for cumulative effects of multiple operators' production on adjacent tenements from the same reservoir that could reduce the volume of water production required to achieve sufficient depressurization to desorb gas.

Industry development scenarios will, necessarily include their own aggregate water and gas production rates as well as 'name plate' throughput capacity for key equipment such as compressors or water treatment plants. Third party forecasters will then use this information

Table 3
Descriptive statistics of major ion chemistry for the Bandanna and Walloon Coal Measures.

	n	Mean	Median	Min	Max	20th%	80th%	s.d.
Bandanna Coal Measures								
TDS (mg/L)	11	8767	8920	7160	10200	8290	9160	822
pH	7	7.96	7.88	7.79	8.36	7.79	8.02	0.20
Ca (mg/L)	11	22	22	17	32	18	24	5
Mg (mg/L)	11	5.5	5.0	5.0	7.0	5.0	6.0	0.7
Na (mg/L)	11	3219	3260	2060	3710	3200	3480	441
K (mg/L)	11	81	74	49	139	63	90	26
Cl (mg/L)	11	4095	4310	2850	4660	3910	4490	514
SO_4 (mg/L)	11	19	17	2	56	3	26	17
HCO_3+CO_3(as $CaCO_3$) (mg/L)	11	1894	1850	1090	2630	1730	2080	382
Walloon Coal Measures								
TDS (mg/L)	717	2827	2500	326	18154	2100	3300	1430
pH	689	8.49	8.50	6.60	9.50	8.30	8.70	0.26
Ca (mg/L)	723	13.7	6.4	0.08	920	4.9	8.6	47.4
Mg (mg/L)	723	6.8	0.8	0.03	850	0.6	2.2	39.2
Na (mg/L)	723	1061	950	42	4550	760	1200	505
K (mg/L)	722	6.2	3.7	0.5	270	3.0	6.0	14.5
Cl (mg/L)	723	890	570	60	10000	320	1200	979
SO_4 (mg/L)	720	7.1	1.0	0.5	1650	0.5	2.0	65.3
HCO_3+CO_3(as $CaCO_3$) (mg/L)	723	1221	1300	28	2500	738	1600	455
CRA-WCM								
TDS (mg/L)	9	494	396	258	894	390	872	226
pH	9	8.19	8.20	7.60	8.90	7.70	8.40	0.39
Ca (mg/L)	9	34	34	4	61	30	37	14
Mg (mg/L)	9	21	23	2	28	21	26	8
Na (mg/L)	9	124	81	66	286	77	270	88
K (mg/L)	9	3.3	3.4	0.9	5.1	2.8	4.4	1.2
Cl (mg/L)	9	105	71	46	236	65	235	75
SO_4 (mg/L)	9	10	10	6	13	8	11	2
HCO_3+CO_3(as $CaCO_3$) (mg/L)	9	298	268	95	462	258	462	113

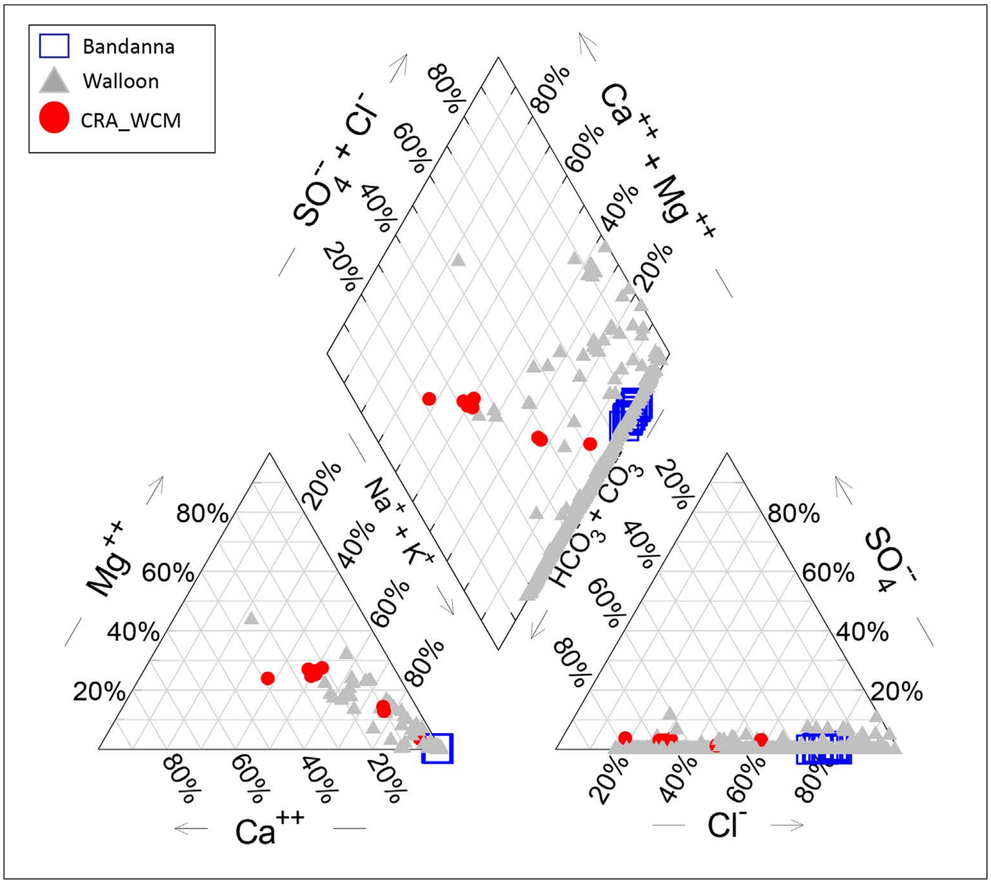

Fig. 9. Trilinear diagram for the major ion composition of Permian aged Bandanna Coal Measures and Jurassic aged Walloon Coal Measures. Walloon Coal Measures data are further subdivided by well type (CSG wells and Groundwater bores from the GWDB database).

to inform, constrain or develop their own model predictions. Often the confidence levels in water production rates derived from these scenarios and 3rd party models is unstated. The tendency is for third parties to assume that industry forecasts and specifications are 'base-case' or 'mid-case' case estimates. However, several factors combined mean that this may not be a sound 3rd party assumption. Industry development scenarios (i.e. engineering choices made on the numbers and spacing or wells, the sizing of pipelines and water holding and treatment infrastructure) are driven by gas and water production forecasts. Because of large uncertainties in reservoir properties (connectivity, permeability, gas yield etc.), a suite of forecasts have to be produced in order to capture the range of uncertainties in well by well and aggregate fluid production (Shields et al., 2015). Within this suite, gas and water production forecasts are critically dependent on subsurface data and models, which cannot be fully constrained and therefore require additional assumptions. Where water production is concerned in CBM/CSG modelling, there are likely to be inherent modelling biases which cause estimates to be on the high side of actuals (e.g. Moore et al., 2015).

4.1. Bias due to engineered system sizing

The nature of CSG production is such that produced water must be managed in order to assure continued gas production. In the face of high water production rate uncertainties, discrete engineering choices need to be made about the maximum throughput of facilities. To make these on a P50 basis, for example, would incur (by definition) a 50% risk that the facilities would be too small and thus gas production would need to be curtailed. However, engineering to a very high (but far less certain) water production estimate would incur significant cost. A trade-off between cost and risk must be arrived at. Clearly a 50% chance that insufficient gas would be produced is too high, however a company may be able to accept a 10%–20% or higher chance depending on what other gas supply mitigation measures they might have in their wider business portfolio (Shields et al., 2015). This might also depend on what mitigation measures they have to quickly build extra capacity if the down-side risk eventuates and more water is produced than was engineered for. In addition to the factors relating to modelled production uncertainty, engineers must also account for facilities availability (across a system) to allow for continuation of gas and water throughput during planned maintenance and unplanned downtime. Further complicating matters for 3rd party estimators seeking to derive production rates from published development plans, equipment can run with higher physical throughput than name-plate capacity (name-plate is not an absolute maximum). Given this, it is highly likely that industrial development scenarios will involve *over*-sized equipment. Discussions with gas industry professionals have indicated that engineered systems are built for a range of production forecasts from P50 + 10% to P50 + 100%. As an example of this, in 2012 a significant amount of water treatment capacity was reportedly built or under construction in Queensland (GWI, 2012) with a total capacity of 152 GL/yr. This is approximately 20% higher than the combined company forecasts in the period 2010–2011 (Fig. 6) and 90% higher than the more recent "current" history-matched, company consolidated forecasts (Underschultz et al., 2016).

4.2. Bias due to numerical simulation

By their nature CBM/CSG resources occur across wide geographic regions at depths up to about 1,000 m which means that the coal reservoir often occurs adjacent to usable groundwater aquifers. In order to understand, model and predict the water and gas production behaviour of a single production well the simulation software needs to account for a number of physical processes such as: Darcy flow from the coal cleat system, gas desorption according to Fick's law from the coal matrix, and then multiphase Darcy flow in the cleat system that takes into account relative permeability and compressibility of multiple fluid and solid phases (Moore et al., 2015; Herckenrath et al., 2015). Complicating things further, the in-situ stress and its anisotropy, coal compressibility and coal matrix shrinkage can also significantly impact production characteristics due to transient permeability.

A number of multi-phase flow simulators can account for coupled processes but they tend to be limited to modelling the detail of the reservoir horizon (multiple individual coal seams with interburden layers) over a limited geographic area such that the model domain can be discretised into sufficiently small grid blocks that the model remains stable (i.e. achieves convergence). It is also at this scale and location of the reservoir that there is often the most data that can be used to parameterise the discretised model domain. Conversely, the requirement to understand produced water volumes across a broad region and the cumulative effects of gas development on adjacent aquifers precludes the ability of having a detailed modelling mesh considering multiple coupled processes. As a result there is an upscaling that must occur that simplifies the detailed geological heterogeneity (Moore et al., 2015).

Many of the regional models used to predict cumulative effects are run using single phase regional groundwater flow models such as MODFLOW (Cox et al., 2001; Myers, 2009; QWC, 2012) or FEFLOW (Moore et al., 2015) and their derivatives. In Queensland one of the operators used oil industry simulation software ECLIPSE and ECLIPSE H2O as a regional impact assessment tool (Howell et al., 2013) in addition to groundwater models. They found that the regional scale and the low data density for some parameters such as recharge, water use distributions and rock properties, resulted in a high degree of non-uniqueness in the calibration process. A code comparison study (Moore et al., 2015) on a Surat Basin case study in Queensland that focused on the prediction of pressure decline, found that single phase groundwater models systemically overestimated the pressure drawdown compared to dual phase reservoir models. This was mainly due to the transient reduction in the relative permeability of water near production bores as the gas saturation increases within the cleat porosity. This effect is not accounted for adequately in the single phase regional groundwater models. Although this is a detailed scale near wellbore process, it has significant implications to prediction of regional water phase pressure decline. They also noticed an impact from upscaling the detailed geometry and rock properties of individual coal seams and inter-burden, to bulk coal measure equivalent rock properties in regional groundwater models. The combination of systemic and potentially cumulative conservatism with the inherent bias of regional single phase groundwater models to overestimate water production, provides an understanding of why historically produced water forecasting early in the resource development cycle has consistently overestimated produced water volumes.

In the case of Queensland CSG development each of the four major CSG operators has, based on a common understanding of the science, tailored its own modelling approach to forecast water production, reservoir depletion and potential impacts on adjacent aquifers. Each operator has access to different data both in terms of the static geological model, rock properties to parameterise the model and the field development plan. The Government regulator OGIA has also developed and maintains a regional geological model for what they define as the Surat Cumulative Management Area (CMA), but they have access to all of the operator's data. A summary of these models and their attributes is given in Table 4. USQ (2011) conducted a comparison of the four operator company models and noted that because they had different acreage and different data sets, parameters such a bulk permeability assigned to a particular geological formation could be quite different between them. The significance of the variation in parameterisation appears to be more acute for the low permeability sealing horizons such as the Eurombah Formation where assigned permeability ranged by 2 orders of magnitude (0.00062–0.05 mD) and the Walloon Coal Measures upper confining layer (0.00044–0.05 mD). Two main contributors to the tendency for regional groundwater models to over-predict CSG produced water were found to be: 1) the effects of scale, and 2) the effects of simplifying coupled processes.

4.2.1. The effects of scale

Many of the key governing processes in the multi-phase flow behaviour of CSG/CBM production occur at scales much smaller than can be represented in regional groundwater models, thus some up-scaling is required. For example, regional groundwater models are discretised on the order of a 1 km cell size (Myers, 2009; OGIA, 2016; QWC, 2012) and often cell thickness is set to an entire aquifer thickness or large parts thereof. Assigning a single bulk permeability to a cell in the model requires upscaling from core plug or wireline measurements. The upscaling process involved the simplification and loss of detail that may be important to local scale flow processes. This can be mitigated by a combination of history matching to observed transient data and model calibration processes. Not only are the values quite different, but they can't reflect the degree of geological heterogeneity that we know exists on a smaller scale. The difference in selected permeability values from various upscaling techniques tends to be more significant in the low permeability strata than for the higher permeability aquifers and the hydraulic performance of aquitards is crucial when predicting cumulative impacts of resource development on adjacent aquifers.

If we look at the actual vertical distribution of permeability, we see that finer scale, geological heterogeneity will dominate fluid flow. For example, QGC drilled a water monitoring bore Woleebee Creek GW4, and collected a continuous core. From this core, they had a complete vertical profile of core plug analyses conducted. Fig. 10 shows the measured permeability presented as a vertical distribution at this location. If we look at the Hutton Sandstone section it is possible to see several higher permeability values but with the bulk of the Hutton Sandstone strata having much lower permeability. Both the flux of formation water and the transmission of pressure perturbations will be significantly impacted by this permeability distribution. Yet this detail is impossible to replicate with a single permeability value for a model cell representing the entire Hutton Sandstone thickness (Bachu and Underschultz, 1992). Making the bias worse, normal procedures for coring and plug selection for routine core analysis may be skewed towards the more permeable sections of the stratigraphy. The vertical profile shown in Fig. 11 will also vary from one geographic location to the next and high permeability sand bodies may be individually laterally discontinuous (USQ, 2011). Moore et al. (2015) noted that this bias in sampling and subsequent upscaling processes inherently leads to an overestimate of the formation water flux at production bores in regional models.

4.2.2. The effect of simplifying coupled processes

A second underlying cause for regional groundwater models to bias overestimation of water production is related to simplifying “coupled” multiphase flow and geomechanical processes. For example, KCB (2012) use a modified Thiess solution to estimate water production from individual “cells” across a model domain and made allowances for interference effects. This approach however assumes an availability of water without considering either material balance (Shields et al., 2015) or coal matrix shrinkage with gas production or compressibility of both the water and fractured rock matrix under changing effective stress and differential confining stress (Palmer and Mansoori, 1996; Wang et al., 2014). By not taking these coupled processes into account the water production component will be overestimated.

The nature of coal seam production is a progression from high water

Table 4
Attributes of the groundwater models initially run by each of the four main CSG operators and the government regulator in Queensland (modified from USQ (2011)).

Project	Purpose	Code	Area (km^2)	# Layers	Calibration	Sensitivity Anal
APLNG	Regional Surat	FEFLOW	172,740	23	Steady State	Yes
QGC	Local Models	MODFLOW	17,280	18	No	No
Santos	Regional Surat	FEFLOW	153,100	19	Steady State	No
Arrow	Regional Surat	MODFLOW	122,763	15	Steady State/transient	No
OGIA (2012)	Bowen/Surat CMA	MODFLOW	363,000	19	Steady State/transient	Yes
OGIA (2016)	Bowen/Surat CMA	MODFLOW USG	299,000	32	Steady State/transient	Yes

cut to low water cut as reservoir pressure declines and gas desorption from the coal matrix increases. The nature of fluid migration along the cleat system to the production bore is a multiphase flow process that is highly dependent on the relative permeability of the cleat to water and methane. The relative permeability can be a function of the fluid saturation, coal mineralogy, rank, and organic and clay content (Mahoney et al., 2015). While most of these factors are fixed, the relative water and gas saturation changes with production. As the reservoir rock near the production bore changes from high water saturation to low water saturation the relative permeability to water decreases and thus the flux of water decreases for the same hydraulic gradient. The details of this near wellbore effect are not typically accounted for in regional groundwater models. Moore et al. (2015) discusses how this coupled process is important at regional scale and why regional groundwater models systematically overestimate water production.

4.3. Predicted and actual rate of gas development in Queensland

There is a possibility that gas asset development has been slower than outlined in initial field development plans and that this could have contributed to less than predicted associated water production. To investigate this we looked at the long term contracted gas delivery upon which the final investment decision was made to build CSG to LNG export facilities. Fig. 11 shows the published contracted gas volumes as reported to the COAG Energy Council in 2015, with data that are shaded according to gas operator where they appear cumulatively and over time. The total volume of gas for international export contracts peaks at just under 25 MT/a (~1200 bcf or ~1300 PJ) in 2019. If we compare this with the actual gas production (Fig. 2) we can see that 2016 Bowen and Surat production was already ~1000 PJ combined of which CSG makes up some 900 bcf (19 MT). This would suggest that the gas development is roughly on track to meet international contract schedules. However, the current development area is ~45% less that planned to be developed, reducing from ~21,000 km^2 (OGIA, 2012) to ~12,000 km^2 (OGIA, 2016). The well count is also less than originally predicted for this stage of development. Fig. 12 A shows the production well count over time together with the actual gas (PJ per 6 months) and water (GL per 6 months) production to 2016. The slope of the curves suggests that gas production is increasing faster than water production and more importantly, despite the well count tapering from 2015 onwards, the gas rate continues to climb.

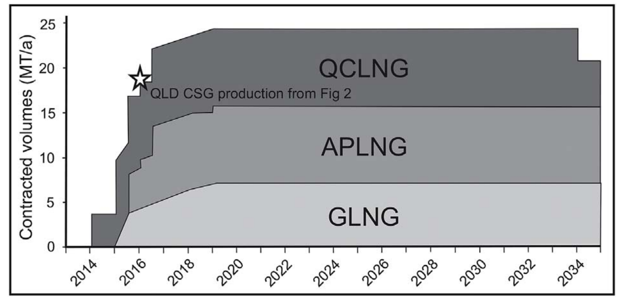

Fig. 11. Contracted gas volumes as reported to the COAG Energy Council in 2015, with data that appear cumulatively and over time.

To examine the effectiveness of production wells we use the data from Fig. 12 A and calculate the average ML water production per PJ of gas production per 6 month interval. This ratio is plotted in Fig. 12 B. The trend of data in Fig. 12 B shows that during the period from 2005 to 2014 there was a general improvement of reducing ML of water per PJ of gas production. This is a period of reasonably few CSG assets being developed, exclusively for domestic consumption, with fewer than 2000 production wells. However, over that time there are consistent production gains relative to the produced water with the water/gas ratio consistently dropping. From 2015 onwards there is first a spike in water production relative to gas production followed by a sharp and continuous decline. This second cycle corresponds to the start-up and development stage of CSG to LNG export. It indicates that the initial spike

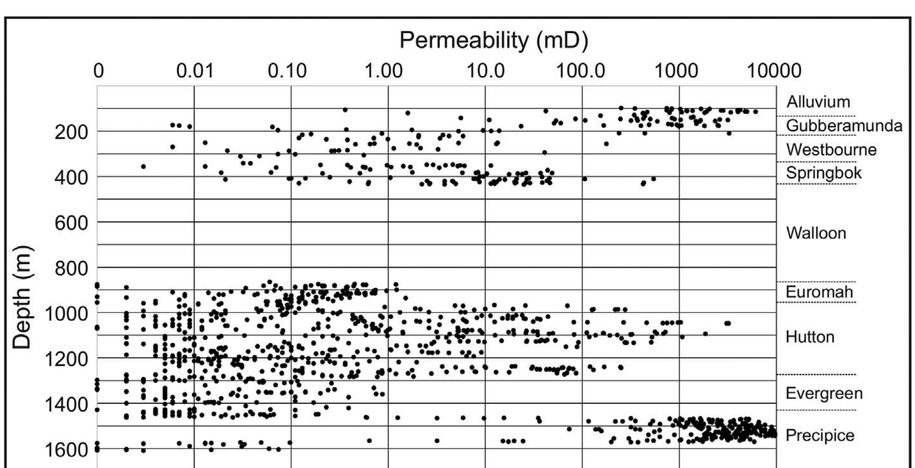

Fig. 10. The vertical permeability profile (black dots) based on routine core analysis on core plugs from continuous core taken from the QGC Woleebee Creek GW4 bore in the Surat Basin. The main stratigraphic horizons are marked with a colour coded background to the plot.

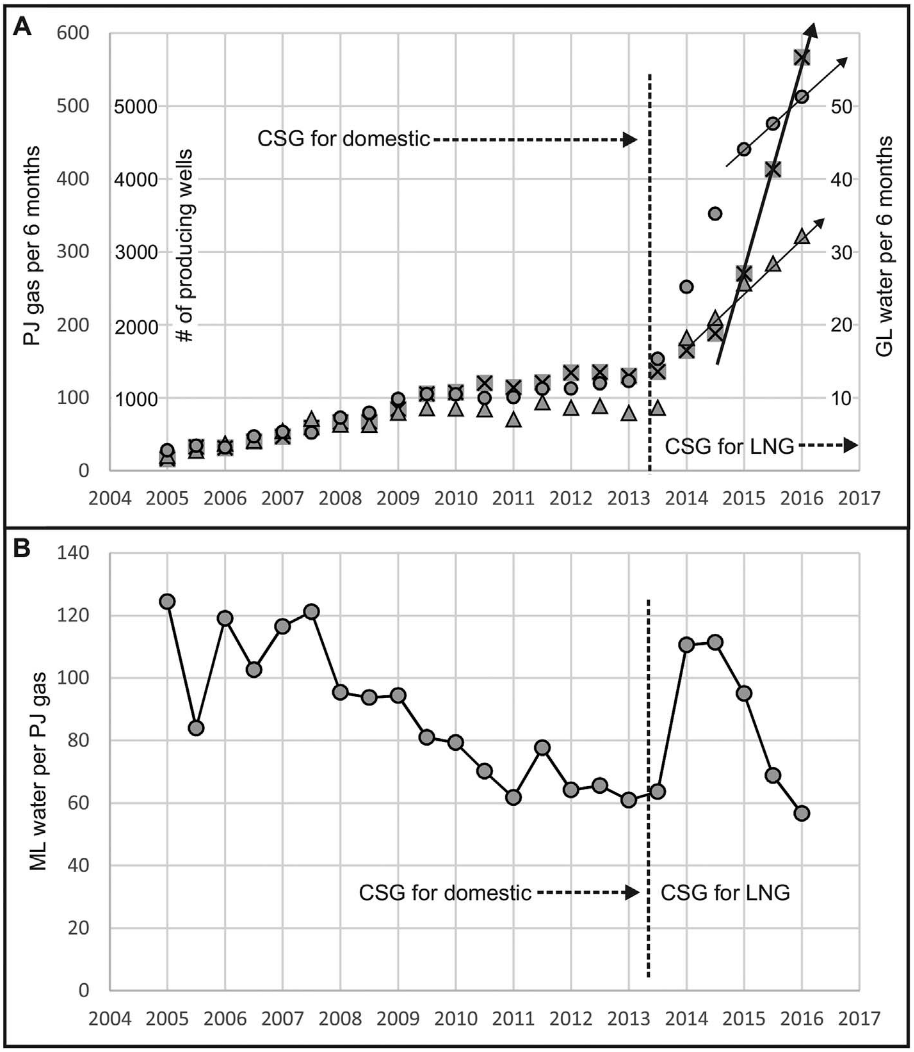

Fig. 12. A) Number of CSG production wells in the Surat and Bowen basins combined (circles), gas production in PJ per 6 month interval from production wells in the Surat and Bowen basins combined (squares with an X), and water production in GL per 6 month interval from production wells in the Surat and Bowen basins combined (triangles). B) CSG production well efficiency plotted as a ratio of average ML water production per PJ gas production across the Surat and Bowen Basin. Data from Fig. 12. A was used to calculate the production ratios in this plot.

in water production relative to gas production is the result of initial depressurization of new asset development. Subsequently, there are gains in gas production evident that may be due to cumulative effects from regions already depressurised. USQ (2011) noted that individual operator models (Table 4) did not account for neighbouring operator's activities because they had no access to competitor's field development plans or data. Pressure interference between neighbouring operations could result in achievement of the target reservoir pressure depletion with less water production. The significant changes in water to gas production ratio at the asset level (Fig. 12B), with a clear trend towards less water per PJ of gas, is not accounted for in the standard approach to estimating water production based on a per well average production profile.

5. Discussion

In Queensland, the actual produced water in the operational phase of CSG to LNG production, and the current forward forecast based on recent production history matching is about 70% of industry estimates made in 2010-11 and only 25% of some early estimates made by government and academia. Early production information would suggest that the industry conservatism built into water production estimates also applies to the gas production, with the average well producing both less water but also more gas than the early estimates predicted. Part of the lower than expected water production could be attributed to slippage in field development planning schedules, but gas production appears to be on track to meeting long term contracts on LNG export. It appears that this will be achieved with fewer than the originally anticipated number of wells. We have seen that depending on the purpose of the modelling (field development planning to minimise project risk, prudent regulatory governance or environmental impact assessment and management) there are legitimate reasons why conservative approaches are taken. However, when these become cumulative it can result in very high estimations of produced water from CBM/CSG development, particularly at early stages of the resource development cycle.

The Queensland gas industry project development plans for CSG to LNG export revolve around achieving a target gas delivery. The infrastructure required to accomplish this is dependent on model predictions of production well performance that are based on a host of uncertain subsurface variables. Engineers thus factor modelled production uncertainty and account for facilities availability (across a system) to allow for continuation of gas and water throughput during various operational phases of a project. The requirement to maintain gas supply results in field development plans that are purposefully conservative resulting in high side water production estimates. Government and academic modelling of CSG produced water normally require industry development scenarios as a starting point. As has been seen, these should not be considered to be mid-case or P50 estimates. Failure to recognise this by others who use this information such as government or academia, will likely lead to further over-estimates.

One purpose of government and academic modelling of associated water production, particularly in Queensland, was to predict the volume and distribution of CSG produced water over time so that beneficial use schemes could be matched to availability of water (KCB, 2012). Additionally, these forecasts were also required to characterise a 'worse case' risk of CBM/CSG development that could lead to an environmental impact. This could be any of the previously identified concerns: 1) reduction in water levels in aquifer systems adjacent to CSG reservoirs (DNRM, 2013; Moore et al., 2015), 2) risk of leaks and spills from surface saline water storage facilities (Davies et al., 2015; Khan and Kordek, 2014; U.S. EPA, 2015), and 3) where CSG produced water is treated for beneficial use, concerns about the handling and storage of brine or salt (Davies et al., 2015; Dean and D'Hautefeuille, 2012). The extent and degree of concern in all of these cases is at least partly related to the forecast annual volume of produced water expected by CSG development.

Early in the resource development cycle when uncertainty is highest, the inherent tendency in industry, government and academia is to produce conservative forecasts of worst case scenarios so that the down side environmental impacts of the future mature industry can be considered and planned for with adequate monitoring and mitigation strategies put in place. Therefore the tendency is to take the industry scenarios (which are already conservative due to the modelling approaches taken and for engineering and economic reasons as explained above) and add additional uncertainty related to the potential environmental impact, and then ensure forward modelling covers these worst case scenario. This inadvertently compounds the conservatism in the forward modelling.

In addition to the inherent conservatism discussed previously, there are key physical processes acting at various scales that typically are not adequately accounted for in modelling approaches commonly used. Relative permeability and multi-phase saturation changes of water and gas in the near well environment (metres away from the production bore) during the initial stages of gas production are difficult to account for in a regional reservoir or groundwater model with a necessarily large cell size (hundreds of metres). At a larger scale, cumulative impacts of pressure depletion from initial water production, particularly when large adjoining assets are being developed concurrently, will reduce the water production requirements to obtain optimal bottom hole pressures on subsequent production wells. This is not normally accounted for when basing water production on a typical well production profile and multiplying it by the estimated number of development wells.

If we consider the importance of accurate water production forecasts, one example is the estimated volume of salt that ultimately needs to be managed if the produced water is amended for beneficial use, as is the case in Queensland. In this paper we have described that between very early estimates and current estimates with substantial production as a history match, cumulative produced water forecasts range from 5000 GL to 1700 GL respectively. The current forecast of 1700 GL is 800 GL less than the low case of a forecast from Vink et al. (2008) which was one of the earliest forecasts with least constraining data. If we couple this with early estimates of the salinity for CSG water from 79 to 11,300 mg/L (DNRM, 2013) we could calculate a range of salt over the life of the industry to be anywhere between 0.134 megatonnes and 56.5 megatonnes of salt respectively. KCB (2012) forecast an average case to be ~39 megatonnes. The current industry estimates for water production presented here coupled with a better knowledge of the produced water salinity results in an estimated 5.5 megatonnes of salt. The difference in risk of environmental impact between the extremes of this salt production range is significant as are the associated management implications required to mitigate the risk.

The motivation for conservatism can be rationalised and is understandable. However, it is important to recognise that this approach could contribute to pre-resource development predictions that are higher than the actual produced water volume and the associated level of environmental risk and mitigation requirements. Technical and non-technical factors indicate that in future, better pre-production estimates are critical to better characterise uncertainty ranges based on analogue forecasting experience and a rigorous analysis of the sources and compounding of uncertainty.

6. Conclusions

Now that six LNG trains are running, we have collected current CSG production data and interviewed the four main operating companies in Queensland regarding their most recent history matched model forecasts of CSG produced water over the life of the resource. We found the median CSG produced water chemistry from the Surat Basin Walloon Coal Measures is TDS = 2500 mg/L, pH = 8.5 in a sodium-bicarbonate water type. By comparison the median CSG produced water chemistry from the Bowen Basin Bandanna Formation is TDS = 8920 mg/L, pH = 7.9 in a sodium-chloride water type. The Jurassic Walloon Coal Measures CSG reservoir of the Surat Basin accounts for ~90% of the water production and the Permian coal reservoirs of the underlying Bowen Basin make up ~10% with a small amount from conventional oil and gas production. The latest available measured associated water production from CSG development (December 2016) equates to ~60.5 GL/yr with combined operator forecasts defining a peak projected to occur for about 10 years at 70–80 GL/yr. When this is converted to cumulative water volumes over the life of the industry (based on combined operator forecasts), just over 1700 GL of water is expected to ultimately be produced. If all this water were treated for freshwater beneficial use, it translates to ~5.5 megatonnes of salt.

Current estimates of water and salt production are about 25% of those made by government and academia prior to the expansion of CSG to LNG export or ~70% the 2010–11 industry estimates. We show that this overestimation of produced water to be attributable to the following factors:

1. Gas industry conservatism (over-estimation) driven by the bias to reduce project risk and achieve gas delivery targets
2. Government conservatism driven by a bias for prudent forecasting i.e. to assure that a credible worst case can still be managed within the regulatory framework
3. Academia conservatism driven by a bias for understanding worse case scenarios of environmental impact
4. The use of numerical models for basin scale impact assessment that do not take account of near-well multi-phase flow characteristics of saturation and relative permeability
5. A systemic underestimation of the cumulative effects on depressurization of the coal resource where one operator's asset requires less water production to reach target reservoir pressures due to neighbouring operator production. This is mainly because each operator only has access to its own development plans.

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