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Uncertainty analysis of CSG-induced GAB flux and water balance changes in the Narrabri Gas Project area

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Gas Industry Social and Environmental Research Alliance

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Executive summary

The proposal for coal seam gas (CSG) development in the Pilliga forest in northern NSW has raised several environmental concerns. The Pilliga Sandstone aquifer in this region is an important fresh water source that is used for irrigation, stock and domestic uses. The Pilliga forest is also the main recharge area for the Pilliga Sandstone aquifer, which is part of the Great Artesian Basin (GAB) aquifers. There is concern that depressurization of coal seams for producing gas may potentially impact groundwater pressure in the Pilliga Sandstone aquifer and affect the quantity of water recharged into the GAB. This report provides a probabilistic quantification and uncertainty of potential groundwater flux and water balance changes in the GAB aquifer caused by the Narrabri Gas Project in the Gunnedah Basin. This provides an estimation of potential regional scale CSG-induced impacts to the groundwater resource in this GAB aquifer which is extensively allocated for other beneficial uses.

A probabilistic groundwater modelling method was applied for the preliminary assessment of potential flux and water balance changes and associated uncertainties in the GAB aquifer – the Pilliga Sandstone caused by coal seam gas development through the Narrabri Gas Project. The groundwater model built for the Namoi subregion in the Bioregional Assessments Programme (http://www.bioregionalassessments.gov.au/) was used for this purpose. The changes in flux and water balance induced by extraction of water from the coal seams was quantified as the difference between the CSG development and the baseline scenarios of groundwater flow. Uncertainty in the CSG water production rates, hydraulic characteristics of the geologic formations and groundwater flow components including recharge were accounted for by varying their respective parameters in the model in a wide range. Three thousand five hundred sets of model parameters sampled from a uniform distribution were initially evaluated to characterise the potential model states and to compare the model predictions to the limited amount of available observations. Five hundred posterior parameter sets were selected from these 3500 parameter sets by using an objective function that characterised the difference between the model predictions and available observations. These 500 parameter sets were then used to undertake the predictive analysis of CSG induced GAB flux changes.

The results of the analyses indicated that CSG development could potentially induce flux changes in the GAB aquifer – the Pilliga Sandstone. One of the most important variables of interest in the prediction analyses was the increase in flux from the Pilliga Sandstone to the deeper formations due to the lowering of groundwater pressure in the coal seams due to gas and water extraction. This increase in the rate of flow from the Pilliga Sandstone to the deeper formation could be considered as temporary flux losses from the Pilliga Sandstone. The median value of simulated maximum flux losses from the Pilliga Sandstone to deeper formations is 85ML/year. The 5th and 95th percentile of the distribution are respectively 0.28 to 2299ML/year. The median value corresponds to approximately 0.29% of the Long Term Annual Average Extraction Limit of 29.68 GL/y from the GAB groundwater source in this area called the Southern Recharge Source. The median value and the 95th percentile also corresponds respectively to about 0.2% and 5.3% of the estimated annual recharge for the Southern Recharge Source.

The median value of 85 ML/year is comparable to the corresponding values of 60 ML/year simulated for the base case water production scenario reported in Santos' Groundwater Impact Assessment report (CDM Smith, 2016). In their groundwater impact assessment Santos considered 3 cases of water production:, the base case, the low case and the high case. In our study uncertainty in the water production rates were explicitly accounted for in the modelling as uncertain variables. The 5th and 95th percentiles of the total CSG water extraction simulated by this approach are respectively 4.41 GL and 107.11 GL. This range encompasses the total water production of the Base (37.5 GL), Low (35.5 GL) and High cases (87.1 GL) of water production that Santos reported in their Groundwater Impact Assessment report. This enabled the simulation of flux

changes for a wide range of uncertain water production rates, including the three scenarios considered in the Santos GIA report (CDM Smith, 2016).

The potential increase of groundwater flow from the Pilliga Sandstone to deeper formations in the Surat and Gunnedah basins is also accompanied by increased rate of water flow into the Pilliga Sandstone from the alluvial aquifer, inter-burden formations and the water courses overlying it. The ensemble predictive simulations resulted in a 5th and 95th percentile values of annual maximum influx changes 0.00 and 30.19 ML/year respectively from the alluvial aquifers to Pilliga Sandstone. The median value of annual maximum influx change is 0.89 ML/year.

The changes in water balance induced by CSG development was evaluated as the difference in the water balance components between the baseline and CSG development cases over the simulation period of 120 years. The probabilistic simulation of the water balance components indicates that changes to the water balance components induced by the gas development are relatively small compared to the probabilistic estimates of their baseline values. Simulations indicate that small changes could be induced to interactions of the Pilliga Sandstone with the overlying and underlying formations and with the surface water courses.

The groundwater modelling undertaken in this study focuses on probabilistic prediction of regional scale flux impacts of CSG development to the GAB aquifer in the Pilliga Sandstone. The modelling, based on the current understanding of the interactions of the Surat and Gunnedah basins, provides a range of potential impacts rather than a single number predicting the flux impacts.

1 Introduction

1.1 Overview

The proposal for coal seam gas (CSG) development in the Pilliga forest in northern NSW has raised several environmental concerns. The Pilliga Sandstone aquifer in this region is an important fresh water source that is used for irrigation, stock and domestic uses. The Pilliga forest is also the main recharge area for the Pilliga Sandstone aquifer, which is part of the Great Artesian Basin (GAB) aquifers. There is concern that depressurization of coal seams for producing gas may potentially impact groundwater pressure in the Pilliga Sandstone aquifer and affect the quantity of water flow in the GAB aquifer. The Gas Industry Social and Environmental Research Alliance is currently undertaking a research project to improve the conceptual understanding and predictive reliability of the groundwater impacts of coal seam gas development in the Pilliga forest region of northern NSW.

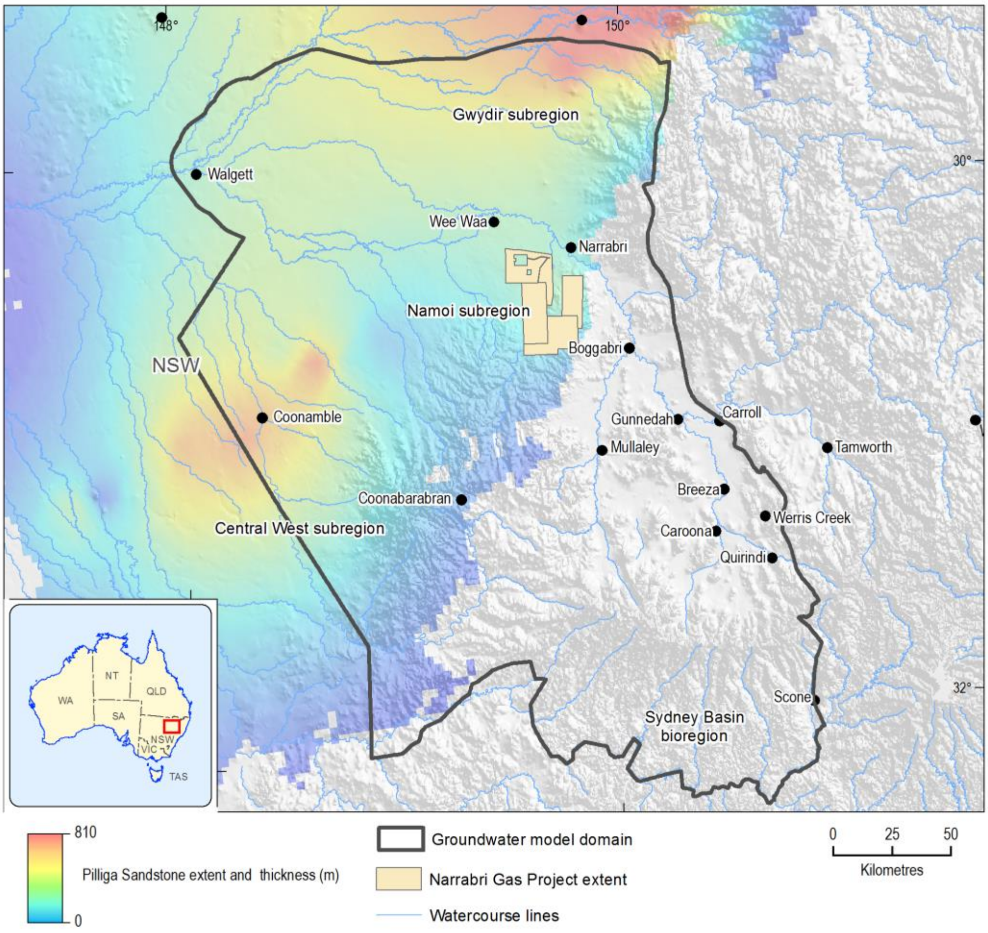

Figure 1: Extent and thickness of the Pilliga Sandstone within the study area.

This report provides a preliminary assessment of potential groundwater flux (flow volume) changes in the important GAB aquifer called the Pilliga Sandstone parts of which overlies the Gunnedah Basin from which it is proposed to extract water for coal seam gas development. The study area is shown in figure 1. The figure shows the extent of the Pilliga Sandstone within the domain of the groundwater model used in this study.

Groundwater flow models can be used to gain quantitative understanding of the groundwater system changes and impacts caused by external stresses. The conceptual understanding about the groundwater system informed by many different types of groundwater data underpins the reliability of model predictions. There is only limited amount of data available to underpin the conceptualization of interactions between the Surat and Gunnedah basins and the Namoi River alluvial aquifers in the Pilliga area. It is therefore important to use probabilistic approaches to provide conservative estimates and uncertainties of potential impacts of coal seam gas development on changes in the water balance and flow volumes in the GAB. Such an approach should also help to integrate emerging knowledge from multiple lines of evidence and determine the key structural and parameter uncertainties that have a significant impact on predictions. Only this allows to, subsequently collect additional data that contain most information to progressively minimize uncertainty in the prediction of CSG impacts on GAB flow.

The groundwater model developed for the Namoi subregion as part of the Bioregional Assessments (BA) Programme is used for probabilistic quantification of GAB flux impacts in this study. Given the GISERA focus on environmental and social impacts of onshore gas development, the current study focuses on quantifying the impacts from only coal seam gas development in the Pilliga forest region. This is different from the BA objective of quantifying cumulative impacts from coal mining and coal seam gas development. While the BA groundwater modelling focussed on quantifying maximum drawdown and time of drawdown at risk receptors, the focus of this study is probabilistic quantification of potential groundwater flux and water balance changes in the GAB aquifer because of water extraction from the coal seams of the Gunnedah Basin for gas development.

The quantification of long-term groundwater flux changes, if any, because of gas development is important to identify potential implications to water sharing plans operating in the region. The NSW government’s new aquifer interference policy (2012) sets out licensing requirements for water taken from water sources through CSG activities. Independent assessment of flux losses from important water sources and progressively minimising the uncertainty in these estimates using emerging data and knowledge are important for informing licensing requirements as per the water sharing policies and regulatory decision making on make good arrangements by the extractive industries.

The major groundwater sources around the Narrabri Gas Project area near the Pilliga forest region include the key aquifers in the alluvial cover of the Namoi river and its tributaries. Aquifers in the sedimentary rocks of the Great Artesian Basin forms another major groundwater source that is used for beneficial purposes. A detailed analysis of potential groundwater level drawdown in these aquifers caused by the cumulative impacts of coal seam gas and coal mining developments in this region has been undertaken as part of the Bioregional Assessments for the Namoi subregion (Sreekanth et al., 2017).

1.2 The Pilliga Sandstone

The geologic formation called the Pilliga Sandstone that forms part of the Surat Basin in northern NSW contains the main GAB aquifer in this region. The thickness of Pilliga Sandstone varies generally between 100 m to 250 m near the Narrabri Gas Project area. The formation is thickest on the eastern side of the Surat Basin and progressively thins out towards the west to less than 100 m thickness. The formation outcrops along the eastern margin of the NSW portion of the Great Artesian Basin. Pilliga Sandstone is also the main outcropping aquifer in the Pilliga forest region and are important intake beds for the GAB in NSW. The intake beds of GAB (Habermehl et al., 2009) within the extent of the groundwater model built for the Namoi subregion in Bioregional Assessments is shown in figure 2. Groundwater in the aquifers of the Pilliga Sandstone flows from south-east to west and north-west.

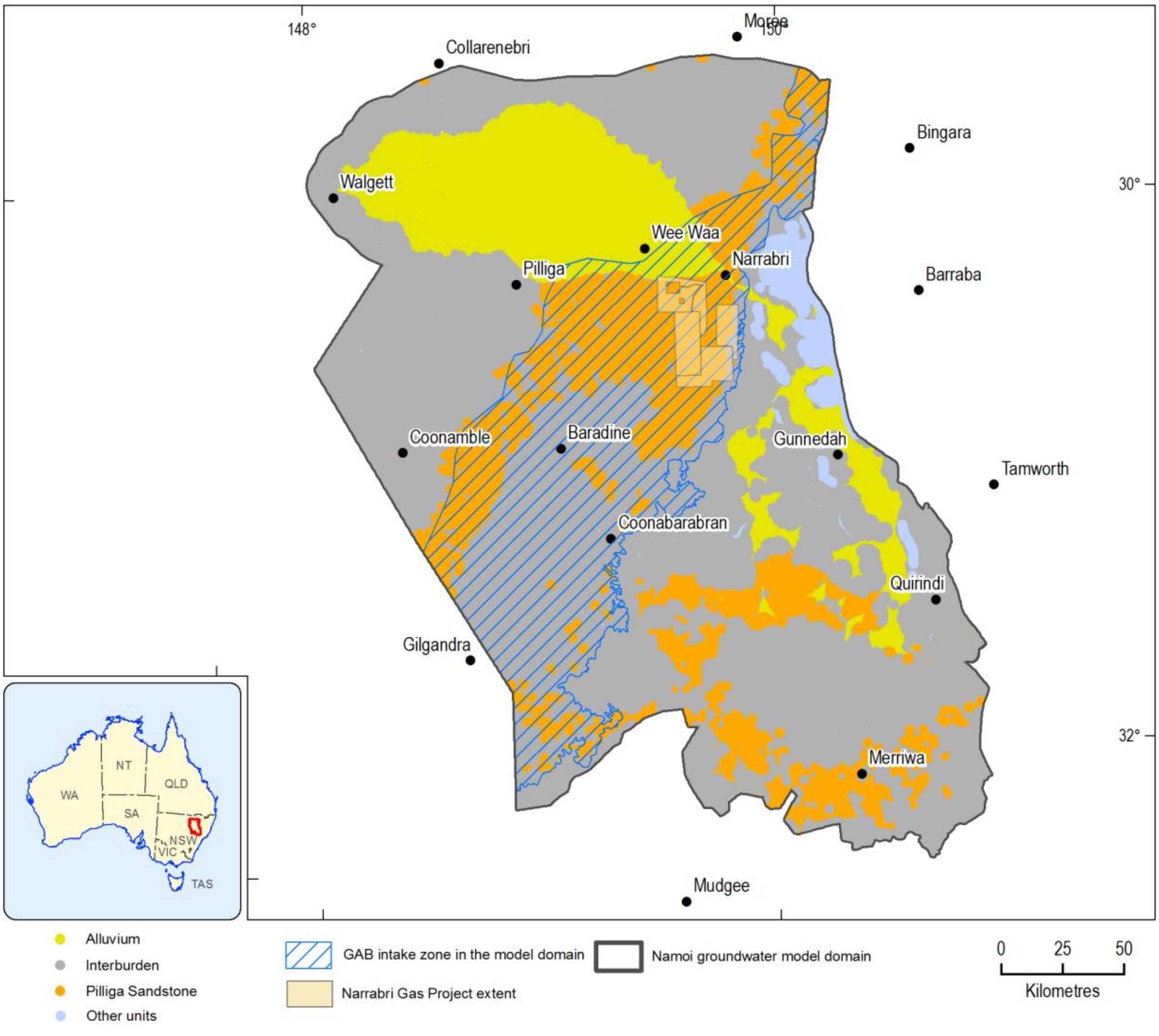

Figure 2: The GAB intake beds within the groundwater model area

Groundwater usage in some parts of the GAB in northern NSW has been considered to exceed recharge (Habermehl et al., 2009). This is attributed to significant increase in groundwater extraction in the recharge areas due to development of the agricultural industries. It has been estimated that the long-term average annual net recharge across the eastern intake beds (19,000 ML/year for the eastern recharge zone and 42,400 ML/year for the southern recharge zone) of the GAB is 61,400 ML/year. The total entitlements of domestic and stock rights in the eastern recharge zone currently stands at 33,100 ML/year. The groundwater sources some of these areas are classified as at high risk of over-extraction if all users extracted water to the level of their entitlement (Habermehl et al., 2009). This also informs that the investigation of any potential additional stress on the regional water balance because of coal seam gas development is important.

The Great Artesian Basin Water Resource Assessment (CSIRO, 2012) indicates that, the Pilliga Sandstone is an aquifer but the Purlawaugh Formation that underlies the Pilliga Sandstone and forms the bounding formation of the Surat Basin is an aquiclude suggesting limited vertical connectivity with the underlying Gunnedah Basin. The vertical connectivity of the inter-burden formations that lies between the coal seams of the Gunnedah Basin and Pilliga Sandstone is one of the most important parameters that influences the propagation of depressurization into and redirection of flux from Pilliga Sandstone.

1.3 Objectives

GISERA NSW project on 'Impacts of CSG depressurization on GAB flux' focuses on refining the conceptual understanding of the hydrogeological system in the Narrabri Gas Project area by the analysis of existing and new hydrogeological data including environmental tracers and quantification of uncertainty in the estimation of potential GAB flux and water balance changes in the region caused by coal seam gas development in the Narrabri Gas Project. As part of this GISERA study, this report provides a preliminary assessment of the GAB flux and water balance changes and associated uncertainties using the groundwater model developed for the Namoi subregion in the Bioregional Assessment Programme. This model is henceforth referred to as the Namoi BA model in this report.

The following are reported as part of the preliminary assessment:

- Probabilistic assessment of potential flux losses from the Pilliga Sandstone because of additional flows towards the Gunnedah Basin formations because of the low pressure in the coal seams resulting from coal seam gas development
- Probabilistic assessment of potential water balance changes in the Pilliga Sandstone aquifer caused by the depressurization of coal seams in the Gunnedah Basin.

1.4 Methodology

A groundwater modelling methodology like that used in Bioregional Assessments (Crosbie et al., 2016) is used in this study. The modelling focuses on quantifying the changes in flux in the model layer corresponding to the Pilliga Sandstone due to changes in the hydrogeological stresses caused by coal seam gas development from the Hoskissons Coal and Maules Creek formations of the Gunnedah Basin. Thus, the focus of modelling is on the changes in hydrogeological variables caused by changes in stress regimes rather than on prediction of future state variables. This modelling approach evokes the principle of superposition to compute the changes in prediction corresponding to changes in stresses. The principle of superposition enables the modelling to focus on the change in hydrogeological stress and the hydraulic properties, rather than on reproducing historical conditions or predicting future state variables of the system, such as groundwater levels or fluxes.

The volume of water extracted during the coal seam gas development is largely uncertain although modelled estimates are currently available. Similarly, the hydrogeological characteristics of the geologic formations of the Surat and Gunnedah basins and their hydraulic properties are also largely uncertain. The probabilistic assessment of these effects enables evaluation of a wide range of values of these uncertain stresses and parameters and evaluate the prediction uncertainty of the impacts.

A large number of model parameter sets of the groundwater model are evaluated to generate an ensemble of predictions. The ranges used for the model inputs and parameters reflects both the natural variability in the hydrogeological system and the uncertainty in the understanding of the stresses. In this study a data set comprising 3500 parameter fields/ model inputs were used to characterise the wide range of variability of these inputs. The maximin Latin Hypercube sampling procedure (see Santner et al., 2003, p. 138) was used to generated the 3500 parameter sets uniformly from the entire parameter space. The 3500 models were ranked according to predefined objective functions that characterise the difference between the model predictions and the available observations. The groundwater level objective function was defined as,

$$O_h = \sum_{j=1}^{m} \left(r_j f_w\left(d_j\right) \frac{1}{n_j} \sum_{i}^{n_j} \left(h_{obs,i} - h_{sim,i}\right)^2 \right),$$

with m the number of observation bores, n_j the number of observations at one specific location j, r_j the distance of observation bore j to the nearest watercourse line network, $h_{obs,i}$ the head observation and $h_{sim,i}$ the simulated equivalent. $f_w\left(d_j\right)$ is a distance weighting function as,

$$f_w\left(d_j\right) = 1 - \tanh\left(\frac{d_j}{D}\right),$$

where coefficient D controls how rapidly the weight decreases with increasing distance. The tanh function allows the weight of an observation to decrease almost linearly with distance and to gradually become zero at a distance of approximately $3D$ (Sreekanth et al., 2017). The design of the objective function represents a pragmatic trade-off between capturing local and regional groundwater flow dynamics. The distance between the observation bore and the nearest river is included in the objective function to reduce the weight of groundwater level observations in the immediate vicinity of rivers. At these locations, groundwater level observations are dominated by surface water – groundwater interaction on a local scale. The top 500 best-performed parameter/input combinations that resulted in the least deviations from the observations were used for the predictive simulations. The prior parameter combinations are not constrained, when no relevant observations are available. A detailed description of this methodology can be found in Peeters et al. (2016).

2 The Bioregional Assessments' Groundwater Model for the Namoi subregion

The BA groundwater model for the Namoi subregion (Sreekanth et al., 2017) is used for probabilistic flow simulation in this study. The model encompasses an area of approximately 59000 km^2 and covers the Gunnedah basin and parts of the Surat Basin in northern NSW. This section gives a brief overview of the development of this groundwater model that is relevant to the present study.

2.1 Geology

The geologic model developed for the Namoi subregion covers the Gunnedah Basin, portions of the Surat Basin and the smaller Werrie Basin. The geological model is an interpretation of the subsurface geology and structure of the Gunnedah and Surat basins. The three-dimensional geologic model developed for the Namoi subregion used CDM Smith's geological model that was developed for Santos' Gunnedah Coal Seam Gas Project. The CDM Smith geological model was carefully evaluated for its suitability to form the basis for the numerical model in Bioregional Assessments.

A detailed evaluation of the CDM Smith geologic model is reported in Aryal et al., (2017a). The evaluation concluded that more up-to-date knowledge of the Surat Basin formations and alluvium was available from other studies. Based on this evaluation, the geologic model developed for the Bioregional Assessments used the information pertaining to the Gunnedah Basin formations from the CDM Smith model and the Surat Basin formations from the Hydrogeological Atlas of the GAB (Ransley et al., 2015). The extent of the alluvium layers was determined using the regolith map (Craig 2013) and depth to alluvium was determined using the alluvium layer from the Schlumberger groundwater flow model (Schlumberger Water Services, 2012). The details of development of this model is reported in Aryal et al., (2017a).

2.2 Hydrostratigraphy

A simplified representation of hydrostratigraphy as described in table 1 was adopted for the Bioregional Assessments' groundwater model development for the Namoi subregion. The formations of the Surat and Gunnedah basins were classified as aquifer, inter-burden or coal formations. The major groundwater sources comprising the Narrabri and Gunnedah formations of the Namoi alluvium and the Pilliga Sandstone of the Surat Basin were classified as aquifers and represented as individual layers in the numerical groundwater model. Similarly, the Gunnedah Basin formations that encompass the coal seams from which gas development has been proposed were also represented as independent layers in the numerical model. Thus, the Hoskissons coal and Maules Creek Formation were represented as independent layers in the numerical groundwater model with relatively higher hydraulic conductivity values compared to the surrounding aquitard formations.

Table 1: Conceptualisation of hydrostratigraphy units and numerical model layers for the formations of the Gunnedah and Surat basins

Province	Period	Formation	Layer in geologic model	Layer in GW model	Hydrostratigraphic unit
Namoi Alluvium	Pleistocene	Narrabri Formation	1	1	aquifer
Namoi Alluvium	Pliocene	Gunnedah Formation	2	2	aquifer
Namoi alluvium	Miocene	Cubbaroo Formation	2	2	aquifer
Surat Basin	Cretaceous	Rolling Downs Group and Liverpool Range Volcanics	3	3-5	Inter-burden
Surat Basin	Creteceous	Blythsdale Group	3	3-5	Inter-burden
Surat Basin	Jurassic	Pilliga Sandstone	4	6	aquifer
Surat Basin	Jurassic	Purlawaugh Formation	5	7-9	Inter-burden
Surat Basin	Jurassic	Garrawilla Volcanics	6	7-9	Inter-burden
Gunnedah Basin	Triassic	Napperby and Deriah formations	7	7-9	Inter-burden
Gunnedah Basin	Triassic	Digby Formation	7	7-9	Inter-burden
Gunnedah Basin	Permian	Black Jack Group – Coogal and Nea Subgroup	7	7-9	Inter-burden
Gunnedah Basin	Permian	Hoskissons Coal	8	10	Coal
Gunnedah Basin	Permian	Black Jack Gropu – Brothers Subgroup	9	11-13	Inter-burden
Gunnedah Basin	Permian	Watermark Formation	9	11-13	Inter-burden
Gunnedah Basin	Permian	Porcupine Formation	9	11-13	Inter-burden
Gunnedah Basin	Permian	Upper Maules Creek Formation	10	11-13	Inter-burden
Gunnedah Basin	Permian	Maules Creek coal seams	10	14	Coal
Gunnedah Basin	Pemian	Lower Maules Creek Formation	10	14	Coal
Gunnedah Basin	Permian	Goonbri Formation	NA	15	Basement
Gunnedah Basin	Permian	Leard Formation	NA	15	Basement

Gunnedah Basin	Permian	Werrie Basalt and Boggabri Volcanics	NA	15	Basement

The aquitard formations and non-significant aquifers that lie in between these aquifer and coal formations were classified as inter-burden layers in the geological model. The inter-burden formation between the alluvial aquifers and the Pilliga Sandstone were further divided into three layers in the numerical groundwater model. Similarly, the inter-burden geological layer between the Pilliga Sandstone and Hoskissons coal and the inter-burden layer between Hoskissons coal and Maules Creek Formation were sub-divided into three layers in the numerical groundwater model.

2.3 Model grid and solver

The numerical model was designed to have an unstructured grid with Voronoi cell sizes chosen to be 300 m close to the coal seam gas development area, rivers and coal mines and up to 3 km in the periphery of the model. This grid structure was adopted to improve the accuracy of prediction of drawdown impacts in the areas of coal resource development and in regions where hydraulic gradients are high. Figure 3 shows the model grid and an inset view of the grid refinement around the Narrabri Gas Project area.

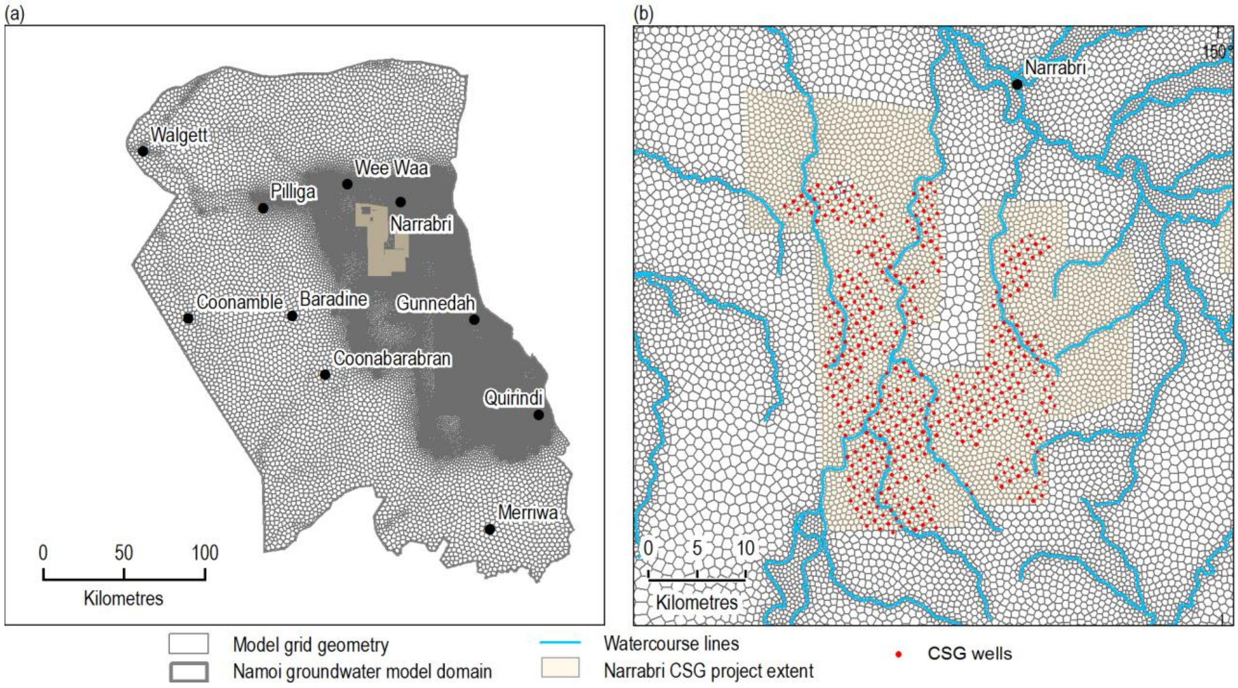

Figure 3 Plan view of the model grid and refinement of the Voronoi grid within the Narrabri Gas Project area

Unstructured grid version of MODFLOW called MODFLOW-USG is the code used for solving this model. MODFLOW-USG permitted other advantages over traditional MODFLOW code including improved accuracy in representation of pinching out layers and reducing computational burden of the model.

2.4 Model boundary conditions

The eastern boundary of the model is along the Hunter-Mooki Thrust Fault and is assumed to be a no-flow boundary. No-flow boundary conditions were also assumed along the northern boundary which approximately aligns with the regional flow direction within the GAB aquifers in this region. Head dependent flow boundary conditions were used for the northwest, west and south-east boundaries of the model. A detailed description of the lateral and other boundary conditions of the groundwater model can be found in Sreekanth et al., (2017)

One of the major inflows into the model domain is the recharge. The recharge is characterised to include three components – the diffuse recharge, recharge due to overbank flooding and irrigation recharge. The mean annual diffuse recharge was estimated using chloride mass balance and is reported in Aryal et al., (2017a). The temporal variation of diffuse recharge was modelled using the Australian Water Resources Assessment landscape model (AWRA-L) and was used together with the chloride mass balance estimation to provide the land surface inflow boundary condition for the groundwater model (Sreekanth et al., 2017). The depth of flood and irrigation recharge were calculated on a daily time-step at the reach scale in the Australian Water Resources Assessment River model (AWRA-R). The flood and irrigation recharge are applied to the groundwater model cells that are contained within the flood plain and irrigation areas (Sreekanth et al., 2017). Three model parameters are used to vary the recharge volumes based on the trend provided by the AWRA-L and chloride mass balance estimates.

Licensed bore extractions were represented as a deterministic model outflow. Groundwater extraction from a total of 11785 bores that are within the model boundary were represented in the model. Majority of these bores draw water from the alluvial formations and from the GAB aquifer. Depending on the groundwater source from which these licensed bores are known to extract water from, they were assigned to respective groundwater model layers. Sreekanth et al., (2017) gives a detailed description of the method used in making this assignment.

The river (RIV) package of MODFLOW-USG was used to represent the SW-GW exchange within the model domain. Major rivers and creeks within the model domain (54 reaches) are represented in the model. The river stage required for defining the river boundary condition in the groundwater model was obtained from AWRA-R simulations (Aryal et al., 2017b). The river conductance parameter that governs the volume of SW-GW exchange was varied in a specified range to characterise uncertainty in the SW – GW exchanges.

The drain (DRN) package of MODFLOW-USG was used to represent the groundwater outflows due to coal mining and coal seam gas developments within the modelled area. For the coal mines, drain package was defined for all model cells that are within the boundaries of an existing or proposed coal mine foot print. Five-yearly foot prints of the mines were used to define the drain boundary condition corresponding to each mine. The number of drain cells vary between stress periods depending on the extent of the mine pit. Details of representation of coal seam gas wells using MODFLOW drain package is discussed in the section 3.

2.5 Initial conditions and model simulation period

A transient simulation of groundwater flow was undertaken for a period between 1983 and 2102. The initial conditions before 1983 was obtained by solving the groundwater model in a steady-state considering long-term average groundwater stresses and inputs. Groundwater extractions from the agricultural, stock and domestic bores were not included in the steady-state simulation as it is known to correspond to an unsteady state and would artificially lower the initial water levels used for transient simulation. As the model is used in a probabilistic framework by varying model parameters for each distinct simulation, steady-state solution of the first stress period of the model was undertaken for each simulation.

3 Simulation of GAB flux and water balance impacts of CSG development

As described in the methodology section, the focus of this study is probabilistic prediction of changes in the GAB flux and water balance caused by the proposed coal seam gas development. This is accomplished as the difference between model predictions of two possible states of GAB groundwater resource – one corresponding to no CSG development and the other corresponding to the proposed development of CSG. This approach also assumes that all other stresses on the groundwater system remains unchanged over this period and quantifies the changes in flux and water balance resulting from the proposed coal seam gas development only.

3.1 Model runs for baseline and CSG development cases

The baseline case is a modelling scenario that includes all existing and potential future stresses on the groundwater resource in the modelled area except coal seam gas development in the Narrabri Gas Project. This include groundwater stresses due to 5 existing and 8 proposed coal mining projects in the region in addition to agricultural extractions. Both open cut and long-wall coal mines were included. As described in section 2, the coal mines were modelled using head dependent flux boundary conditions implemented by the drain package of MODLFOW-USG. Information about mine footprints and excavation depth were used to define the drain boundary conditions.

The CSG development case considers the stresses due to CSG development in the proposed Narrabri Gas Project in addition to the stresses considered in the baseline case. All other model inputs and parameters remain the same for any pair of baseline and CSG development model runs.

3.2 Representation of water extraction from CSG wells

Extraction of water from 850 wells (425 targeting coal seams in Maules Creek Formation and 425 targeting the coal seams of Hoskissons Coal) for coal seam gas development was represented in the model using drain package. A drain boundary condition was defined for each model cell corresponding to the location of a proposed CSG well of the Narrabri Gas Project. In the Narrabri Gas Project CSG developments are proposed from the Maules Creek and Hoskissons Coal formations. CDM Smith (2016) reported the proposed sequence of drilling CSG wells based on a field development plan. The field development plan considered a maximum of 425 well pairs distributed across 18 water extraction areas. This sequence was adopted for implementing the drain boundary condition. Drain boundary condition was defined for models cells in layers corresponding to Maules Creek Formation (Layer 14) and Hoskissons Coal (Layer 10).

CDM Smith (2016) also reported the modelled water production rates from these wells. However, because of the large uncertainty in the estimation of water production rates, these rates were not directly used in our study to define the groundwater flux through the drain cells. Instead, water extraction from the CSG wells were specified as head dependent flux boundaries. The large uncertainty in the water production curves were addressed by varying the conductance of the drain cells in a wide range.

3.3 Model parameterisation

Hydraulic properties assigned to model cells in each layer are dependent on the composition and architecture of rocks and sediments in the corresponding formations. A detailed analysis of the hydraulic conductivity measurements for the Namoi subregion was conducted during the development of this model for Bioregional Assessments (Aryal et al., 2017a). This analysis showed a correlation of hydraulic properties with depth in majority of the inter-burden and coal bearing formations for which data was available. Based on this finding, a depth-based parameterisation scheme was used for defining the hydraulic properties for the model layers corresponding to these formations. Since the alluvial formations are thin compared to the deeper sedimentary basin formations a depth-based decay was not used for the alluvial formations. The depth-dependent horizontal hydraulic conductivity, Kh, and the specific storage, S_S, were characterised using the equations:

$$k(d) = (1 + 10^{we} * EXP(-0.06 * we^{0.5} * d)) * (k0 * EXP(-\alpha_k * d)) \tag{1}$$

$$S_S(d) = S_S0 * EXP(-\alpha_S * d) \tag{2}$$

where $k(d)$ is the hydraulic conductivity (k, m/day) at a certain depth d, (m), we represent the order of magnitude increase in the property due to weathering enhancement in the top 100m, $k0$ is the hydraulic conductivity of material at zero-depth, α_k is the decay constant, $S_S(d)$ is the specific storage (S_S, m^{-1}), d is the depth (m), S_S0 is the specific storage at the surface and αS is the decay constant. A constant storage coefficient is assumed throughout the simulation using the MODFLOW layer type 0. This means that the model is unable to switch from confined to unconfined condition during the model simulation. This assumption is used primarily to increase the model stability and achieve a robust model that is required for the comprehensive uncertainty analysis. The effect of this simplification on the model predictions is minimised by using storage values based on specific yield in areas where layers are outcropping. The specific yield parameters used for this are also included in the uncertainty analysis to explore prediction uncertainty caused by uncertainty of the specific yield parameters. A full description of the depth-based parameterisation scheme is provided in Sreekanth et al., (2017).

Due to the inherent variability of the hydraulic properties of these formations and large scale uncertainty in the estimation of these properties, a probabilistic approach was adopted for quantifying the effects this has on model prediction of GAB flux changes.

3.4 Uncertainty analysis

The impact of the uncertainty of model inputs and parameters on the prediction of GAB flux and water balance changes was analysed by doing an ensemble of predictive simulations consisting of many model runs. Uncertainty in the model inputs including recharge, SW-GW interactions and evapotranspiration and lateral boundary fluxes were explicitly included in the uncertainty analysis using parameters that are relevant to these inputs. Similarly, uncertainty in the model parameters including horizontal and vertical hydraulic conductivity, specific storage and specific yield were also included.

A total of 3500 parameter combinations were evaluated for their predictive responses in the BA groundwater modelling for the Namoi subregion. Two thousand six hundred and eighteen successful model runs were available from these simulations. These model runs corresponded to 2618 model parameter combinations sampled from a uniform distribution bounded by specified minimum and maximum values of these parameters. These model runs were ranked using an objective function that evaluated the match between simulated groundwater levels to corresponding observations in 134 bores between 1993 and 2012. In the objective function, higher weights were given to groundwater level observations that are closer to the coal seam gas wells as these observations would be more relevant and better inform the prediction of groundwater flux changes in the Narrabri Gas Project area.

After ranking the 2618 model runs based on this objective function, 500 parameter combinations that produced best match with the observations were used for predictive simulation of water balance and flux changes. The choice of 500 model runs for the prediction analysis was primarily based on the amount of time and storage available for completing this task. These 500 model runs were then used for the predictive simulations of the CSG-induced flux and water balance changes in the GAB aquifer – the Pilliga Sandstone. The models were run in parallel on a high performance cluster computing facility. The groundwater head and flux changes for each stress period of the model for both the baseline and CSG development scenario were saved in the model outputs. This resulted in an output dataset with a total size of 27.5 Terabytes. These outputs were post-processed to evaluate the flux changes.

4 Results and Discussion

The results of the simulation of GAB flux changes and uncertainty analysis are reported in this section.

4.1 Zones for reporting flux and water balance changes

The volume encompassed by the groundwater model was divided into four zones; the flux and water balance changes are reported as flows into and out of these zones and the model boundaries. The basins, formations and model layers corresponding to these zones are given in table 2.

Table 2: Zonation of the numerical model layers and hydrostratigraphic units for evaluation of flux changes

Zone No:	Basin	Formation type	Model layer
Zone 1	Namoi alluvium	alluvium	1 - 2
Zone 3	Surat Basin	Inter-burden	3 - 5
Zone 6	Surat Basin	Pilliga Sandstone	6
Zone 8	Gunnedah Basin	Inter-burden and coal	7 - 15

This zonation approach classifies the model layer 6 corresponding to Pilliga Sandstone as a single zone to analyse the water balance changes to the important GAB aquifer resulting from CSG development. The flux changes between these zones as a result of CSG development can be quantified as difference between simulated values for the CSG development and baseline cases. For example, the difference in fluxes from zone 6 to zone 8 between the CSG-development and baseline model runs provide a quantification of potential flux losses from the GAB aquifer to deeper parts of the Surat and Gunnedah basins. Similarly, the difference in fluxes from zone 1 to zone 6 provides a quantification of direct flow from the alluvium to Pilliga Sandstone as a result of CSG depressurization.

4.2 Flux changes to Pilliga Sandstone

One of the potential direct effects of depressurization in the coal seams in Gunnedah Basin is flux losses from the Pilliga Sandstone. This could also trigger other flux changes including groundwater flow from alluvial and other overlying aquifers to Pilliga Sandstone and potential reduction of base flow from the Pilliga Sandstone into the Namoi river. These changes occur in response to the potential propagation of the decrease in groundwater pressure in the coal seams into these aquifers. These are discussed in detail in the following sections.

4.3 Changes in flux from Pilliga Sandstone to deeper formations

One of the most important groundwater flux changes that can be induced by gas development from the Gunnedah Basin is potential increases in the groundwater flow from the Pilliga Sandstone to deeper parts of the Surat and the Gunnedah basins. This is because of increased flow towards the coal seams resulting from large decrease in groundwater pressure there due to water and gas extraction. Additional flux of groundwater from the Pilliga Sandstone to the deeper formations was quantified. Figure 4 shows the time series flux change and the distribution of maximum groundwater flux change from Pilliga Sandstone to deeper formations corresponding from the ensemble predictive model runs.

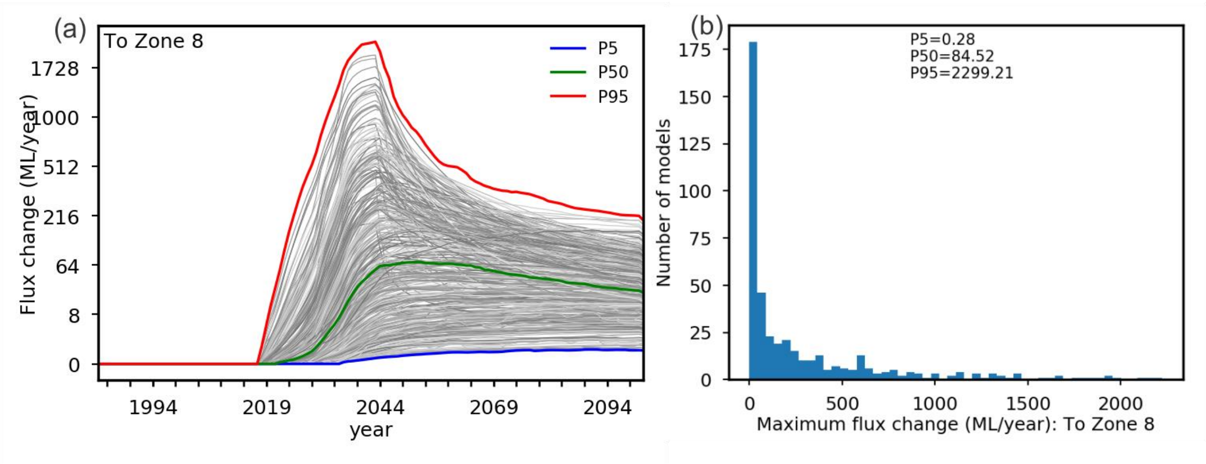

Figure 4: Potential flux losses from GAB aquifer Pilliga Sandstone to deeper formations a) Time series of potential flux losses b) Distribution of maximum flux losses from the ensemble model predictions (The predicted flux changes lower than 5th percentile and higher than 95th percentile are not shown in the time series plot)

The ensemble predictive simulations resulted in a 5th and 95th percentile values of CSG-induced maximum flux losses as 0.28 to 2299.21 ML/year respectively. The wide range of simulated values of flux losses is because of the uncertainty in the hydraulic conductance of coal seams and hydraulic characteristics of the inter-burden formations.

The median value of maximum flux loss is 84.52 ML/year. To put this into perspective, this median value of predicted flux changes is approximately 0.29% of the Long Term Annual Average Extraction Limit of 29.68 GL/y from the Southern Recharge Source (NSW Water Register, DPI Water 2016/17 NSW GAB Groundwater Sources, 2008). This is also equal to about 0.2% of the recharge of 42,400 ML/y estimated for the Southern Recharge Source. Figure 5 and table 3 compares the median and 95th percentile of the predicted maximum flux losses to the groundwater use, recharge and the Long-term Annual Average Extraction Limit prescribed by the water sharing plan. This median value is comparable to the maximum predicted change in flow rate of 60 ML/year between GAB Southern Recharge Zone and Gunnedah Basin reported in Santos' EIS for the Base Case development scenario. Santos considered base, low and high cases of water extraction in their groundwater modelling and predicted the changes in flow rate from GAB aquifer to Gunnedah Basin corresponding to these three cases. These three cases resulted in simulated maximum fluxes of 60 ML/year, 50 ML/year and 130 ML/year respectively from GAB to deeper formations in the Gunnedah Basin. The rate of water removal from the coal seams of the Gunnedah Basin were input as specified extraction rates in their groundwater modelling (CDM Smith, 2016). Unlike that, in the present work we explicitly considered the uncertainty of water production rates and simulated it as a head dependent boundary condition that is controlled by the hydraulic conductivity of coal seams and conductance of the drain cells. Given the large uncertainty associated with this, we used a wide range of values to parameterize the hydraulic conductivity and drain conductance which resulted in wide range of CSG water extraction rates (Figure 5). The 5th and 95th percentiles of the total CSG water extraction simulated by this approach are respectively 4.4 GL and 107.1 GL. This range encompasses the total water production of the Base (37.5 GL), Low (35.5 GL) and High cases (87.1 GL) of water production that Santos reported in the Groundwater Impact Assessment report that is part of their EIS.

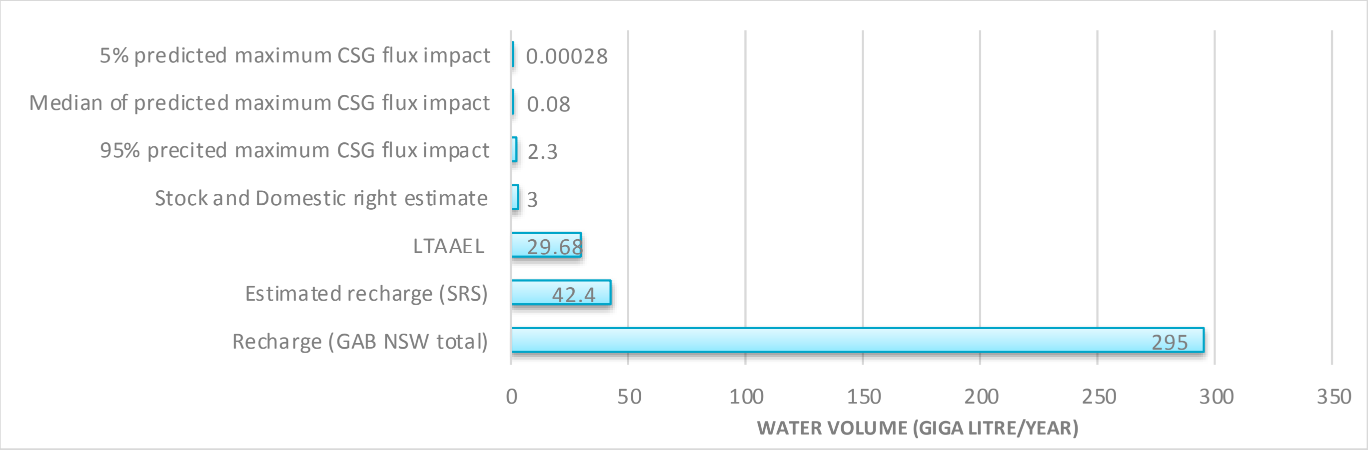

Figure 5: Comparison of predicted CSG flux impacts to estimated recharge and extraction limits set by the water sharing plan.

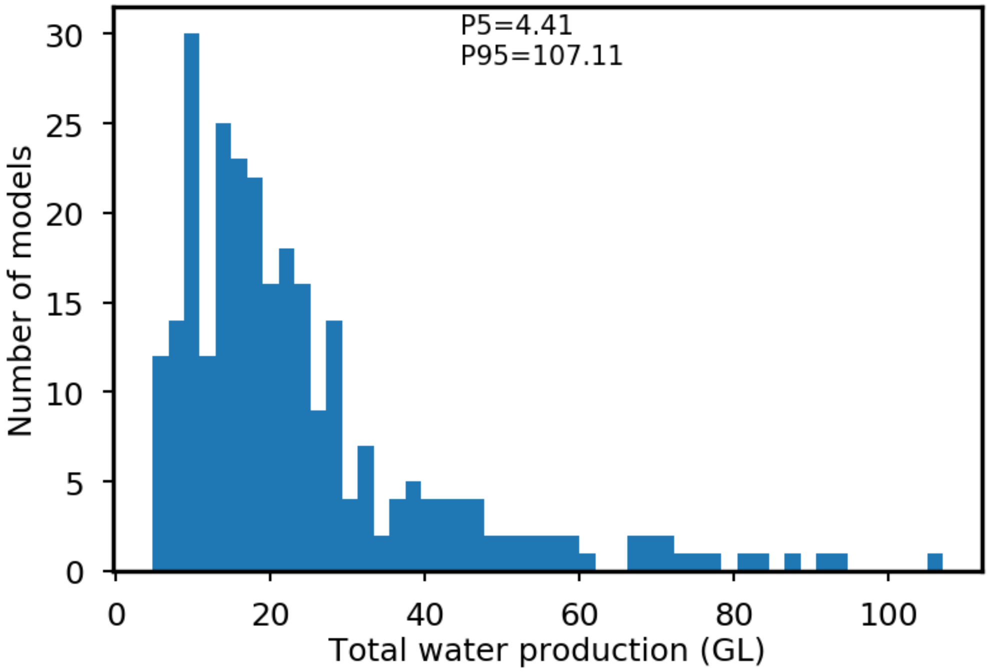

Figure 6: Distribution of the simulated total coal seam gas water production. The CSG water production was simulated as a head dependent flux boundary condition using the drain package of MODFLOW-USG. The parameters of the

drain package and the hydraulic properties of the Hoskissons Coal and Maules Creek formations were varied in a wide range to simulate the water production curves

Table 3: Comparison of predicted CSG flux impacts to estimated recharge and extraction limits

	Volume (GL/y)	Source
Estimated Recharge (GAB NSW Total)	295	BRS report (Habermehl, 2009)
Estimated recharge Southern Recharge Source (SRS)	42.4	NSW Water Sharing Plan
Long-term Annual Average Extraction Limit (LTAAEL)	29.68	NSW Water Sharing Plan
Stock and domestic use	3.0	NSW Water Sharing Plan
Unlikely that the maximum CSG flux impact in any year will exceed	2.3	This study
Likely that the maximum CSG flux impact will be around	0.08	This study
Likely that CSG flux impact will be more than	0.00028	This study

4.4 Time of maximum flux changes to Pilliga Sandstone

It may be noted from figure 4a that the time to maximum flux change varies considerably across the ensemble of simulations. This is also evident from the distribution of the times at which maximum flux changes occur shown in figure 6. The time to maximum flux change is smallest for simulations that indicate highest maximum flux changes. This is because, highest maximum flux changes occur for simulations that consider the inter-burden to offer least resistance and hence faster propagation of pressure changes through them. On the contrary, when the vertical hydraulic conductivity of the inter-burden layers are low, pressure changes take longer to propagate and hence it takes longer for the maximum flux changes to occur. This implies that the maximum flux losses could be relatively higher if it occurs within the period of coal seam gas operations and this may be indicated by drawdown in the bores that monitoring water levels in the Pilliga Sandstone. On the other hand, if the maximum flux losses are smaller it is more likely to happen much later after the CSG operations stop. Such small flux changes can hardly be monitored and as such will have negligible effect on the groundwater resources.

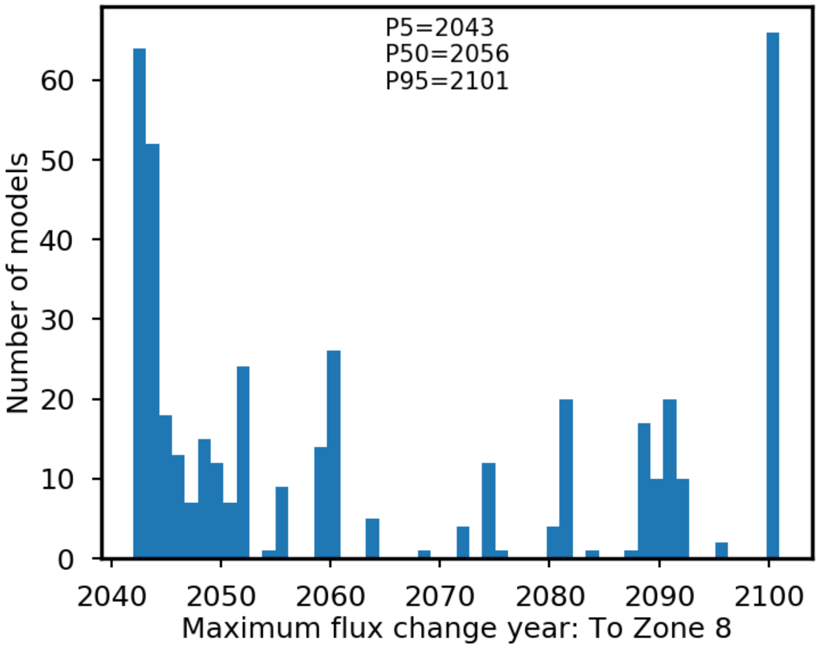

Figure 7: Distribution of times of maximum flux change from the GAB aquifer to the deeper formations

4.5 Additional influx into Pilliga from overlying aquifers

Potential decrease in pressure in the Pilliga Sandstone can result in additional flow of groundwater from overlying aquifers into Pilliga Sandstone. This was evaluated by quantifying the influx from zone 1 (alluvial aquifers) and zone 3 (inter-burden between alluvium and Pilliga Sandstone) into the Pilliga Sandstone (zone 6). The time series of influx and distribution of maximum influx from the alluvial aquifers directly into Pilliga Sandstone obtained from the ensemble model predictions is shown in figure 7.

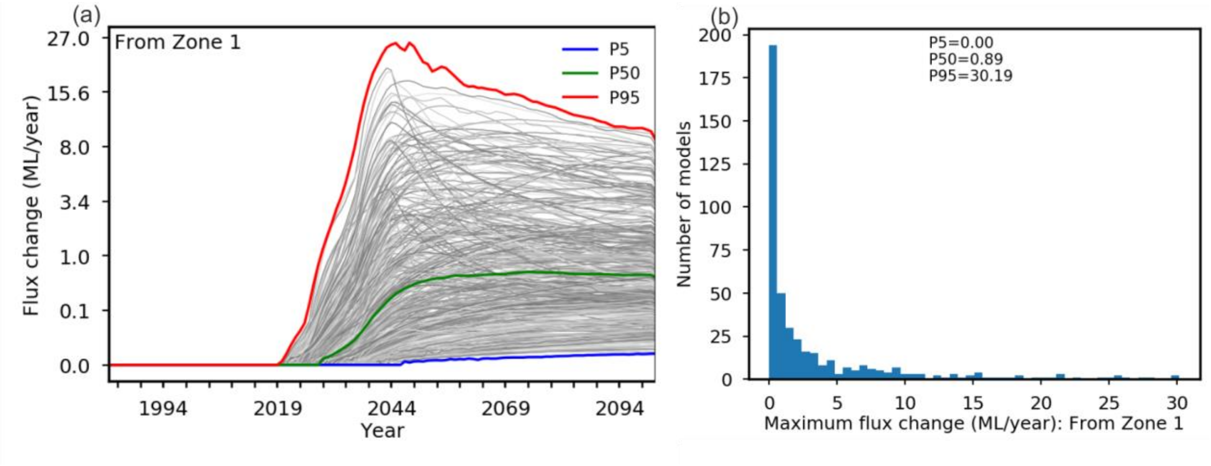

Figure 8: Potential influx from the alluvial aquifers to Pilliga Sandstone a) Time series of potential influx b) Distribution of maximum influx obtained from the ensemble model predictions. (The predicted flux changes lower than 5th percentile and higher than 95th percentile are not shown in the time series plot)

The ensemble predictive simulations resulted in a 5th and 95th percentile values of annual maximum influx 0.00 and 30.19 ML/year respectively from the alluvial aquifers to Pilliga Sandstone. The median value of annual maximum influx is 0.89 ML/year. In comparison, maximum change in flow rate of induced at the base of the Namoi alluvium is described as ‘negligible’ in the Santos’ groundwater modelling report (CDM Smith, 2016)

The 5th and 95th percentile of maximum influx from zone 3 (the inter-burden layers between the Namoi alluvium and Pilliga Sandstone) were quantified as respectively 0.01 and 267.85 ML/y. The median value of maximum flux change is 7.15 ML/y (Figure 8). The distribution of predicted time of maximum flux change from zones 1 and 3 are shown in figure 9.

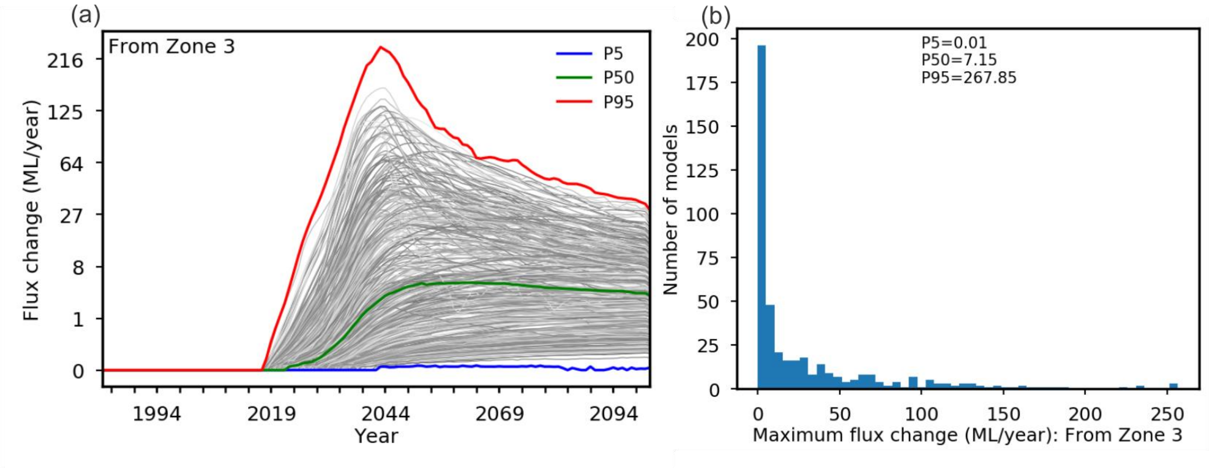

Figure 9: Potential influx into the Pilliga Sandstone from the inter-burden formations above it a) Time series of potential influx b) Distribution of maximum influx from the ensemble model predictions. (The predicted flux changes lower than 5th percentile and higher than 95th percentile are not shown in the time series plot)

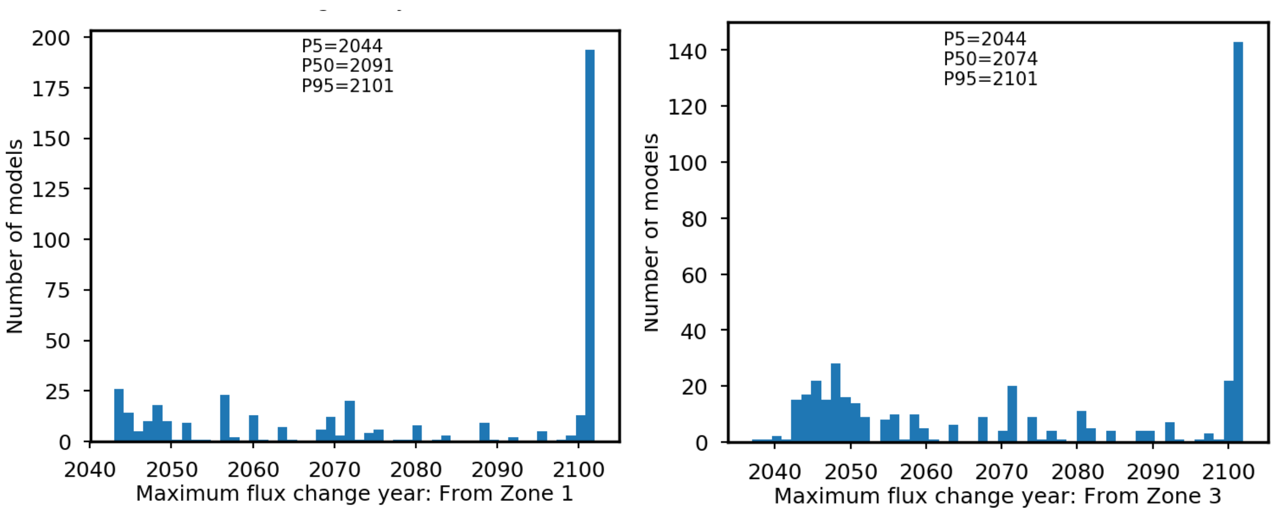

Figure 10: Distributions of the timing of maximum influx into Pilliga Sandstone a) from the Namoi alluvium and b) from the inter-burden formations above the Pilliga Sandstone

It may be observed that the flux changes in the alluvium and the inter-burden above the Pilliga Sandstone is most probable to occur towards the end of simulation period. In this study we considered a simulation period until the year 2102 and a wide majority of simulations indicate that the maximum flux change within this period would be occurring in 2102. This also implies that the maximum flux change in these layers could be occurring much later than this period.

4.6 SW-GW interaction changes

The time series of simulated changes in SW-GW interactions of the Pilliga Sandstone is shown in figure 10. The simulations generally indicate that there might be small increases in the flux from the river to the Pilliga Sandstone in the losing reaches and some decrease in baseflow in the gaining reaches.

The distribution of simulated maximum flux change from and to the river network and the distribution of time of maximum change is shown in figure 11.

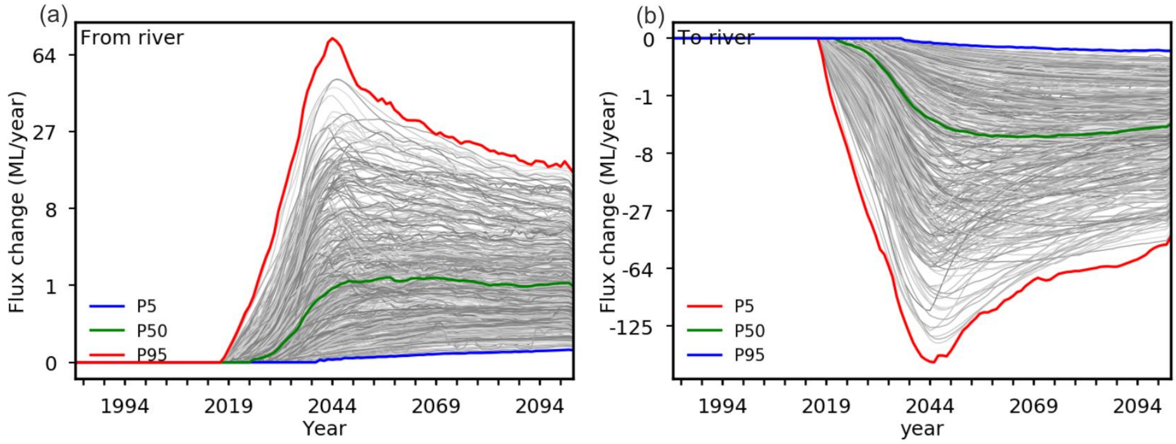

Figure 11: Potential changes in the SW – GW interactions of the Pilliga Sandstone a) Changes in the influx into the Pilliga Sandstone from the river b) Changes in the base flow contribution to the river from the Pilliga Sandstone. (The predicted flux changes lower than 5th percentile and higher than 95th percentile are not shown in the time series plot)

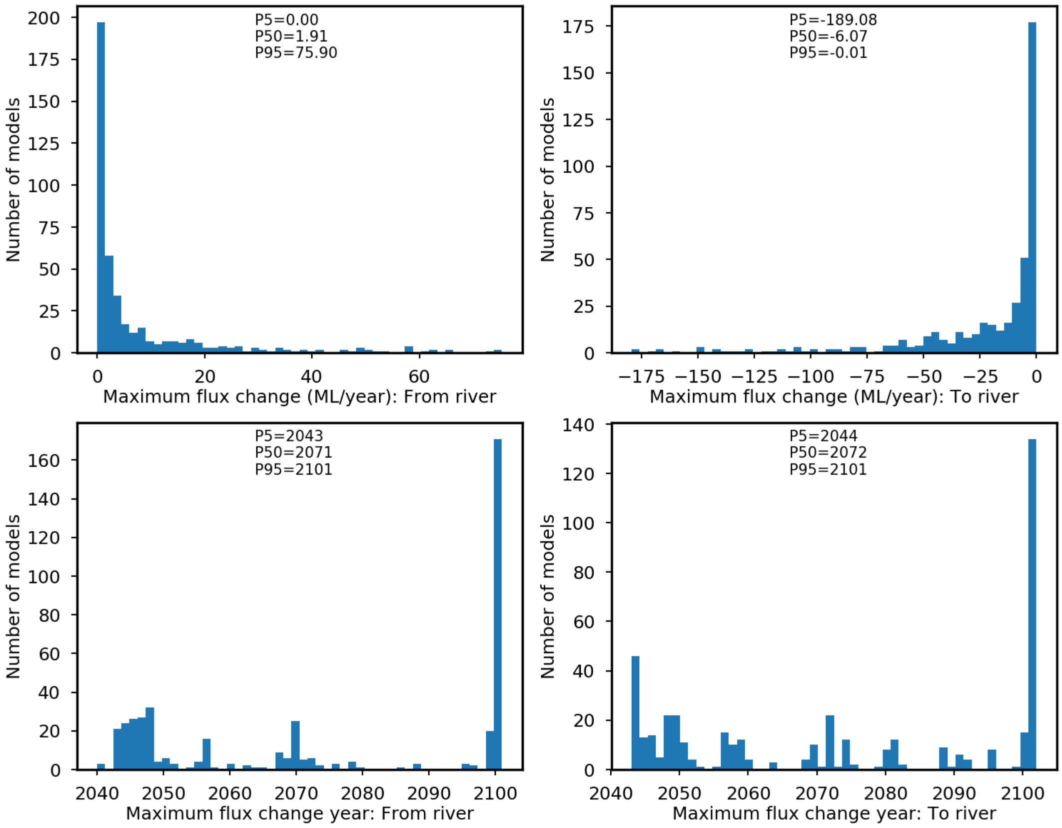

Figure 12: Distributions of maximum changes in the SW – GW interactions and the distribution of the times of maximum change

4.7 Water balance changes in the Pilliga Sandstone

The probabilistic analysis of mean annual water balance changes for Pilliga Sandstone over the simulation period (model layer 6) is shown in the box plot (Figure 12). The box plot provide the mean annual volumes (GL/year) of different components of water balance for the Pilliga Sandstone computed over the simulation period for the baseline and CSG development model runs. The net change in the water balance components between the baseline and CSG development is also shown in the figure 12 as mean annual volumes (ML/year).

All the water balance components except groundwater extraction rates for the GAB aquifers are represented as a distribution with the minimum, 5th percentile, median, 95th percentile and the maximum values of the mean annual fluxes and flux changes over the simulation period. The summary statistics of the distribution are obtained from the ensemble model predictions. The groundwater extractions were considered as deterministic and were input into the model as a specified flux boundary condition for both baseline and CSG development cases. The specified groundwater extraction rate approximately equal to the long term annual average extraction limit of 29.68 GL/year.

The recharge boundary condition of the model comprised diffuse recharge from rainfall, irrigation recharge and flood recharge. The recharge-in component of the water balance represents cumulative value of these three components specified for areas where Pilliga Sandstone is the top-most layer of the model. This recharge is the major component of inflow into the Pilliga Sandstone. The mean value of simulated recharge for both the baseline and CSG development cases over the simulation period is 65.04 GL/year. It is important to note that recharge is input as a specified flux boundary conditions and any potential changes in recharge regime, for e.g., due to land use changes caused by the gas project, is not simulated. Considering large uncertainty in the measurement and modelling of recharge, the specified value of recharge was varied in a wide range using one parameter each for the diffuse, irrigation and flood components of recharge. The 5th and 95th percentile of recharge are respectively 36.75 and 110.71 GL/year for both baseline and CSG development cases.

Some amount of water flows into the Pilliga Sandstone as recharge from the rivers and other water courses. This volume is represented by the river-in component of the water balance. Unlike the recharge boundary condition the river was simulated as a head dependent flux boundary condition. Thus, the difference in the river-in component between the baseline and CSG development cases is indicative of the flux interactions between the Pilliga Sandstone and the river reaches. The median value of river-in component of the water balance for the baseline case is 1.98 GL/year. The ensemble simulations are indicative of a very small increase in the river influx into the Pilliga Sandstone with a median value of 0.72 ML/year over the simulation period.

The major components of discharge include groundwater extractions and evapotranspiration (ET). Relatively wide range of values simulated for the evapotranspiration similar to recharge indicates the large uncertainty in the estimation of this value. As discussed earlier, the ensemble simulations are indicative of decrease in the baseflow from Pilliga Sandstone to the gaining river reaches. The median value of the simulated mean annual base flow for the baseline case is 6.49GL/year. The 5th and 95th percentile of the simulated values are respectively 1.87 and 34.14 GL/year. A small decrease in base flow of 2.50 ML/year (median value) compared to the baseline is simulated for the CSG development case. Simulations indicate that the discharge flux from the Pilliga Sandstone to deeper formations increase for the CSG development case in comparison to the baseline case. The distribution of simulated influx from and discharge to other zones is represented in figure 13.

The baseline case simulations show that groundwater flows from zone 1 (alluvium) and zone 3 (inter-burden between the alluvium and the Pilliga Sandstone) to the zone 6 (the Pilliga Sandstone). There is only very small amount of flow from the deeper formations (zone 8) to the Pilliga Sandstone. The difference between the CSG development and baseline case simulations show that flows from zones 1 and 3 towards zone 6 increases to a small extent. The median value of the simulated long-term average increase in flow from the alluvium to the Pilliga Sandstone over the simulation period is 0.32 ML/year with 5th and 95th percentile values of 0.00 and 8.25 ML/y. Similarly, the median value of the simulated long-term average increase in flow from the inter-burden above the Pilliga Sandstone to the Pilliga Sandstone over the simulation period is 2.86 ML/year with 5th and 95th percentile values of 0.00 and 58.79 ML/year. The median value of the simulated long-term average increase in flow from the Pilliga Sandstone to the deeper formations of the Gunnedah Basin over the simulation period is 35.28 ML/year. The 5th and 95th percentile of this are respectively 0.079 and 493. 36 ML/year.

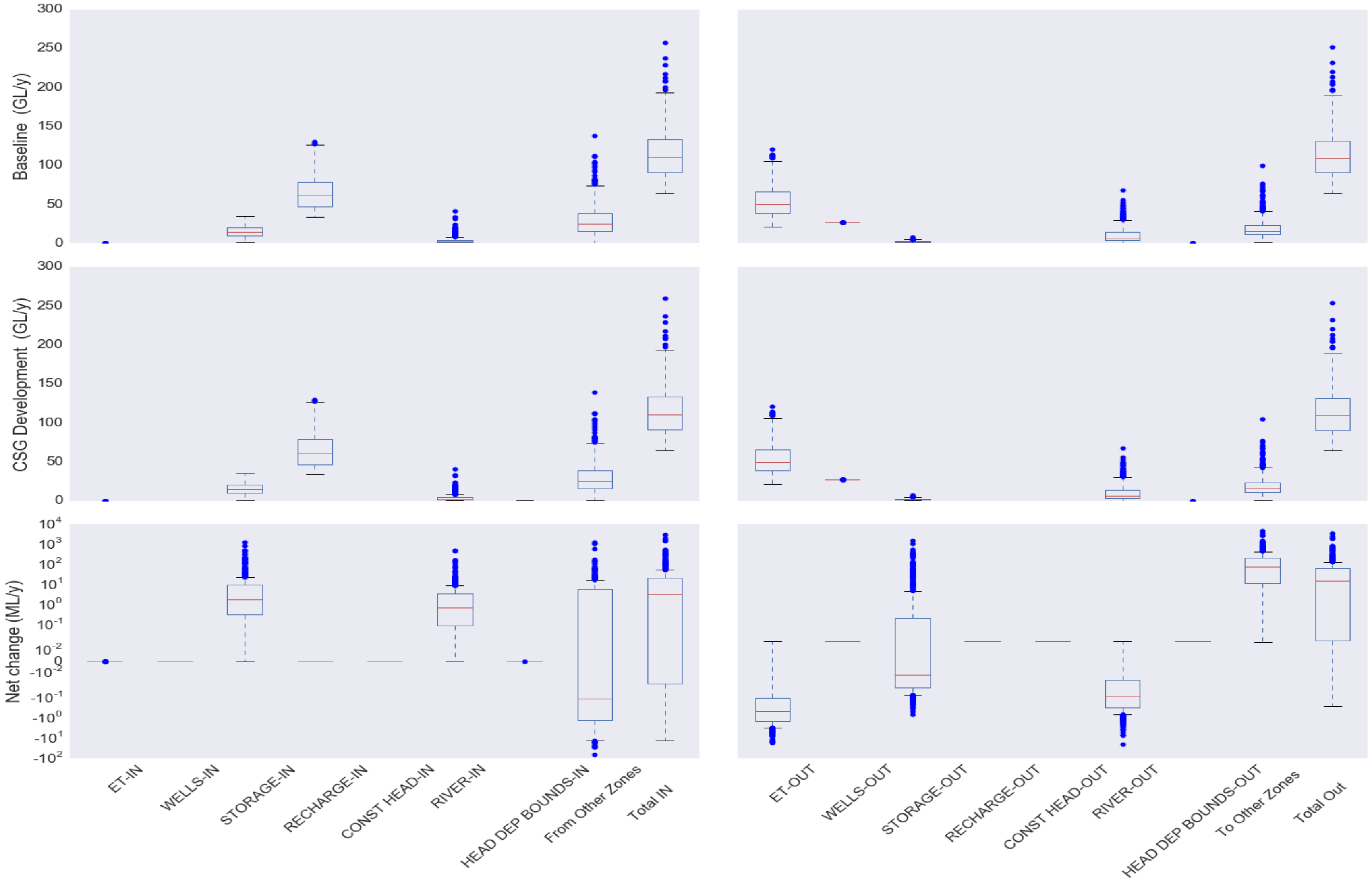

Figure 13:CSG induced water balance changes for the Pilliga Sandstone aquifer

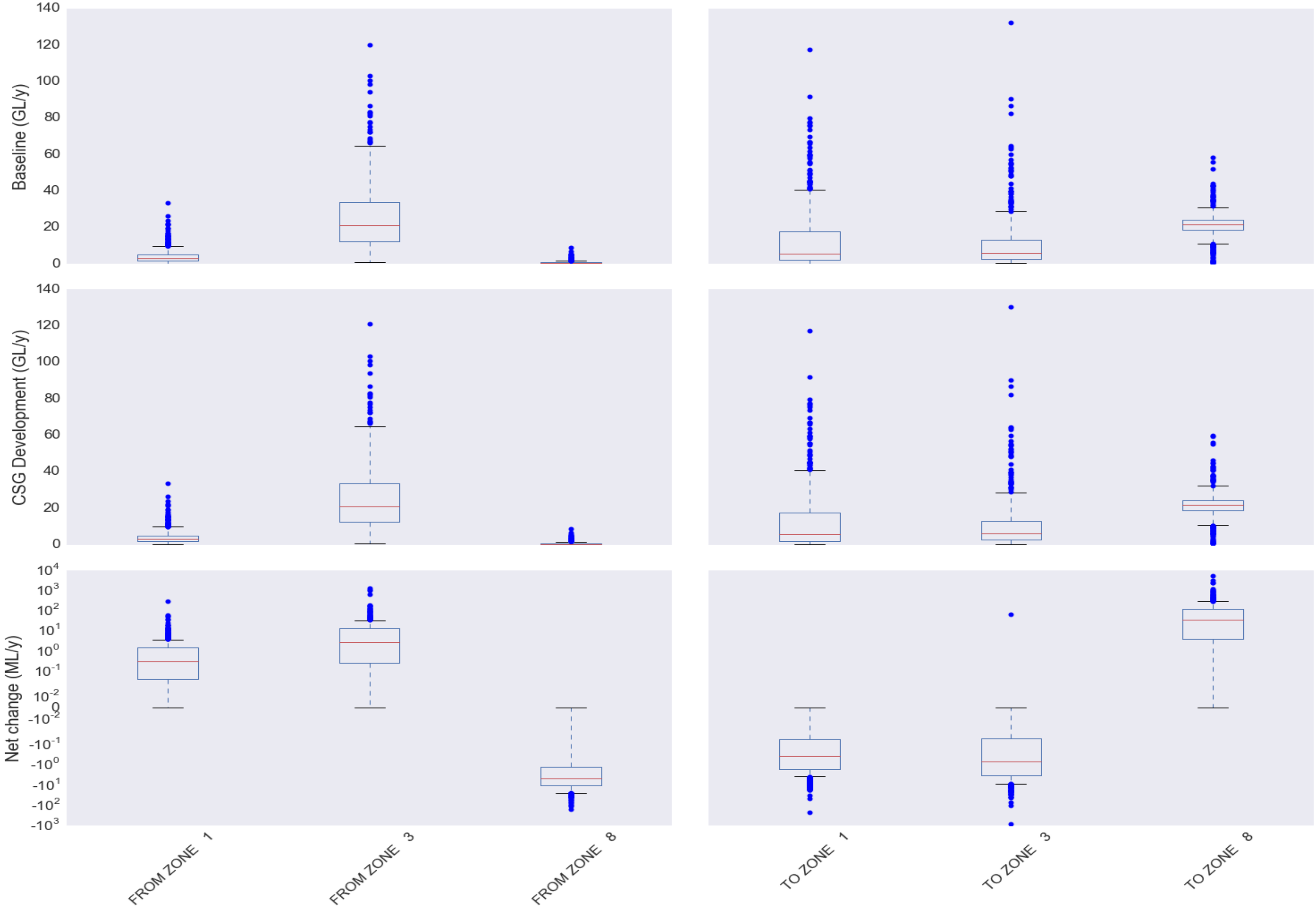

Figure 14 CSG induced flux interactions between the Pilliga Sandstone and the overlying and underlying formations

4.8 Limitations

The present study applied a probabilistic groundwater modelling approach to quantify the prediction uncertainty of flux changes in the Pilliga Sandstone – the main GAB aquifer near the proposed coal seam gas development in the Narrabri Gas Project. The existing regional scale groundwater model developed for the Bioregional Assessments of the Namoi subregion was used for this purpose. The model was originally built for assessing the cumulative impacts of coal mines and coal seam gas development in this region. A comprehensive list of the assumptions that formed the basis of model development is listed in Sreekanth et al. (2017). The assumptions and limitations of the modelling approach that may influence the prediction of the flux changes of the Pilliga Sandstone are given in the following:

- The conceptual model used for building the numerical groundwater model development in is underpinned by the existing geologic and hydrogeologic data and current state of knowledge about the Gunnedah and Surat Basin formations. Collection of more hydrogeologic datasets including environmental tracers can improve the conceptual understanding of the groundwater system and help better constrain the prediction uncertainty.
- Geologic structures including faults have not been included in the regional groundwater model used in this analysis. Further studies are required to quantify the effect of the presence of faults on the flux changes induced by CSG development.
- The hydraulic characteristics of aquitards in the inter-burden layers between the coal seams and the Pilliga Sandstone play an important role in the propagation of pressure and flux changes. Hydraulic properties of the inter-burden layers were characterized using a depth dependent decay function based on the trend observed in the available datasets. Highly parameterised approaches could be used to more comprehensively explore the spatial variability of these properties, to constrain the prediction uncertainty and evaluate the data-worth of measurement of these properties.
- Recharge from rainfall, irrigation and flood was represented as a specified flux boundary condition in the model for both the baseline and CSG development cases. Any potential change in the recharge regime, for e.g. because of the land use changes induced by the gas project, was not simulated in the current study. Similarly offsetting of licenced extractions by means of buy-back by the coal mines was also not accounted for in the specified flux boundary condition for groundwater extractions.

4.9 Scope for further work

The study presented here provides a probabilistic assessment of GAB flux and water balance changes and associated uncertainty resulting from the development of coal seam gas in the Narrabri

Gas Project. This was undertaken as two tasks of the phase I of the GISERA project 'Impacts of CSG development on GAB flux in the Narrabri Gas Project area'. The following two tasks are currently being undertaken as part of the phase II of this project:

- Task 4 of the project aims to improve the conceptual understanding of the Gunnedah and Surat basins in the gas development area by measuring and interpreting environmental tracers and analysing the hydrogeological and hydrochemistry data sets available from the NSW Government and Santos' EIS datasets.
- Task 5 of the project will integrate knowledge emerging from these analyses conducted in the task 4 and improved understanding of the water production rates to underpin the numerical groundwater model to further constrain and improve the confidence in the prediction of drawdown and flux changes caused by the CSG development. The improved model will be used for testing whether the occurrence of some hypothesized impacts that are of concern to the community could be rejected or accepted with high confidence given the current level of knowledge available about the deep groundwater system.

Beyond the scope of the GISERA project, it is also important to minimise uncertainty in the estimation of the groundwater recharge in GAB Intake Beds in order to minimise uncertainty and underpin the allocation and management of groundwater resources in this area using improved understanding of the groundwater system.

4.10 Comparison between 'Bioregional Assessments', 'GISERA' and 'Faults and Aquitards' groundwater models developed for the Namoi subregion of New South Wales.

Three parallel groundwater modelling studies for the Namoi subregion have recently been completed by CSIRO and the Department of Environment and Energy (DoEE) Office of Water Science. One study was commissioned through the Bioregional Assessments Programme, the second study was delivered through GISERA, and the third study was the DoEE knowledge project on Faults and Aquitard Modelling - 'F&A model'. Each of these studies addressed different aspects of the research priorities identified by the IESC and GISERA, i.e.:

1. "to increase the scientific evidence that underpins decisions about coal seam gas (CSG) and large coal mining development, enabling decisions to be based on the most rigorous science."
2. "to improve understanding of the GAB groundwater flow in the Pilliga region by integration of existing information from models, hydrochemical data and environmental tracers"

Each of these models were developed for the Namoi subregion within the Gunnedah and Surat basins of New South Wales. Results from these three models provides an opportunity to obtain a more comprehensive understanding of the groundwater system when assessing the risks associated with deep groundwater extraction and depressurisation for CSG developments.

The focus, purpose and objectives of these three modelling studies were different:

1. The Bioregional Assessment (BA) model focussed on cumulative impacts arising from coal resource developments, including open-cut and underground mining operations, proposals to expand existing open-cut and underground mines and proposals for new open-cut and underground mines and a CSG development. This model (a) calculated maximum drawdown and time to maximum drawdown and (b) generated the change in surface water-groundwater flux along selected sections of the stream network to inform surface water modelling.
2. The GISERA model examined changes to the water balance and flux losses of the Pilliga aquifer due to CSG development through the Narrabri Gas Project. The GISERA model used the BA model as starting

point, but focussed on determining changes in regional-scale water balance and groundwater flux in the Great Artesian Basin aquifer (i.e., Pilliga Sandstone aquifer). The GISERA model shares the coal resource development pathway implemented in the BA model.

The DoEE 'F&A model' evaluated different strategies of representing aquitards in regional scale models based on permeability data collected during the project. The DoEE F&A model evaluated different approaches to representing aquitards in regional scale groundwater models based on permeability data collected during this project to improve flow simulations taking into account risk of CSG-induced depressurisation. This model demonstrated a practical workflow to improve aquitard parameterisation and the quantification of predictive uncertainty. Only CSG development is considered in this model

The details of the GISERA study and key findings are presented in this report. Interested readers are referred to the other two reports for the key findings from those two studies.

5 Conclusions

An assessment of potential flux and water balance changes and associated uncertainties in the GAB aquifer – the Pilliga Sandstone caused by coal seam gas development in the Narrabri Gas Project was undertaken using probabilistic groundwater modelling. The groundwater model built for the Namoi subregion in the Bioregional Assessments Programme was used for this purpose. The changes in flux and water balance induced by the extraction of water from the coal seams was quantified as the difference between the CSG development and the baseline cases of groundwater flow. Uncertainty in the CSG water production rates, hydraulic characteristics of the geologic formations and groundwater flow components including recharge were accounted for by varying their respective parameters in the model in a wide range. Five hundred posterior parameter sets selected from a uniform prior distribution of 3500 parameter sets and constrained by observations were used to undertake the predictive analysis of CSG induced GAB flux changes.

The results of the analyses indicated that CSG development could potentially induce flux changes in the GAB aquifer – the Pilliga Sandstone. One of the most important variables of interest in the prediction analyses was the increase in flux from the Pilliga Sandstone to the deeper formations due to the lowering of groundwater pressure in the coal seams due to gas and water extraction. The median value of maximum flux increase from the Pilliga Sandstone to the deeper formations is 84.52 ML/year. This value is approximately 0.29% of the Long Term Annual Average Extraction Limit of 29.68 GL/y from the Southern Recharge Source. This potential increase of groundwater flow from the Pilliga Sandstone to deeper formations in the Surat and Gunnedah basins is also accompanied by increased rate of water flow into the Pilliga Sandstone from the aquifer and inter-burden formations and the water courses overlying it. The changes in water balance induced by CSG development was evaluated as mean annual values of the difference in the water balances between the baseline and CSG development cases over the simulation period of 120 years. The probabilistic simulation of the water balance components indicate that small changes could be induced to interactions of the Pilliga Sandstone with the overlying and underlying formations and with the surface water courses.

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