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

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Acknowledgments

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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 resource that is used for irrigation, stock and domestic uses. The Pilliga forest is also a recharge area for the Pilliga Sandstone aquifer, which is part of the Great Artesian Basin (GAB) aquifers. There is community 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 of the range of change in groundwater flux to, and water balance of, the Pilliga Sandstone GAB aquifer arising from specified depressurisation of the underlying coal seams. The report does not reproduce the expected depressurisation of the Narrabri Gas Project in the Gunnedah Basin but, rather, provides results from a broader generalised case of coal seam depressurisation as an independent assessment of the range of potential impacts on GAB aquifer recharge.

A probabilistic groundwater modelling method was applied for the assessment of potential flux and water balance changes and associated uncertainties in the GAB aquifer – the Pilliga Sandstone caused by coal seam depressurisation. The plausible range of flux impacts and water balance changes potentially induced by CSG development were quantified by accounting for the possibility of wide range of values for the uncertain groundwater system characteristics and model parameters. Two distinct modelling schemes were employed to comprehensively evaluate the effects of uncertainty in hydraulic characteristics of aquifers and aquitards and other model inputs and parameters on predictive uncertainty of flux changes. A parsimoniously parameterized modelling scheme was employed for quantifying the probable extreme impacts. A highly parameterized modelling scheme was employed for more realistically quantifying the expected value of flux impacts by accounting for the natural variability of aquitard hydraulic characteristics in the regional scale underpinned by observed spatial variability from measured datasets.

The groundwater model built for the Namoi subregion in the Bioregional Assessments Programme (http://www.bioregionalassessments.gov.au/) was adapted and improved 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. Confidence in the predicted impacts was quantified by varying coal seam depressurisation, hydraulic characteristics of the geologic formations and groundwater flow components across broad ranges. 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 model predictions and available observations. These 500 parameter sets were then used in the parsimoniously parameterized modelling scheme to undertake a generic assessment of coal seam depressurisation on GAB flux changes. Further, another set of 500 models were evaluated using the highly parameterized modelling scheme that more realistically evaluated the natural variability in uncertain hydraulic characteristics of the geological formations.

The changes in water balance induced by coal seam depressurisation indicated that changes to water balance components were relatively small compared to the probabilistic estimates of their baseline values. Simulations also indicated that small changes could be induced to interactions between the Pilliga Sandstone and overlying and underlying formations, and with the surface water courses.

The results indicated that coal seam depressurisation could potentially induce an 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 was calculated as 85 ML/year using the parsimoniously parameterized modelling scheme. The 5th and 95th percentile of the distribution calculated using this scheme are respectively 0.28 to 2299 ML/year. The median value corresponds to approximately 0.3% of the Long Term Annual Average Extraction Limit of 29.68 GL/year from the GAB groundwater source in this area called the Southern Recharge Source. The median value and the 95th percentile also corresponds, respectively, to 0.2% and 5.3% of the estimated annual recharge for the Southern Recharge Source indicating that the impacts are relatively small compared to recharge to and water use from the Pilliga Sandstone aquifer. The highly parameterized modelling scheme resulted in a median value of simulated maximum flux losses as 60 ML/year within the 5th to 95th percentile range of 0.01 to 267 ML/year. The range of predicted impacts is smaller for the highly parameterized scheme because this scheme is further constrained by observed spatial trends in hydraulic characteristics of the aquitard formations that separate coal seams from the Pilliga Sandstone.

In our generalised depressurisation case, the predicted median values of 85 and 60 ML/year was consistent with the estimated 60 ML/year of the ‘base case’ water production scenario reported in Santos’ Groundwater Impact Assessment report (CDM Smith, 2016). In our study, the range of water production rates (4.4 – 107.1 GL; 5th – 95th percentile) spanned the Narrabri Gas Project estimates of 35.5 (Low), 37.5 (base) and 87.1 GL (high) cases of the Groundwater Impact Assessment report (CDM Smith, 2016). This enabled the simulation of flux changes for a wide range of water production rates that were smaller and greater than the three scenarios considered by the Groundwater Impact Assessment report.

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 using the parsimoniously parameterized model 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 was 0.89 ML/year, equivalent to nearly 0.001 % of the average annual extractions from the alluvium. Similar values were also predicted by the highly parameterized model.

Between the two modelling schemes 920 constrained model simulations were undertaken in a Monte Carlo framework to evaluate the effect of CSG development on GAB flux changes. However, many more combinations of parameters and model inputs, virtually infinite combinations, are plausible within the range accounted for within the Monte Carlo simulations. Including many more thousands of model runs using the physically based model is challenged by the computational and other resources available for most modelling studies. To overcome this challenge we developed a surrogate modelling method where by the physically based numerical model is replaced by a simpler surrogate model that can approximate the MODFLOW model predictions. The surrogate model is trained using the predictions obtained from the MODFLOW model. The surrogate model is further coupled with an optimization algorithm in a simulation-optimization framework to evaluate the trade-off between maximum flux losses, CSG water production and average of the predicted maximum drawdown in the Pilliga Sandstone. The simulation-optimization analysis that evaluated 1.5 million combinations sensitive model parameters that are most sensitive to prediction of CSG-induced impacts, CSG water production and predicted maximum drawdown in the Pilliga Sandstone aquifer illustrated that when the realization of the hydraulic characteristics, within the plausible range, are most favourable for maximum flux losses, the CSG-induced flux loss would linearly increase with increase in the total CSG water production. It was also found that, the CSG-induced flux losses could linearly increase with increase in the average of the maximum CSG-induced drawdown observed in the Pilliga Sandstone aquifer.

The simulation-optimization analysis provided the following two important insights. Given the current conceptual understanding of the groundwater system as encapsulated in the numerical groundwater model it is highly unlikely that CSG-induced maximum flux losses from the Pilliga Sandstone aquifer would be more than 2000 ML/year if the total CSG water production is less than 40 GL, i.e. similar to what is currently predicted for the proposed coal seam gas project. While the flux losses from the relatively deep aquifer is difficult to measure, the analysis shows that the flux losses would be directly proportional to the average of the maximum CSG-induced groundwater head drawdown in the Pilliga Sandstone aquifer. This implies that, measuring of the groundwater head changes in the gas development region using dedicated monitoring network can provide valuable information regarding potential flux losses from the aquifer induced by CSG development. A companion GISERA report on ‘monitoring network design’ (Sreekanth et al., 2018) discusses in detail about potential CSG-induced drawdown and optimal monitoring strategies. Such ongoing monitoring programmes are essential for identifying any changes or deviations from predicted impacts. Future modelling efforts for quantifying CSG-induced impacts should ideally use such monitoring data to improve the conceptual understanding of the groundwater system and refine the prediction of impacts.

The groundwater modelling undertaken in this study focuses on probabilistic prediction of regional scale flux impacts of coal seam depressurisation 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 an independent estimate of potential changes in net flux to the Pilliga Sandstone aquifer arising from generic depressurisation of the Gunnedah Basin coal seams.

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 part of a broader region of recharge 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 has completed 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.

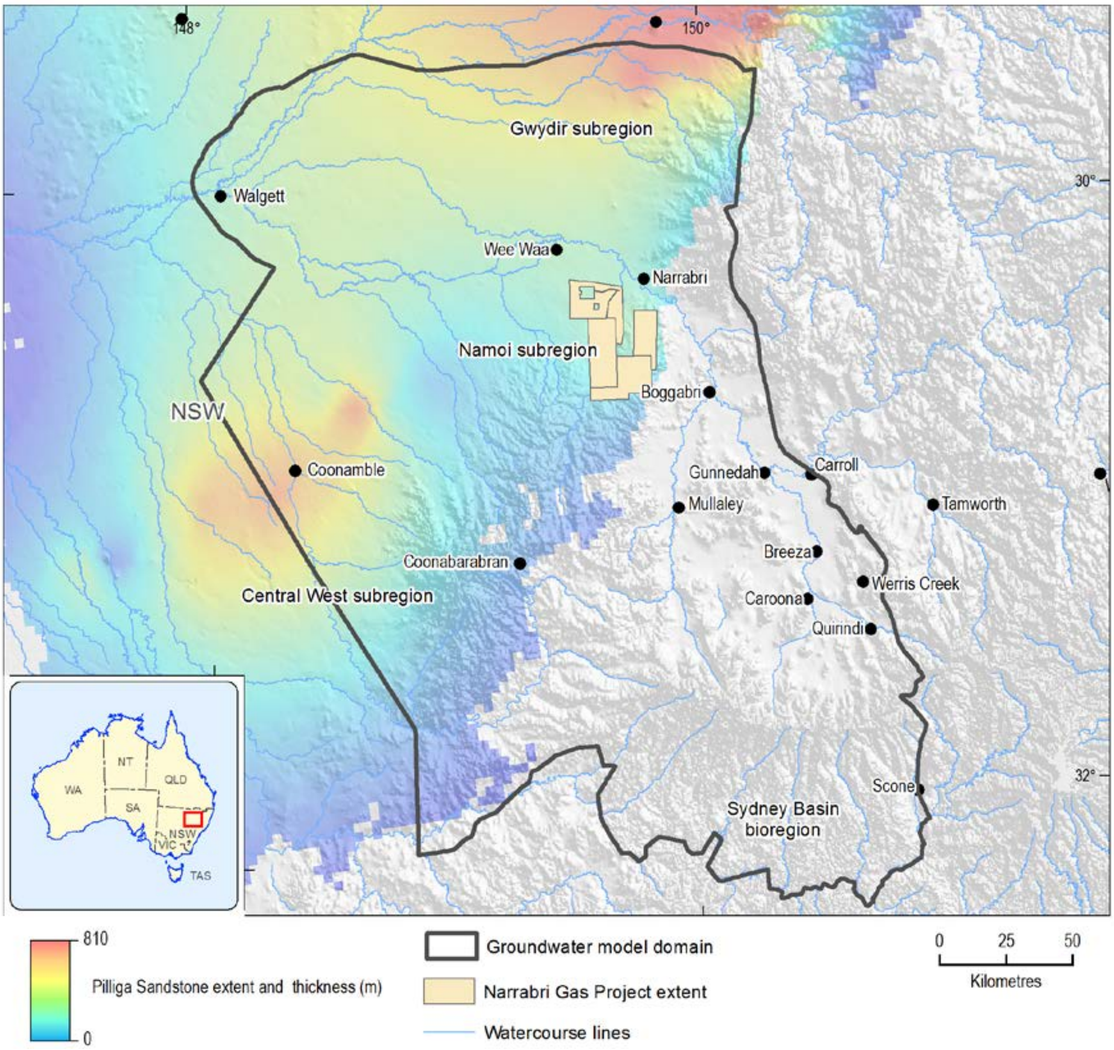

Figure 1: Extent and thickness of the Pilliga Sandstone within the study area.

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 increase confidence 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 increasing confidence in the estimated impacts through improved data and groundwater modelling are important for informing water licensing requirements as per water sharing regulations and development approvals.

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 east 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 this region along with outcropping along the Warrumbungle Range are recharge 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 are shown in Figure 2. Groundwater in the aquifers of the Pilliga Sandstone flows from south-east to west and north-west.

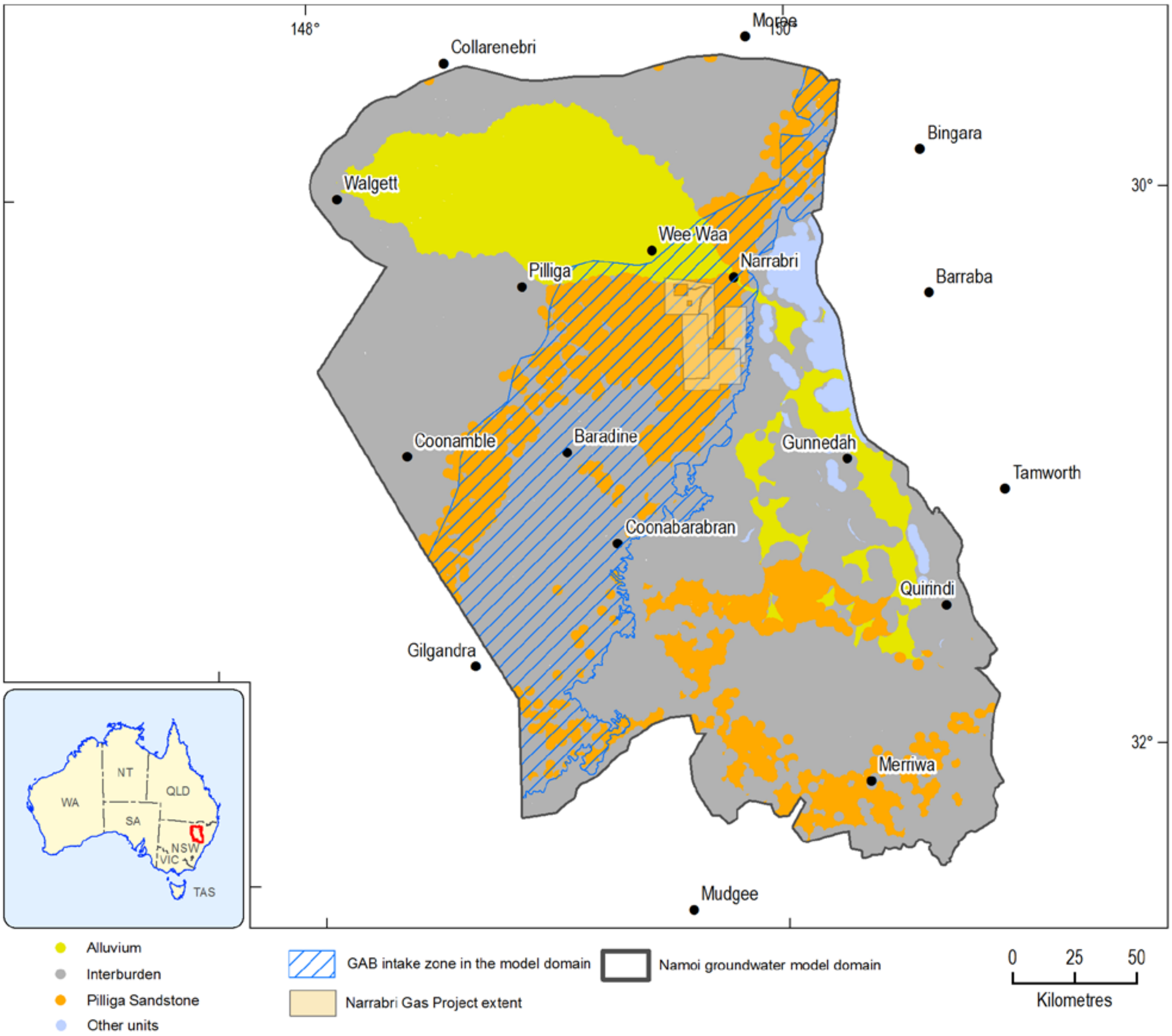

Figure 2: The GAB intake beds within the groundwater model area

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 confidence in the estimation of potential GAB flux and water balance changes in the region caused by coal seam gas development. As part of this GISERA study, this report provides the 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 modelling 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
- Simulation-optimization analysis to test the hypothesis on potential maximum flux impacts from the considered generic scenario of CSG development

1.4 Methodology

A probabilistic groundwater modelling methodology similar to that used in Bioregional Assessments (Crosbie et al., 2016) and previous GISERA (Sreekanth and Moore, 2015) 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 has been specified by the proponent in their Groundwater Impact Assessment report (CDM Smith, 2016). We considered a broader range of water extraction rates arising from coal seam depressurisation along with broad ranges of hydrogeological characteristics and properties of the geologic formations of the Surat and Gunnedah basins. The probabilistic assessment of these ranges enables evaluation of a wide range of potential impacts and therefore quantify confidence levels of the impacts.

Two different schemes were evaluated for the parameterization of the uncertain hydraulic property fields of the aquifer and aquitard formations in the model. Past analysis of observed hydraulic conductivity data revealed depth-dependency of hydraulic conductivity values for some of the formations in the Surat and Gunnedah basins (Aryal et al., 2017a). Considering this, one of the two schemes we evaluated considered depth-dependency for a parsimonious parameterization of hydraulic properties in the model. Another recent study (Turnadge et al., 2017) investigated the spatial variability in the hydraulic characteristics of aquitards in the Surat and Gunnedah Basins. We leveraged that study for the second parameterization scheme that we implemented to investigate the effects of spatial variability on the prediction of flux impacts to GAB aquifers. These two distinct approaches are described in detail in the following sections.

1.5 Monte Carlo simulations

A large number of model parameter sets of the groundwater model are evaluated to generate an ensemble of predictions. Monte Carlo simulations were first performed using the parsimoniously parameterized model. 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 generate the 3500 parameter sets uniformly from the entire parameter space. The 3500 models were ranked according to an objective function that characterises the difference between the model predictions and the available observations from monitoring wells. 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).

Once the predictive simulations were undertaken using the parsimoniously parameterized model, the model was updated using the highly parameterized scheme and the model runs were repeated to evaluate the difference in the prediction of flux changes.

2 The Bioregional Assessments' Groundwater Model for the Namoi subregion

The BA groundwater model for the Namoi subregion (Sreekanth et al., 2018) is used for probabilistic flow simulation in this study. The model encompasses an area of approximately 59,000 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. (2018a). 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. (2018a).

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.

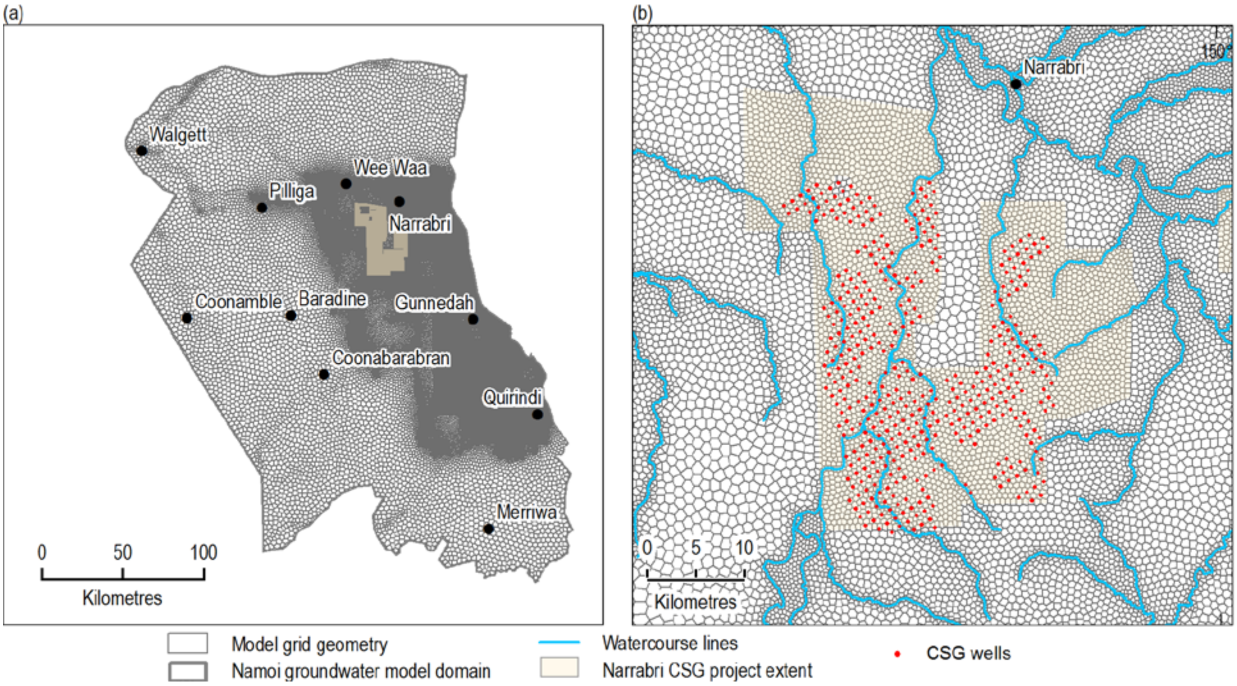

Figure 3 Plan view of the model grid and refinement of the Voronoi grid within the Narrabri Gas Project area

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. (2018).

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. (2018a). 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., 2018). 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., 2018). 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 11,785 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. (2018) 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., 2018b). 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 potential changes in the GAB flux and water balance caused by depressurisation of coal seams in the Gunnedah Basin. This is accomplished as the difference between model predictions of two possible states of GAB groundwater resource – one corresponding to no depressurisation and the other corresponding to depressurisation based on a generic case of gas development. This approach assumes that all other uses of groundwater remain unchanged over this period and quantifies only the changes in flux and water balance resulting from depressurisation only. This report does not reproduce the expected depressurisation of the Narrabri Gas Project in the Gunnedah Basin. Rather, it presents a broader generalised case of coal seam depressurisation as an independent assessment of the rage of potential impacts on GAB aquifer recharge.

3.1 Model runs for baseline and CSG development cases

The baseline case is a modelling scenario that includes all existing and expected future stresses on the groundwater resource in the modelled area except for depressurisation under coal seam gas development. 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 MODFLOW-USG. Information about mine footprints and excavation depth were used to define the drain boundary conditions.

The gas development case considers the potential stresses due to CSG development in a generalised sense in addition to the stresses considered in the baseline case. That is, the approach here does not exactly reproduce the Narrabri Gas Project modelling but rather presents an independent and plausible scenario of groundwater fluxes given depressurisation of coal seams. All other model inputs and parameters remain the same between the baseline and gas development model runs.

3.2 Representation of water extraction from CSG wells

We modelled 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. The representation of CSG extraction is different to that used in CDM Smith (2016) and specifies a more generic case. A drain boundary condition was defined for each model cell corresponding to the geographic location of proposed CSG wells of the Narrabri Gas Project. 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. We adopted this sequence for implementing the drain boundary condition. The 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, we considered a broader range of water production rates in our study to consider the more generic case. We modelled water extraction rates from the CSG wells as specified head dependent flux boundaries in these cells. A broad range in the water production rates was addressed by varying the conductance of drain cells widely. This represents a boarder range of conditions than considered in CDM Smith (2016).

3.3 Model parameterisation

As described earlier, two parameterization schemes were implemented to evaluate the effects of uncertainty in hydraulic properties of aquifers and aquitards on the CSG-induced flux changes. The first scheme used a parsimonious parameterization of hydraulic properties and the second scheme used a highly parameterized approach.

3.4 Parsimoniously parameterized scheme

The parsimoniously parameterized approach was developed and implemented in the Bioregional Assessments Programme for modelling cumulative drawdown impacts from CSG and coal mine development (Sreekanth et al., 2018). This approach assumed that the hydraulic properties in the Surat and Gunnedah Basin formations decreased with the depth of the formation from the surface. Measured values of raw hydraulic conductivity were used to obtain least square fit curves for these formations.

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., 2018a). 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:

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

$$S_S(d) = S_S0 * EXP(-\alpha_S * d) \quad (2)$$

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 does not 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 our confidence in predictions caused by uncertainty of the specific parameters. A full description of the depth-based parameterisation scheme is provided in Sreekanth et al. (2018).

One specific advantage of the parsimonious parameterization approach is that variability of hydraulic properties in all layers of the model can be characterized using relatively small number of variables that can be perturbed in the uncertainty analysis. Following the Namoi BA study, 81 parameters were identified and a sub-set of 37 parameters were used in the sensitivity and uncertainty analysis by the parsimoniously parameterized scheme to investigate the effects of model parameters on prediction of GAB flux changes. These parameters related to hydraulic properties of 15 model layers, boundary conditions including diffuse recharge, flood recharge, irrigation recharge, river exchanges, and model stresses including coal seam gas development and coal mining.

The smaller number of parameters involved in this approach enabled to evaluate extreme combination of parameters that may potentially result in extreme CSG-induced flux impacts. Several realizations of the horizontal hydraulic conductivity for the Pilliga Sandstone aquifer obtained using this parameterization is shown in Figure 4.

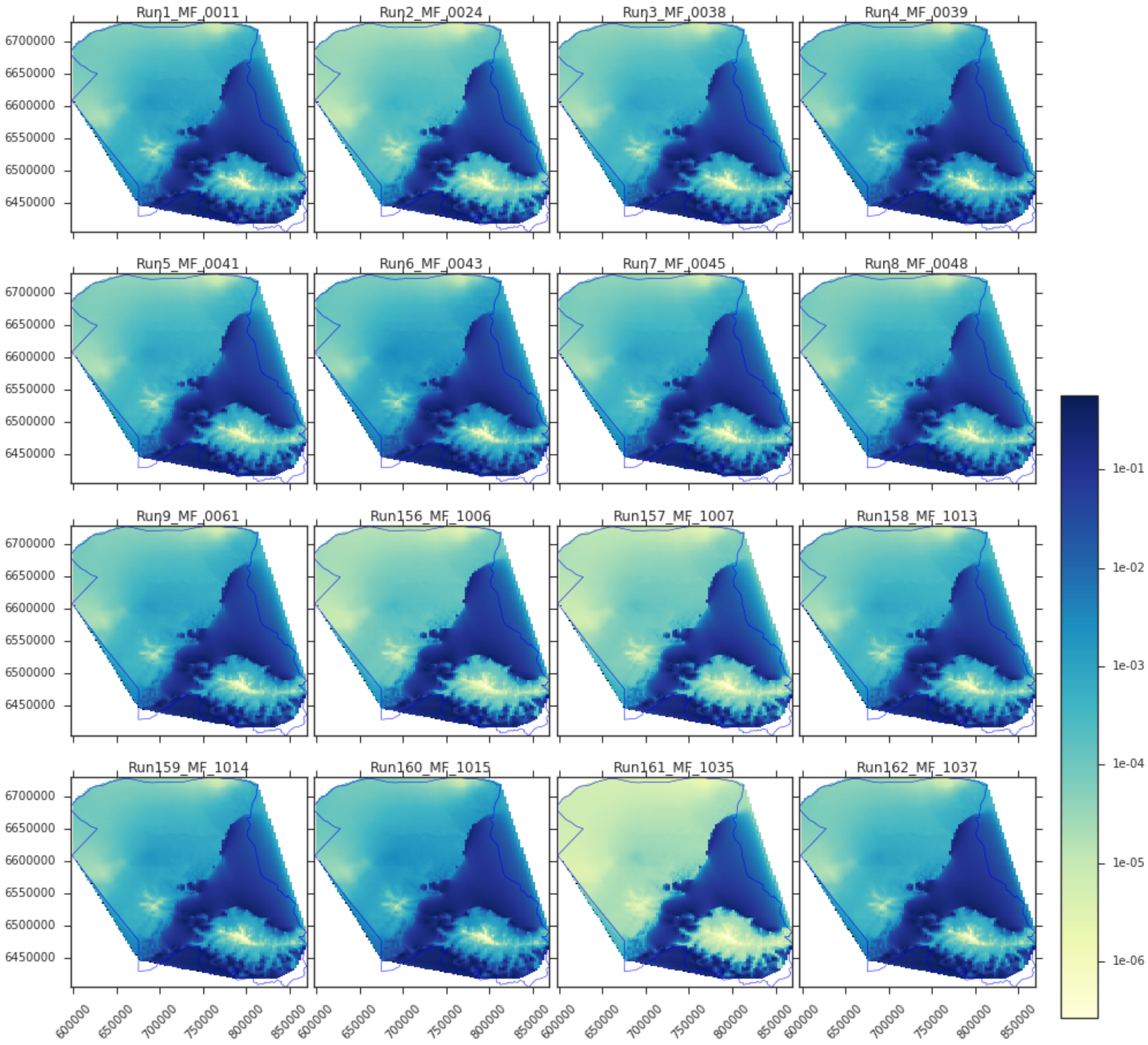

Figure 4: Sixteen realizations of horizontal hydraulic conductivity field for model layer 6 representing the Pilliga Sandstone aquifer generated using the parsimonious parameterization scheme.

3.5 Highly parameterized scheme

While hydraulic property values decreases with depth in the sedimentary basin formations, spatial heterogeneity in aquitards and aquifers can be more complex and uncertain than represented by simple depth-based decay. In order to explore the resulting uncertainty in prediction of GAB flux impacts we evaluated the highly parameterized modelling scheme. In this scheme we used 1672 parameters for parameterizing the groundwater model. Vast majority of these parameters are used for characterizing the heterogeneity and spatial variability in the hydraulic properties in multiple layers of the model. A recent study undertaken by Turnadge et al. (2017) analysed core data from aquitards in the Gunnedah and Surat basins and identified the geostatistical structure in these spatial datasets.

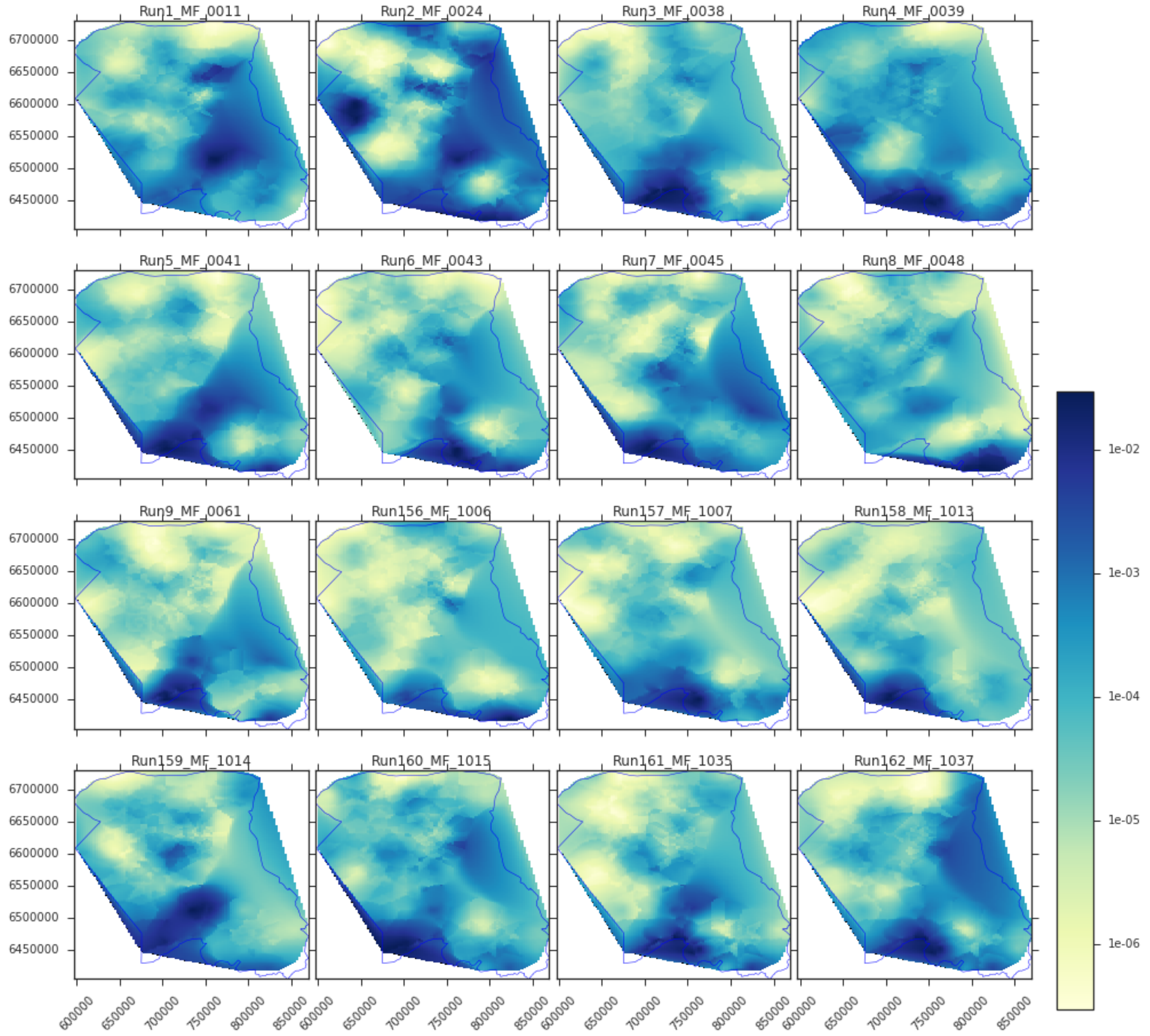

Figure 5: Sixteen realizations of horizontal hydraulic conductivity fields for model layer 6 corresponding to the Pilliga Sandstone generated using the highly parameterized modelling scheme.

Porosity-permeability relationships were derived based on this and where applied to downhole porosity logs obtained from 97 exploration wells located across the Gunnedah Basin. They evaluated upscaling approaches to upscale these core scale aquitard vertical hydraulic conductivity (Kv) values for inclusion in a regional-scale numerical groundwater model (CDM Smith, 2016). Further, they used this upscaled data to fit geostatistical variogram models to characterize the spatial co-variance of hydraulic properties in the aquitard sequences. A spherical variogram with a Sill of 0.764, Nugget of 0.327 and Range of 129 km was used to define the co-variance structure of hydraulic properties horizontally in different model layers. The highly parameterized modelling scheme used in the current study is underpinned by this spatial covariance structure for characterising prior uncertainty in hydraulic properties. Several realizations of Kh for model layer 6 corresponding to the Pilliga Sandstone aquifer are shown in Figure 5.

The two parameterization schemes employed served to explore prediction uncertainty in flux impacts using two different conceptualization of the hydraulic characteristics of aquitards and aquifers. It is notable from Figure 4 that while all the realizations exhibit similar pattern across the layer, very high and very low plausible values of hydraulic conductivity can be realized for all model cells using the parsimonious parameterization approach. This way, this approach enabled sampling of extreme plausible combinations of hydraulic property fields across all model layers that can result in potential extreme impacts of CSG development of GAB fluxes. On the other hand, the highly parameterized scheme enabled sampling of more realistic fields of hydraulic properties in the aquifers and aquitards underpinned by observed spatial trends in measured values of these properties. Thus, this parameterization scheme enabled better estimation of the median or expected values of CSG-induced flux impacts.

Due to the inherent variability of 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.

3.6 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 using the parsimonious parameterization scheme. 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 were used for predictive simulation of water balance and flux changes. The objective function cut-off for the 500 runs is shown in Figure 6. The choice of the 500 parameter combinations were made in such a way to ensure that they were representative of the whole set of 2618 successful model runs.

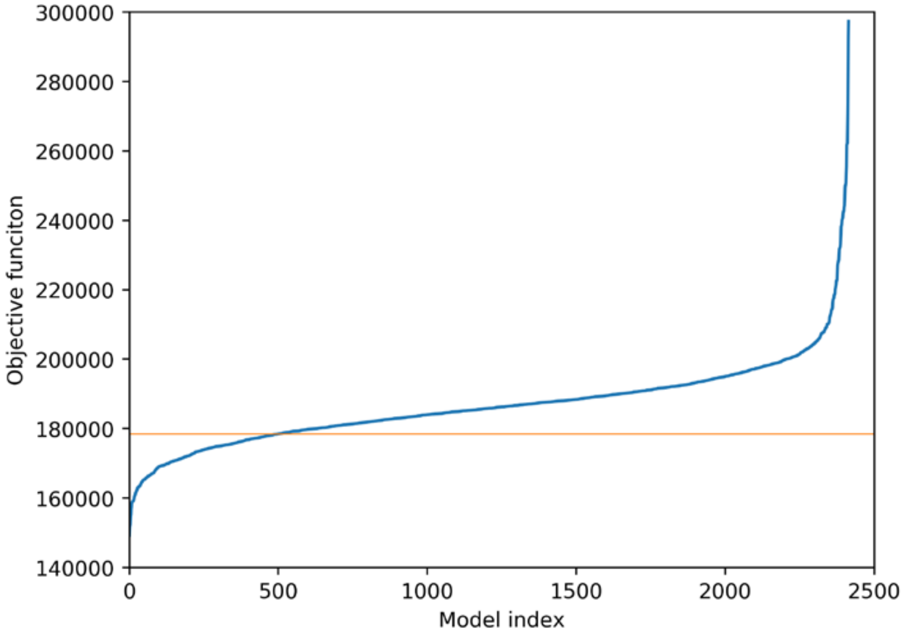

Figure 6: Objective function cut-off for selecting the 500 model runs

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.

The uncertainty analysis was then repeated after updating the model with the highly parameterized scheme. In doing so all parameters of the model in each run were retained at the same values as in the corresponding run of the parsimoniously parameterized model except the parameters corresponding to the hydraulic properties including the horizontal and vertical hydraulic conductivity and the specific storage. This enabled a direct comparison of the influence of parameterization of the connectivity between the coal formations and the Pilliga Sandstone formation on the CSG-induced flux losses.

4 Results and Discussion

The results of the simulation of GAB flux changes and range of impacts 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 7 shows the time series flux change and the distribution of maximum groundwater flux change from Pilliga Sandstone to deeper formations simulated by the parsimoniously parameterized model.

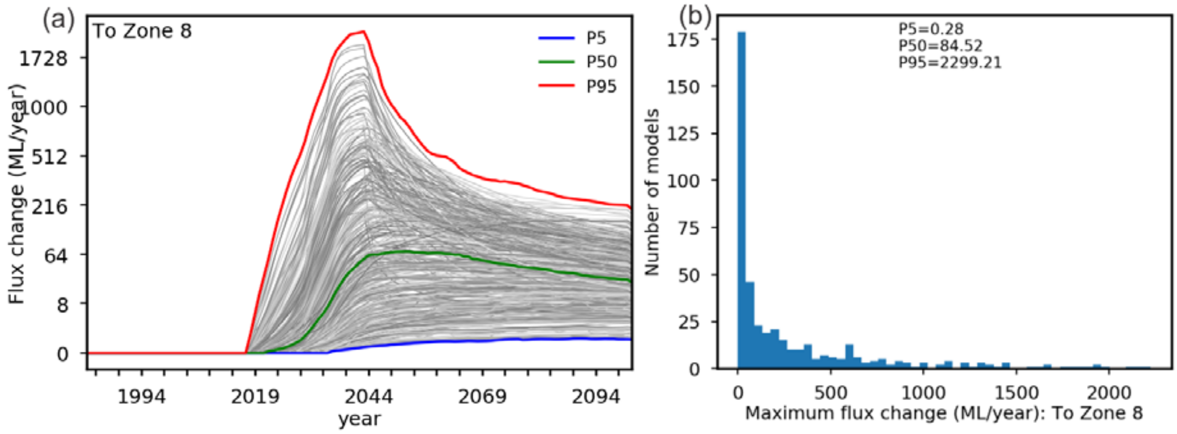

Figure 7: Potential flux losses from GAB aquifer Pilliga Sandstone to deeper formations obtained from the uncertainty analysis of the parsimoniously parameterized model a) Time series of potential flux losses b) Distribution of maximum flux losses from the ensemble model predictions (The predicted flux changes lower than 5th percentile and higher than 95th percentile are not shown in the time series plot)

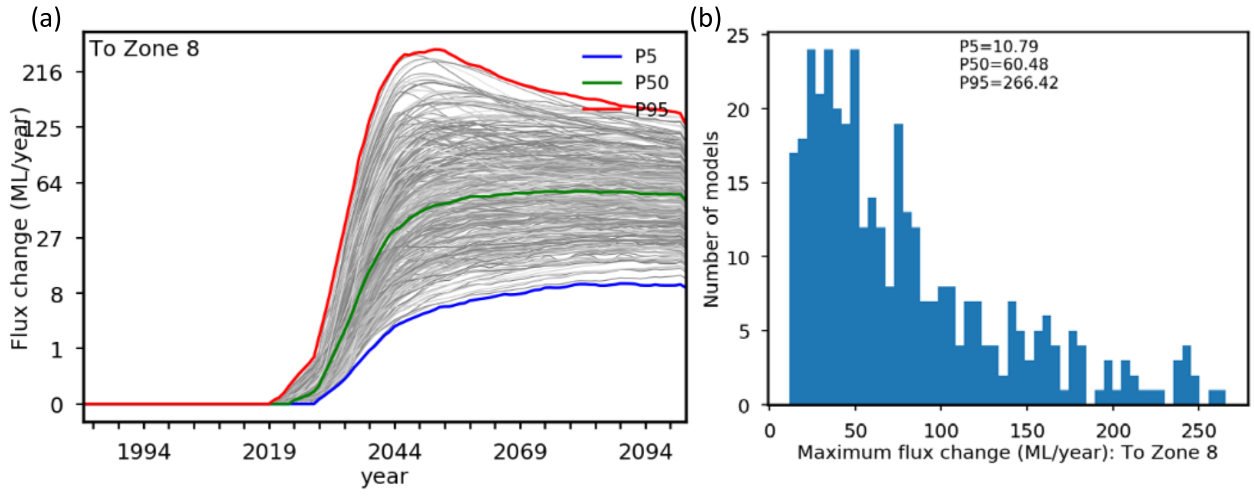

Figure 8: Potential flux losses from GAB aquifer Pilliga Sandstone to deeper formations obtained from the uncertainty analysis of the highly parameterized model a) Time series of potential flux losses b) Distribution of maximum flux losses from the ensemble model predictions (The predicted flux changes lower than 5th percentile and higher than 95th percentile are not shown in the time series plot)

Figure 8 shows the time series flux change and the distribution of maximum groundwater flux change from Pilliga Sandstone to deeper formations simulated using the highly parameterized model. The parsimoniously parameterized model simulations resulted in a 5th and 95th percentile values of CSG-induced maximum flux losses as 0.28 to 2299ML/year respectively. Improving the parameterization of the inter-burden layers based on the spatial variability of the hydraulic properties underpinned by the observed data resulted in the reduction of prediction uncertainty in the highly parameterized model simulations. It is noteworthy that the 95th percentile of the predicted flux losses from the Pilliga Sandstone aquifer reduced to 266 ML/year when simulated using the highly parameterized model. The median of predicted flux losses reduced from 84 ML/year in the parsimoniously parameterized model to 60 ML/year in the highly parameterized model. The wider range of simulated values of flux losses in the parsimoniously parameterized model simulations is because of uncertainty in hydraulic characteristics of the inter-burden formations is constrained only by the observed depth relationship. Whereas, in the highly parameterized model hydraulic conductivity is further constrained by observed trends in spatial variability. This exercise also informs the utility of refining model predictions using more observations to sequentially reduced prediction uncertainty. While the highly parameterized model predictions inform the more likely volumes of flux losses, the parsimoniously parameterized model brackets this estimates with high levels of confidence.

The median value of maximum flux losses predicted by the two sets of simulations are respectively 84.52 ML/year and 60 ML/year. To put this into perspective, these median values of predicted flux changes are respectively 0.29% and 0.2% of the Long Term Annual Average Extraction Limit of 29.68 GL/year from the Southern Recharge Source (NSW Water Register, DPI Water 2016/17 NSW GAB Groundwater Sources, 2008). These are also equal to about 0.2% and 0.14% of the recharge of 42,400 ML/year estimated for the Southern Recharge Source. Figure 9 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 10). 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.

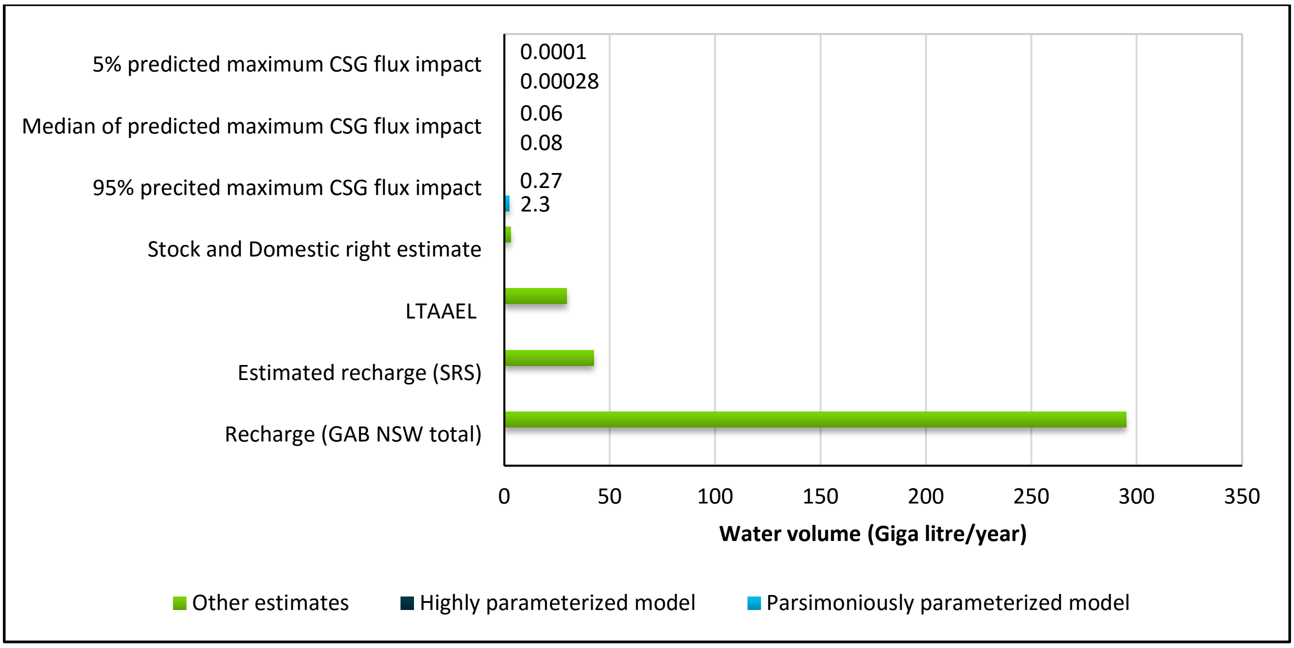

Figure 9: Comparison of predicted CSG flux impacts to estimated recharge and extraction limits set by the water sharing plan.

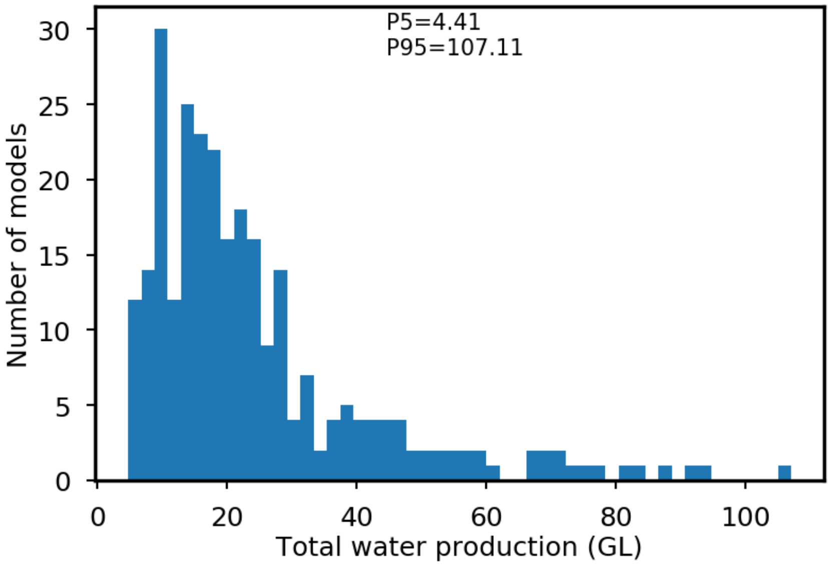

Figure 10: Distribution of the simulated total coal seam gas water production. The CSG water production was simulated as a head dependent flux boundary condition using the drain package of MODFLOW-USG. The parameters of the drain package and the hydraulic properties of the Hoskissons Coal and Maules Creek formations were varied in a wide range to simulate the water production curves

Table 3: Comparison of predicted CSG flux impacts by the parsimoniously parameterized model to estimated recharge and extraction limits

	Volume (GL/year)	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 7and Figure 8 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 11. 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.

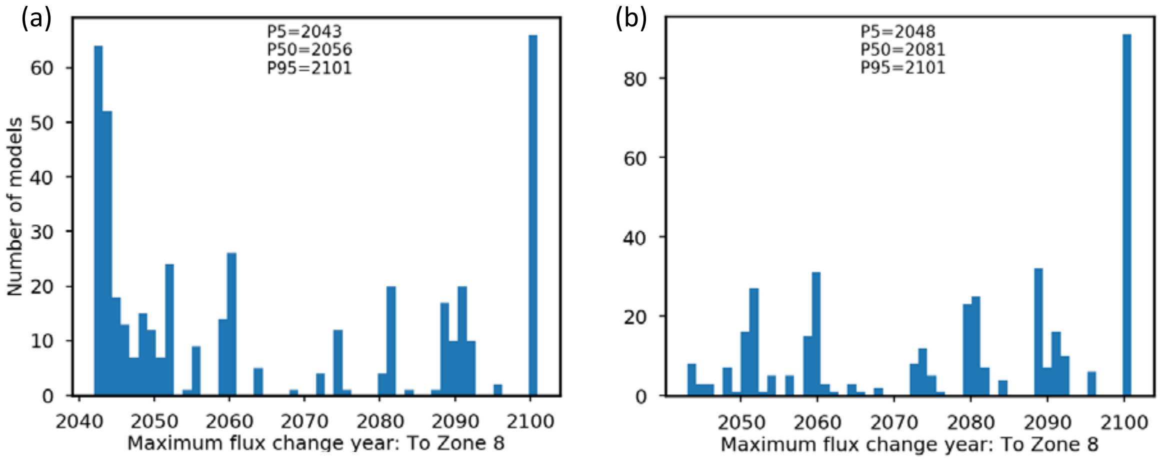

Figure 11: Distribution of times of maximum flux change from the GAB aquifer to the deeper formations simulated using the a) parsimoniously parameterized model and b) the highly parameterized model

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 parsimoniously and highly parameterized models are shown respectively in Figure 12 and Figure 13.

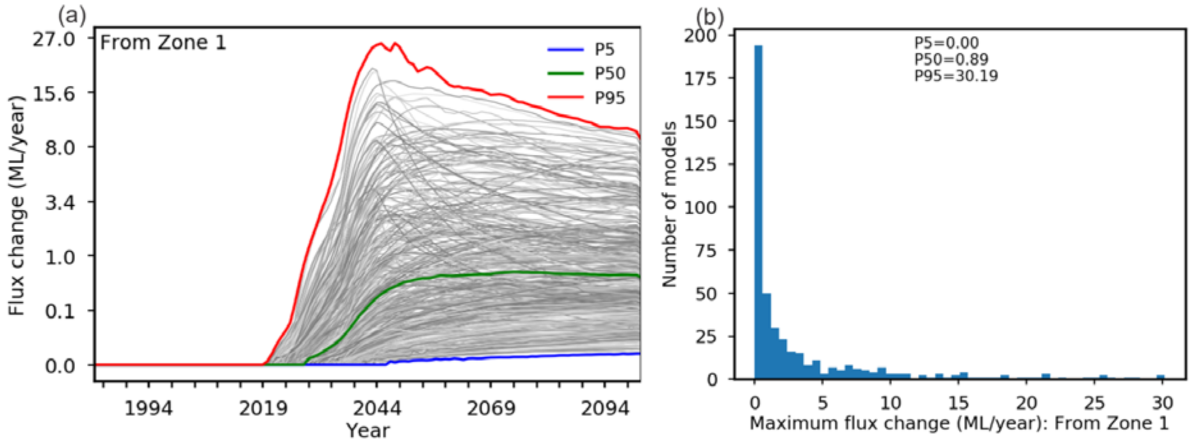

Figure 12: Potential influx from the alluvial aquifers to Pilliga Sandstone simulated using the parsimoniously parameterized model: a) Time series of potential influx; b) Distribution of maximum influx obtained from the ensemble model predictions. (The predicted flux changes lower than 5th percentile and higher than 95th percentile are not shown in the time series plot)

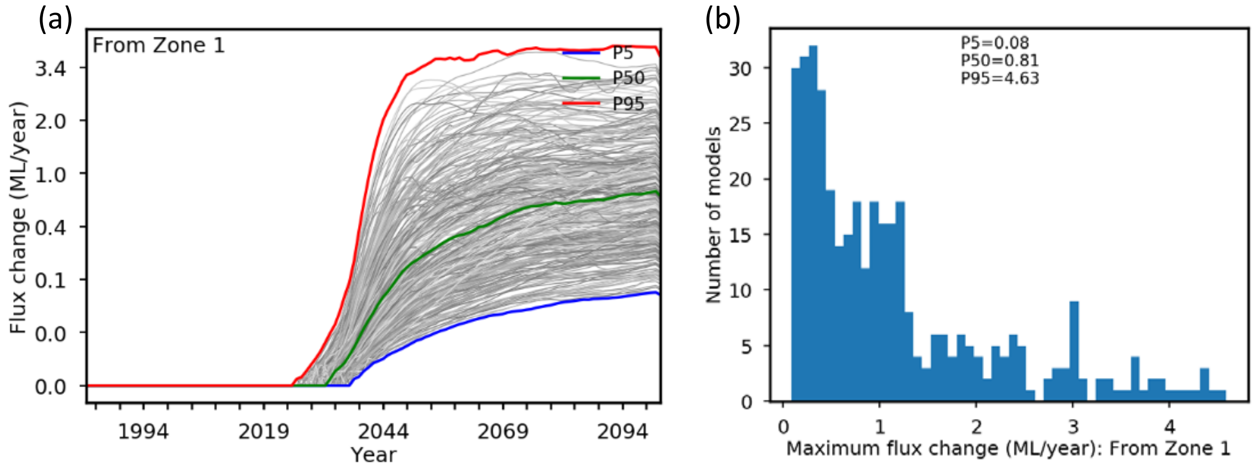

Figure 13: Potential influx from the alluvial aquifers to Pilliga Sandstone simulated using the highly parameterized model: a) Time series of potential influx; b) Distribution of maximum influx obtained from the ensemble model predictions. (The predicted flux changes lower than 5th percentile and higher than 95th percentile are not shown in the time series plot)

Similar to the flux losses predicted from the Pilliga Sandstone, the parsimoniously parameterized model predicted a bigger range of CSG-induced flux movement from the alluvial aquifer to the Pilliga Sandstone although both the schemes indicated that these fluxes are very small.

The parsimoniously parameterized model 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. This is equivalent to approximately 0.001% of the average annual extraction of 75,510 ML/year reported for the Lower Namoi alluvium (Peña-Arancibia et al., 2016). In comparison, maximum change in flow rate induced at the base of the Namoi alluvium is described as ‘negligible’ in the Santos’ groundwater modelling report (CDM Smith, 2016). The highly parameterized model simulations resulted in a 5th and 95th percentile values of annual maximum influx 0.08 and 4.63 ML/year respectively from the alluvial aquifers to Pilliga Sandstone.

The 5th and 95th percentile of maximum influx from zone 3 (the inter-burden layers between the Namoi alluvium and Pilliga Sandstone) simulated by the parsimoniously parameterized model were respectively 0.01 and 267.85 ML/year. The median value of maximum flux change is 7.15 and 8.24 ML/year respectively from the parsimoniously and highly parameterized model runs (Figure 14 and Figure 15). The distribution of predicted time of maximum flux change from zones 1 and 3 are shown in Figure 16.

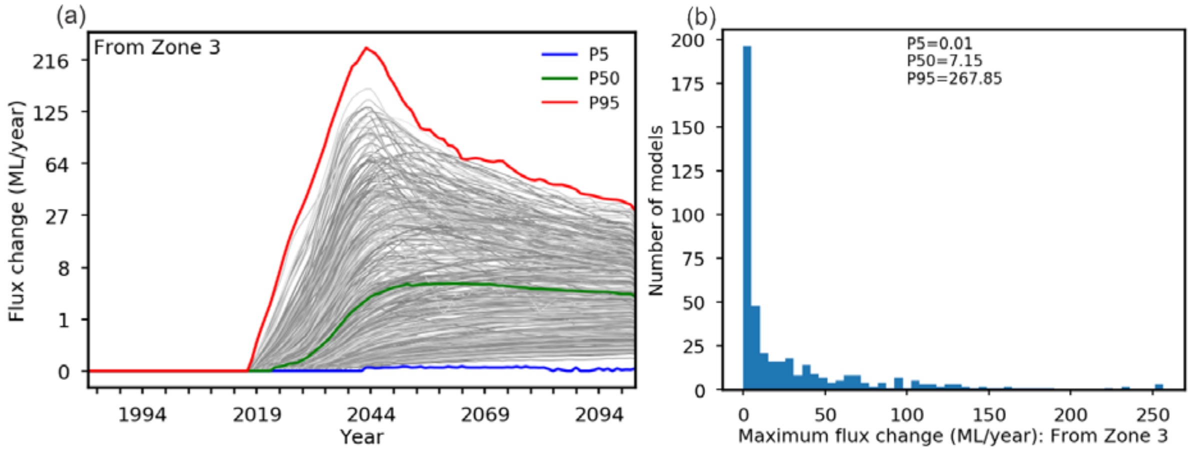

Figure 14: Potential influx into the Pilliga Sandstone from the inter-burden formations above it simulated by the parsimoniously parameterized model: a) Time series of potential influx; b) Distribution of maximum influx from the ensemble model predictions. (The predicted flux changes lower than 5th percentile and higher than 95th percentile are not shown in the time series plot)

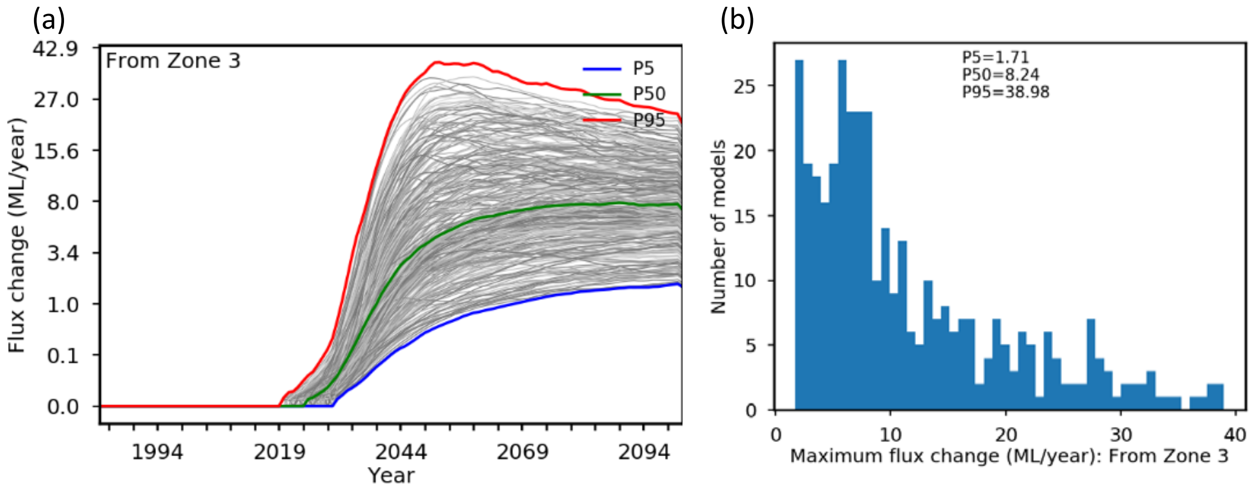

Figure 15: Potential influx into the Pilliga Sandstone from the inter-burden formations above it simulated by the highly parameterized model: a) Time series of potential influx; b) Distribution of maximum influx from the ensemble model predictions. (The predicted flux changes lower than 5th percentile and higher than 95th percentile are not shown in the time series plot)

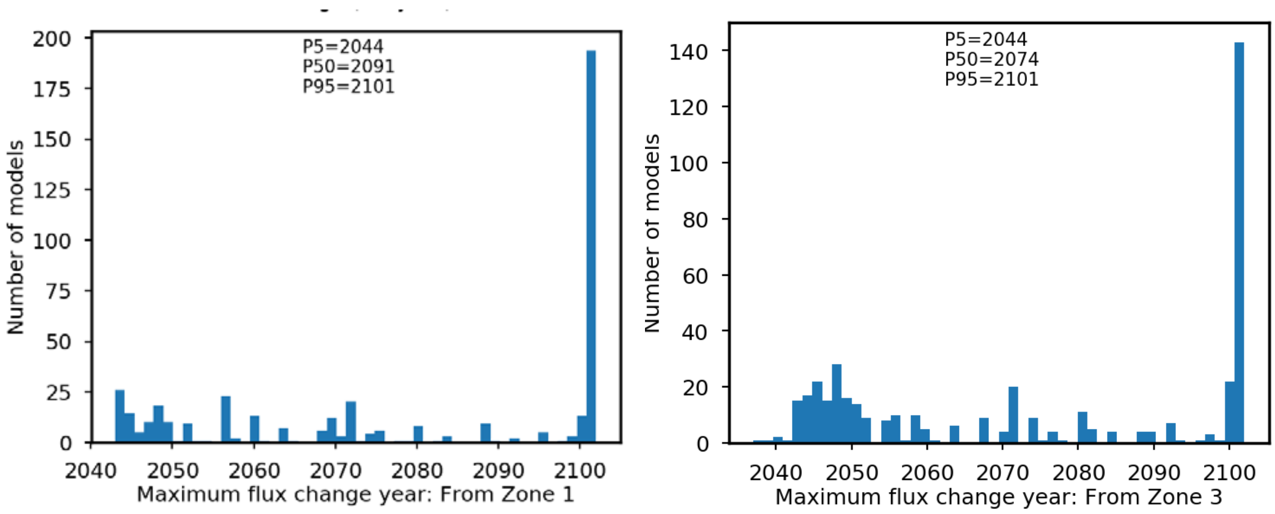

Figure 16: Distributions of the timing of maximum influx into Pilliga Sandstone simulated by the parsimoniously parameterized model a) from the Namoi alluvium and b) from the inter-burden formations above the Pilliga Sandstone. Similar results were obtained from the highly parameterized model

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 GAB aquifers simulated by the parsimoniously parameterized and highly parameterized models are shown respectively in Figure 17and

Figure 18. Both the simulations generally indicate that there might be small increases in the flux from the river to the GAB aquifers 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 are shown in Figure 19 and Figure 20.

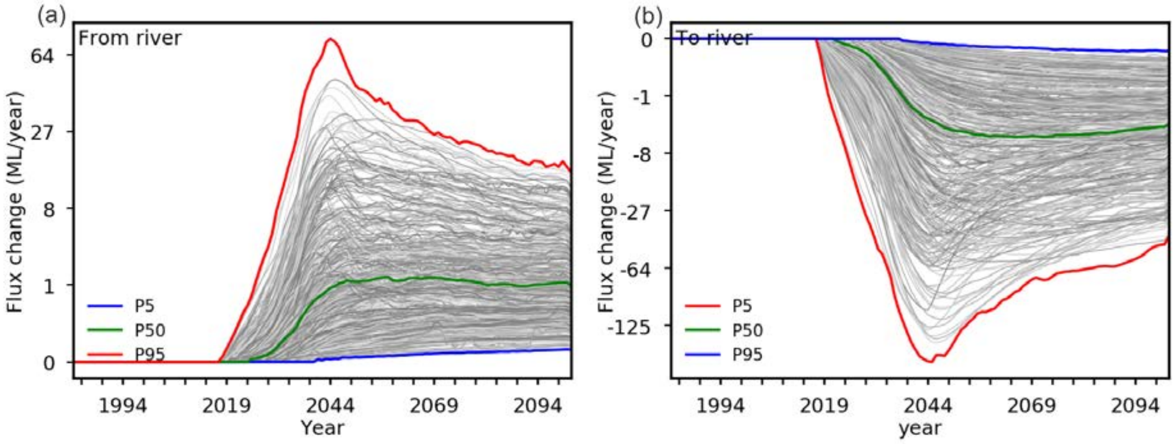

Figure 17: Potential changes in the SW – GW interactions of the GAB aquifers simulated by the parsimoniously parameterized model: a) Changes in the influx into the GAB aquifer from the river; b) Changes in the base flow contribution to the river from the GAB aquifers in their outcrop areas. (The predicted flux changes lower than 5th percentile and higher than 95th percentile are not shown in the time series plot)

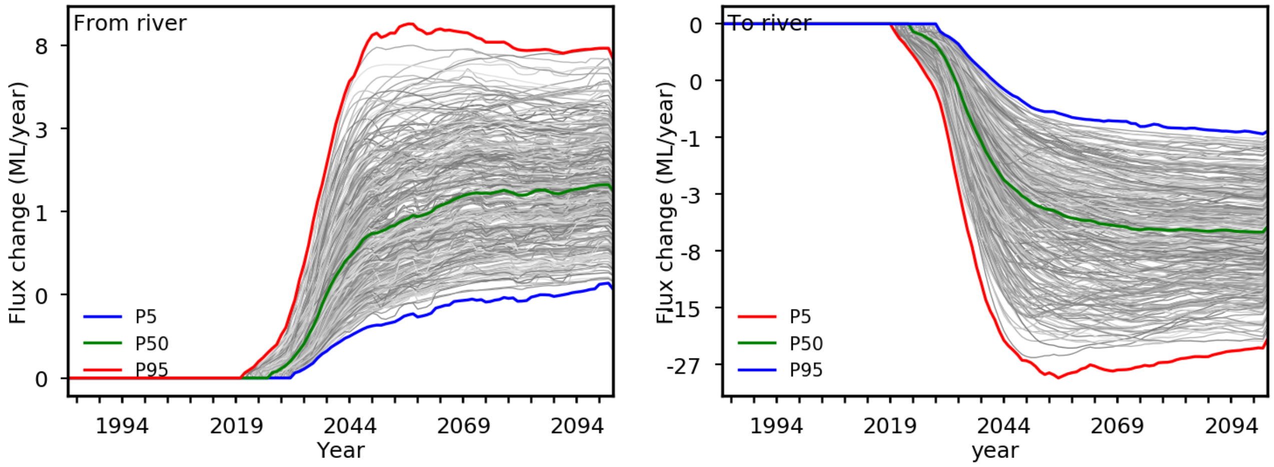

Figure 18: Potential changes in the SW – GW interactions of the GAB aquifer simulated by the highly parameterized model: a) Changes in the influx into the GAB aquifer from the river; b) Changes in the base flow contribution to the river from the GAB aquifer. (The predicted flux changes lower than 5th percentile and higher than 95th percentile are not shown in the time series plot)

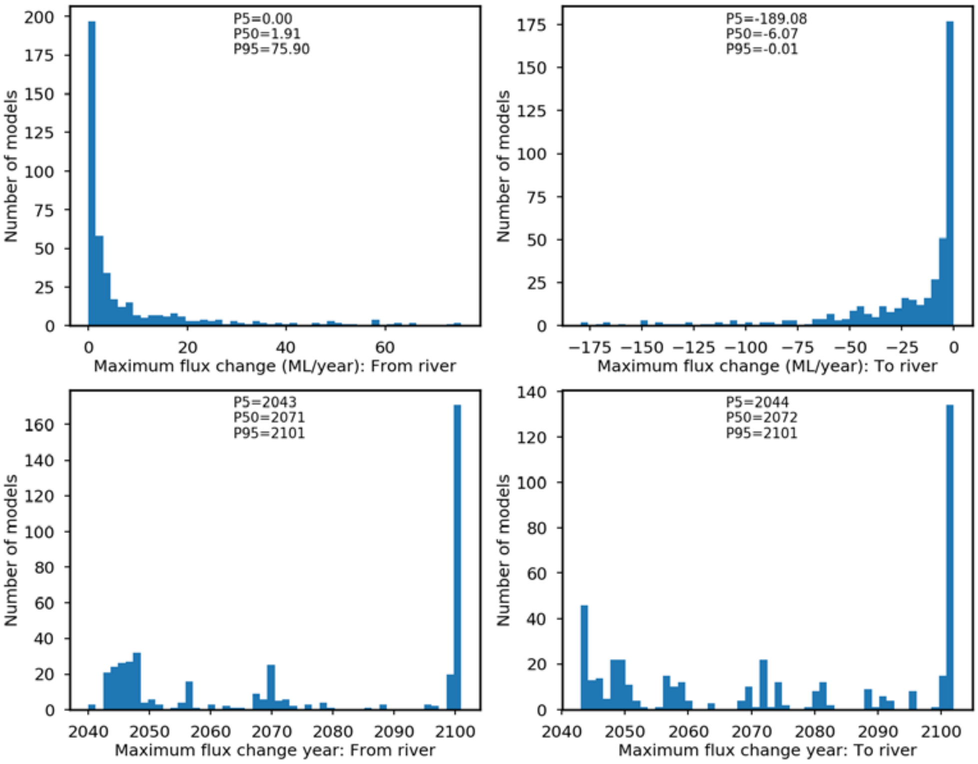

Figure 19: Distributions of maximum changes in the SW – GW interactions and the distribution of the times of maximum change simulated by the parsimoniously parameterized model runs

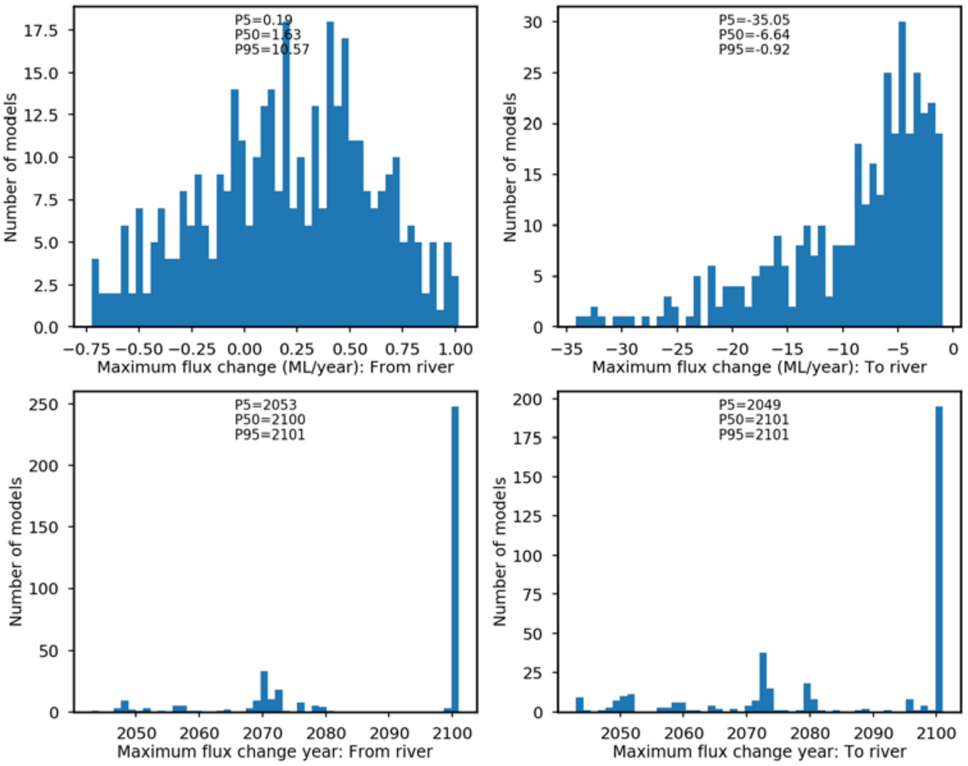

Figure 20: Distributions of maximum changes in the SW – GW interactions and the distribution of the times of maximum change simulated by the highly parameterized model runs

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) obtained from the parsimoniously parameterized model is shown in the box plot (Figure 21). 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 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 GAB aquifers 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 GAB aquifer 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 GAB aquifers to the gaining river reaches. The median value of the simulated mean annual base flow for the baseline case is 6.49 GL/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. Very similar results were obtained for water balance from the highly parameterized model runs as shown in Figure 22. It is noteworthy that all parameter groups other than the hydraulic property parameters were the same between the parsimoniously and highly parameterized model runs, resulting in similar values of inflows and outflows. The difference in the hydraulic properties including specific storage is reflected in the difference in the water balance component of storage release shown in the water balance plots.

The distribution of simulated influx from and discharge to other zones are represented in Figure 23 and Figure 24. Very similar results were observed between the parsimonious and highly parameterized model simulations. 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/year. 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.

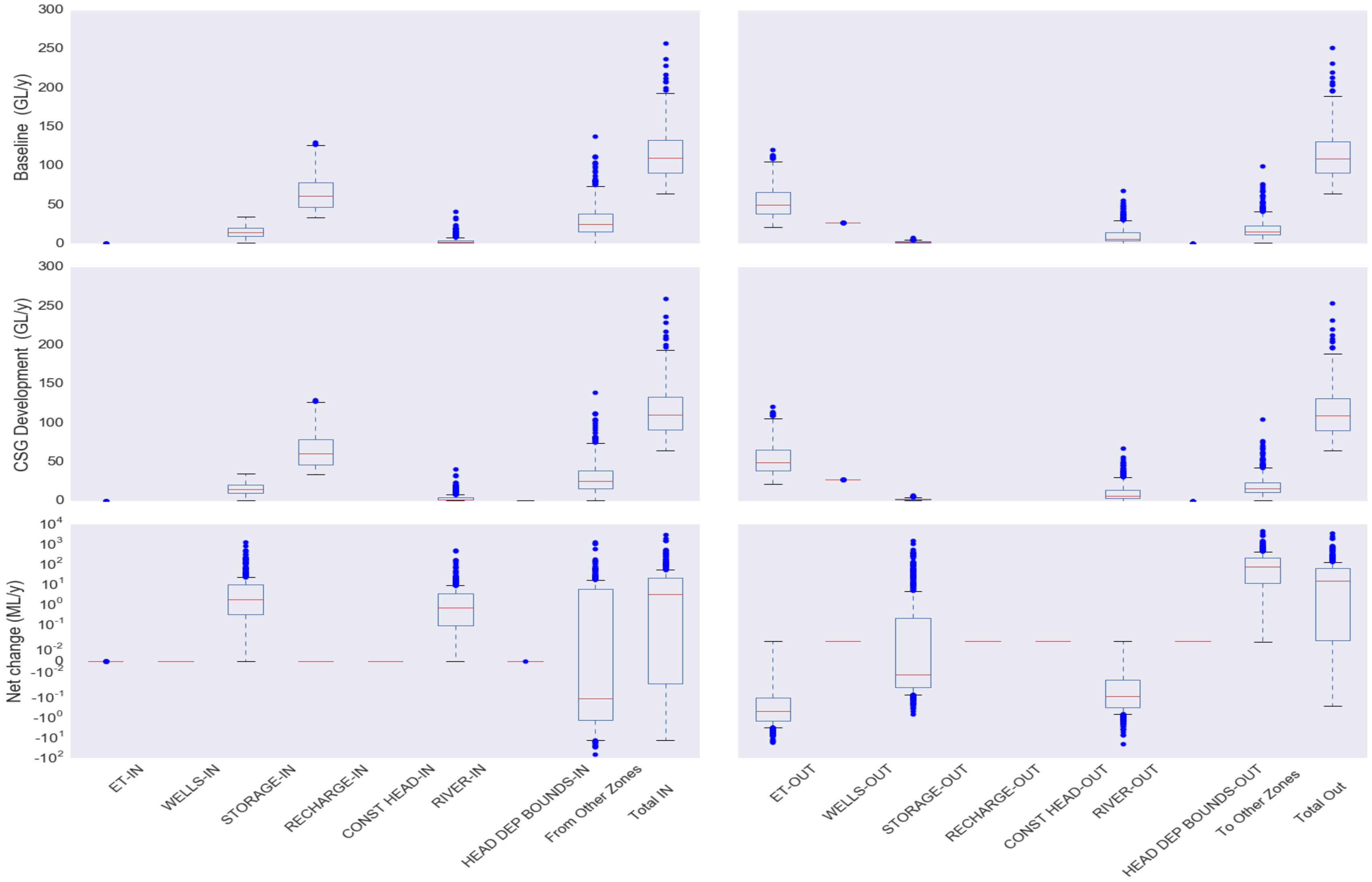

Figure 21:CSG induced water balance changes for the Pilliga Sandstone aquifer simulated by the parsimoniously parameterized model

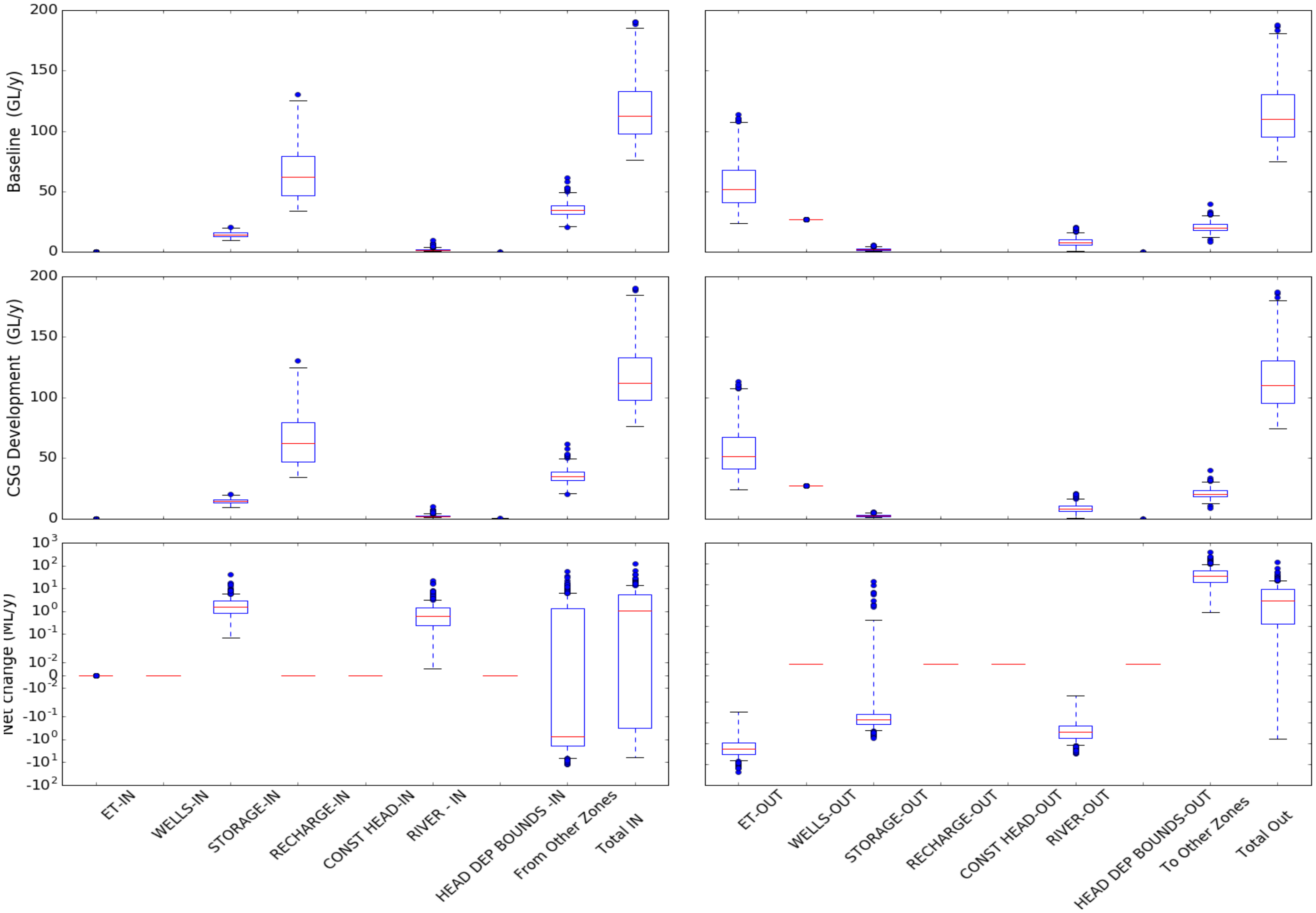

Figure 22: CSG induced water balance changes for the Pilliga Sandstone aquifer simulated by highly parameterized model

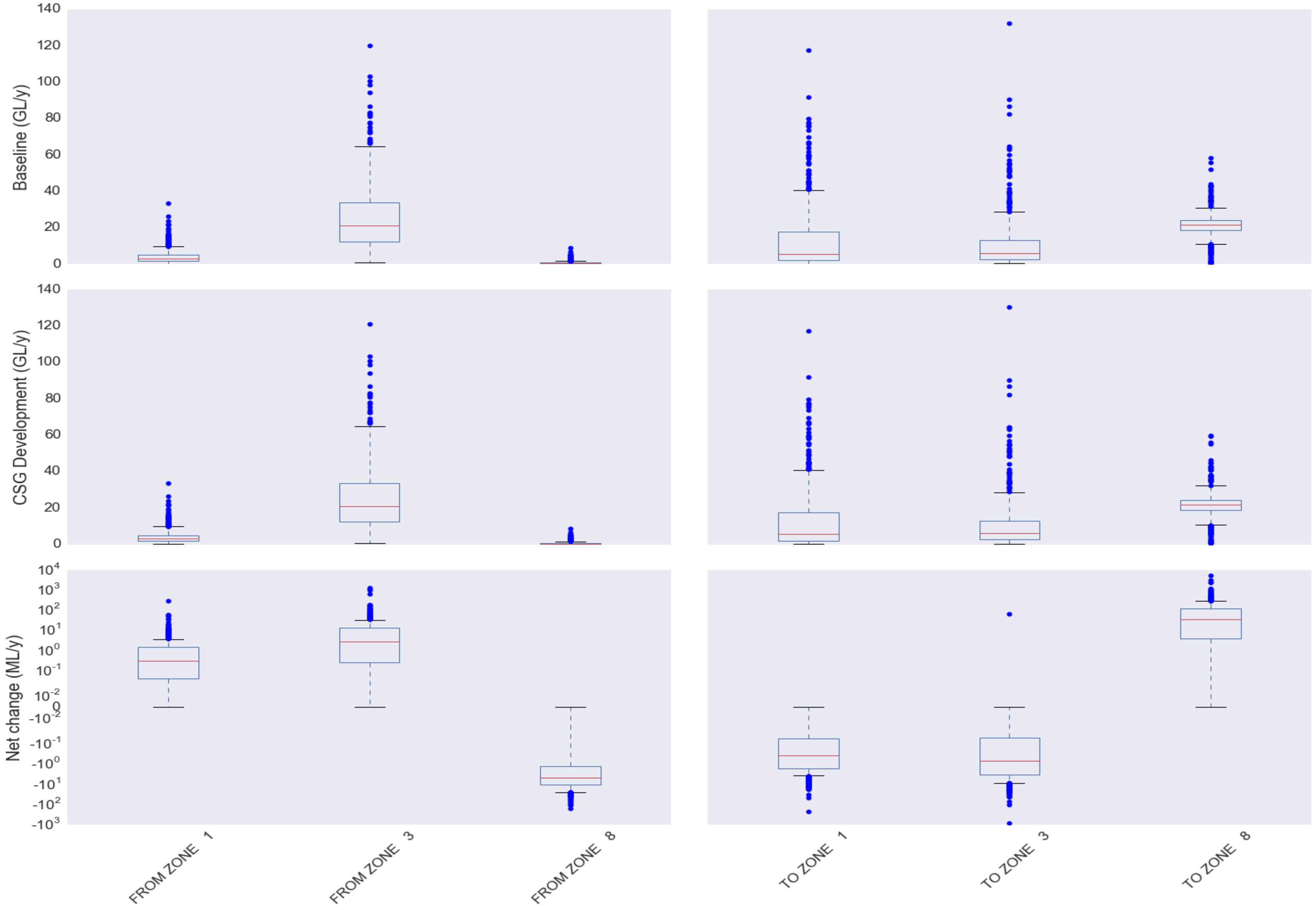

Figure 23 CSG induced flux interactions between the Pilliga Sandstone and the overlying and underlying formations simulated by the parsimoniously parameterized model

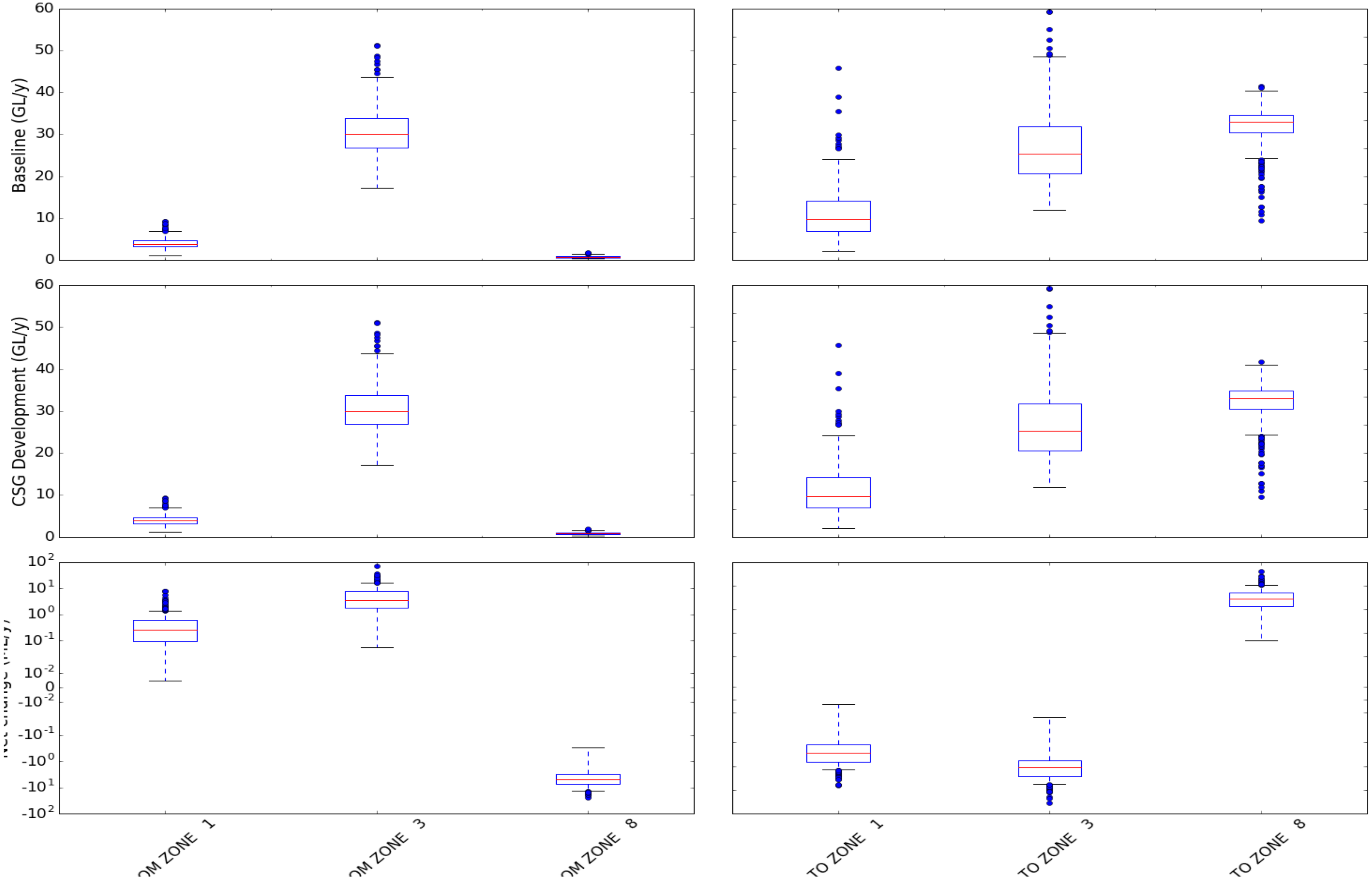

Figure 24: CSG induced flux interactions between the Pilliga Sandstone and the overlying and underlying formations simulated by the highly parameterized model.

5 Simulation-optimization analysis for potential maximum flux impacts

The results of the model simulation analysis using the parsimoniously and highly parameterized models indicated that small volumes of water may flow from the GAB aquifer – the Pilliga Sandstone to the deeper formations as a result of depressurization of coal seams for gas development. Monte Carlo simulations using the two modelling schemes indicated that for the given conceptualization of the groundwater system of the sedimentary basin and plausible combinations of model parameters and inputs, predicted maximum annual GAB flux losses are small compared to annual recharge volumes and long-term annual average extraction limit set by the regulator. The Monte-Carlo simulations considered 920 plausible combinations of model parameters and inputs within their plausible range that resulted in numerically stable model outputs for prediction of flux impacts. These 920 combinations were sampled using Latin Hypercube Sampling to ensure that samples were selected uniformly across the multi-dimensional parameter-input space.

There are virtually many more, potentially infinite, combinations of parameters that could be sampled from this space for evaluating the flux impacts, especially given the parameter uncertainty owing to small number of observations available for the deeper part of the sedimentary basin. In this section we present the results from a proof-of-concept analysis using a simulation-optimization method that was undertaken to evaluate hundreds of thousands of other combinations of model parameters that are within the plausible parameter ranges, but were not considered in the Monte Carlo simulation. As running the physically-based MODFLOW model with large run-times for hundreds of thousands of times is computationally infeasible a method based on surrogate models is adopted (Sreekanth and Datta, 2010) for simulation-optimization. The surrogate model is a simpler model with much faster run-times that captures the functional relationship between the model parameters and model outputs. The surrogate model is trained using the input-output patterns generated from the Monte-Carlo simulations of the physically-based MODFLOW model. The parsimoniously parameterized model was used for this purpose as this model provided the maximum value of 95th percentile of flux impacts between the two models. The surrogate model is then coupled with an optimization model that attempts to maximize the flux losses for plausible combinations of parameters and water extraction by the CSG industry. This exercise helps to identify potential maximum flux changes for any combination of model parameters and CSG water extraction within the plausible range considered in the Monte Carlo simulations. The methods of surrogate model-based simulation-optimization and results from this analysis are described briefly in the following sub-sections.

5.1 Sensitivity analysis

Sensitivity analysis of CSG-induced flux impact predictions to model inputs was the first step in the development of a surrogate model. Sensitivity enables to identify include all key parameters that influenced the prediction of CSG-induced flux changes in surrogate model development. Sensitivity analysis was undertaken using the method introduced by Plischke et al. (2013). It is a density based quantification of the change in a model output due to a change in a model input variable. It is a relative metric in which large values indicate more relevant, whereas low values indicate low sensitivity. This method was recently adopted for sensitivity analysis of receptor impacts to model parameters in several models as part of the Bioregional Assessment Programme (Peeters et al., 2016). The sensitivity of prediction of flux changes to the 37 model parameters used in the parsimoniously parameterized model is shown in Figure 25.

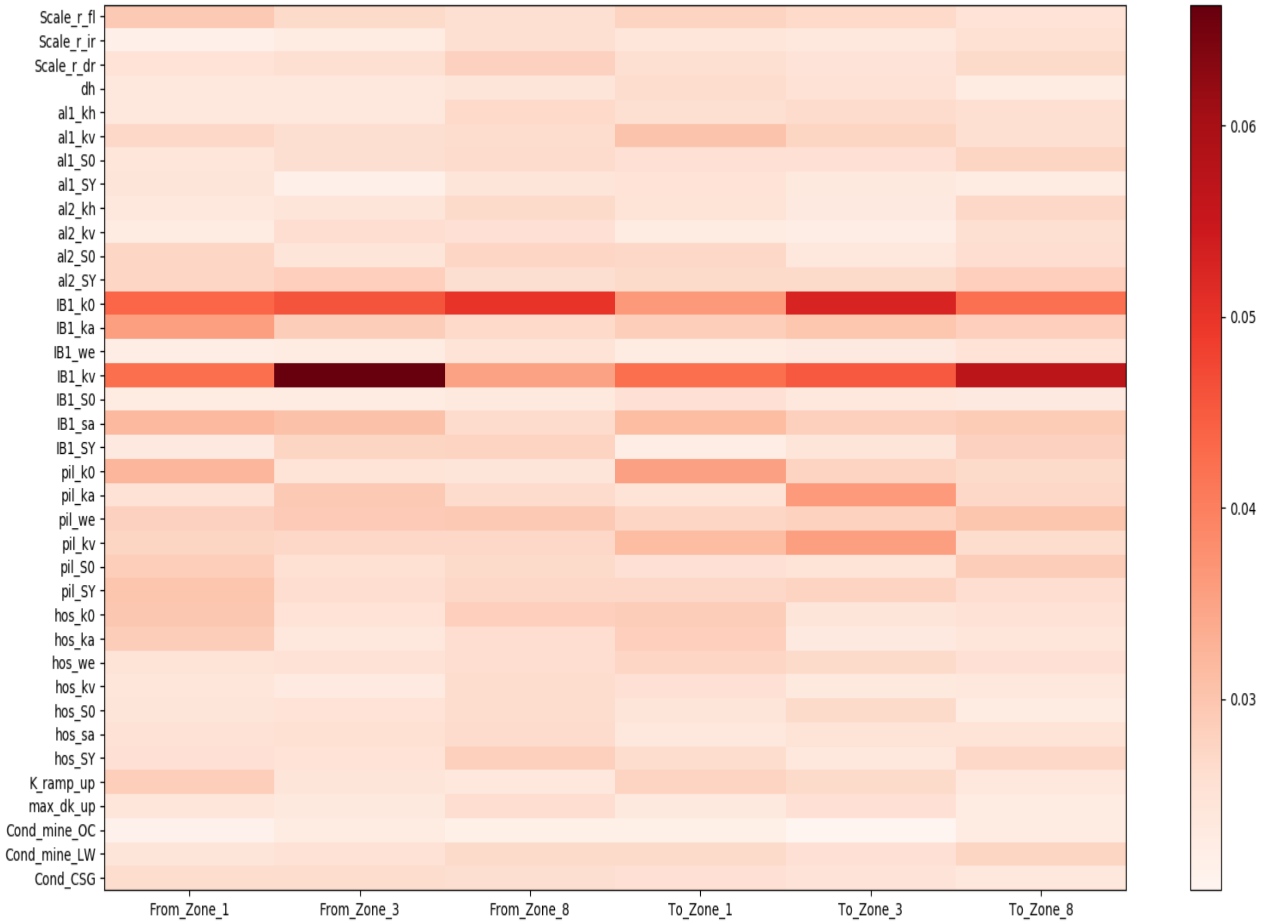

Figure 25: Sensitivity indices of flux changes in different model zones to the parameters of the parsimoniously parameterized model

Based on the parsimoniously parameterized model with the simplified parameterisation, it may be observed that, the parameters IB1_k0 and IB1_Kv are the most influential parameters for flux exchange between the Pilliga Sandstone and other units. Parameters of lesser influence included pil_we, IB1_ka and a few other parameters with distinct effects on flux changes from and to different zones.

5.2 Surrogate model development

Genetic programming (Koza, 1994) is used in this study to develop a surrogate model to represent the functional relationship between model parameters and CSG-induced flux changes.

Genetic programming is an evolutionary algorithm that evolves mathematical functions that maps input variables to dependent outputs. It is similar to genetic algorithm in that it uses the concepts of natural selection and genetics in evolutionary computation. Genetic programming can evolve an optimal functional relationship between model inputs and outputs that minimizes the prediction error of outputs. Genetic programming learns from examples of input-output patterns, which in our case is the input – output patterns of model parameters and CSG-induced flux impacts on the GAB aquifer. The major inputs for the genetic programming model are (1) patterns for learning, (2) fitness function (e.g., minimizing the squared error term), (3) functional and terminal set, and (4) parameters for the genetic operators like the crossover and mutation probabilities (Sreekanth and Datta, 2011) The functional set comprises of the basic mathematical operators and basic functions like addition, subtraction, multiplication, division, trigonometric functions, etc. The complexity of the model depends on the choice of the functional set. For example, linear models can be formulated by including only addition and subtraction in the functional set. On the other hand a functional set which includes exponential or trigonometric functions result in highly nonlinear model structures. The terminal set consists of constants and variables of the model. In our case the variables of the model comprises the MODFLOW model parameters that are sensitive to the CSG-induced flux predictions. The total number of parameters used can be limited to a pre-specified number in order to prevent overfitting of the model. By using functional and terminal sets, valid syntactically correct programs can be developed. Parse tree notation of two such programs are illustrated in Figure 26. Two parent genetic programs are shown in Figure 26a and Figure 26b. The parent programs are crossed over at the dashed sections and mutation operator changes the value of the constant 2 to 6 to generate two new offspring genetic programs shown in Figure 26c and Figure 26d. The Genetic Programming simulator based on the software Discipulus^{TM} was used in this study for developing surrogate models.

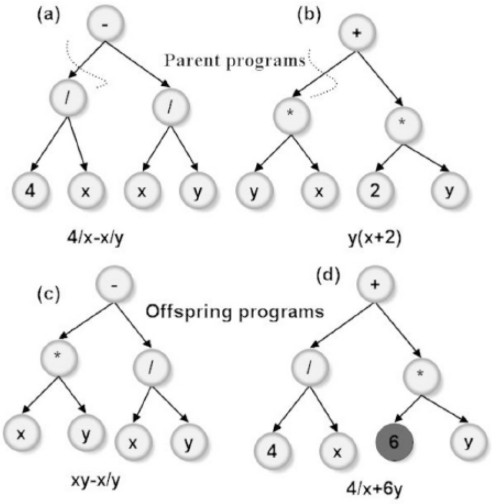

Figure 26: Illustration of cross-over and mutation in genetic programming codes represented using parse tree notation (adapted from Sreekanth and Datta, 2011)

Because of its ability to evolve functional relationship between inputs and outputs, Genetic Programming is able to include or exclude pre-specified input variables in the final function that it evolves. If a variable (input parameter) is not contributing the reduction of prediction error in the output, Genetic Programming will exclude that variable from the development of the functional relationship. The effect of each variable is calculated using the impact factor. We computed the impact factors for all 37 parameters of the parsimoniously parameterized model. This is shown in Figure 27. The impact factors compared by Genetic Programming are similar and comparable to the sensitivity indices obtained using the Plischke (2013) method.

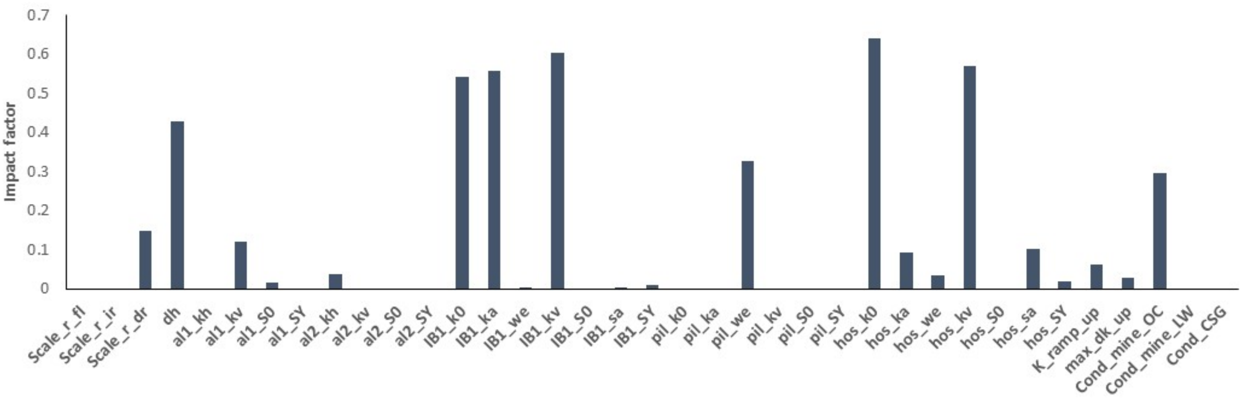

Figure 27: Impact factors computed for the 37 model parameters using Genetic Programming

It may be noted that similar to the findings of sensitivity analysis IB1_k0 and IB1_kv were identified as two impactful variables in predicting the flux changes. In addition to this, the horizontal and vertical conductivity of coal seams (hos_k0 and hos_kv) were also identified as impactful variables in predicting the flux changes in addition to a few other variables that has decreasing levels of impacts.

Six of the impactful parameters were included in the subsequent development of the surrogate model. In addition to these model parameters, predicted average drawdown in the model layer corresponding to the Pilliga Sandstone and the predicted total water extraction from the coal seams were included as variables for predicting CSG-induced maximum flux losses. These two variables were included in surrogate model development to explore their influence on prediction of CSG-induced flux changes. The resulting impact factors obtained from recalculation is shown in Figure 28. The re-calculated impact factors clearly informed that volume of water extracted from coal seams (Total CSG), mean drawdown in the Pilliga Sandstone and parameters influencing the hydraulic properties of the coal seams (hos_ko, hos_kv), inter-burden (IB1_ko, IB1_kv) and the Pilliga Sandstone (pil_we) are the most important variables that affects CSG-induced flux losses from the GAB aquifer.

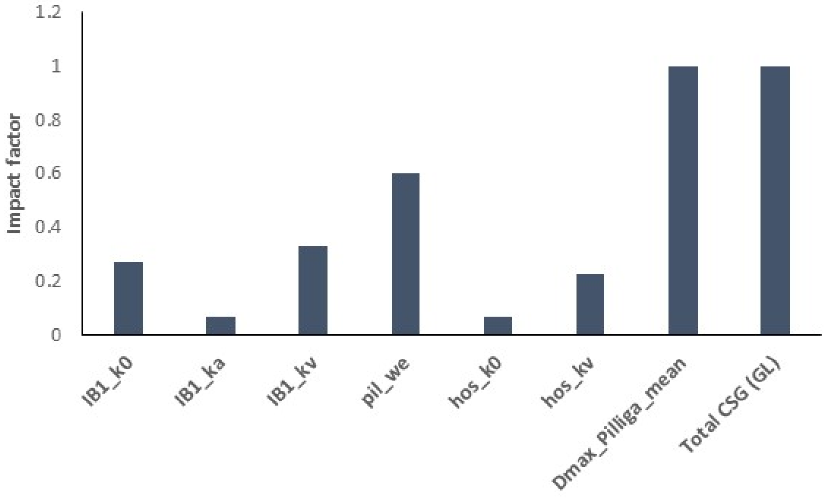

Figure 28: Re-calculated impact factors after addition of mean drawdown in the Pilliga Sandstone and total water extraction for CSG production as variables for prediction flux impacts to the GAB aquifer

These variables were then included for the development of the surrogate model using the input-output patterns obtained from the Monte Carlo simulations of the parsimoniously parameterized model. Two thirds of the input – output pattern was used for training of the surrogate model and the remaining was used for validation. The sorted regression fit obtained for the training and validation sets are shown in Figure 29. The quantile to quantile scatter plots for the training and testing data sets are shown in Figure 30.

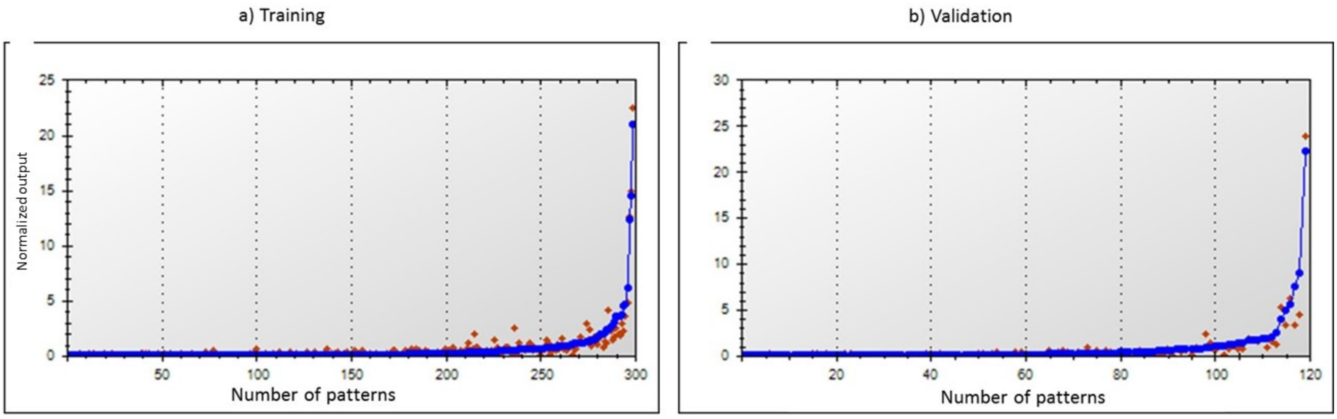

Figure 29: Sorted regression fit obtained for the training and validation data sets. The red dots correspond to the normalized outputs simulated by the MODFLOW model and the blue dots correspond to the equivalent computed by the Genetic Programming surrogate model

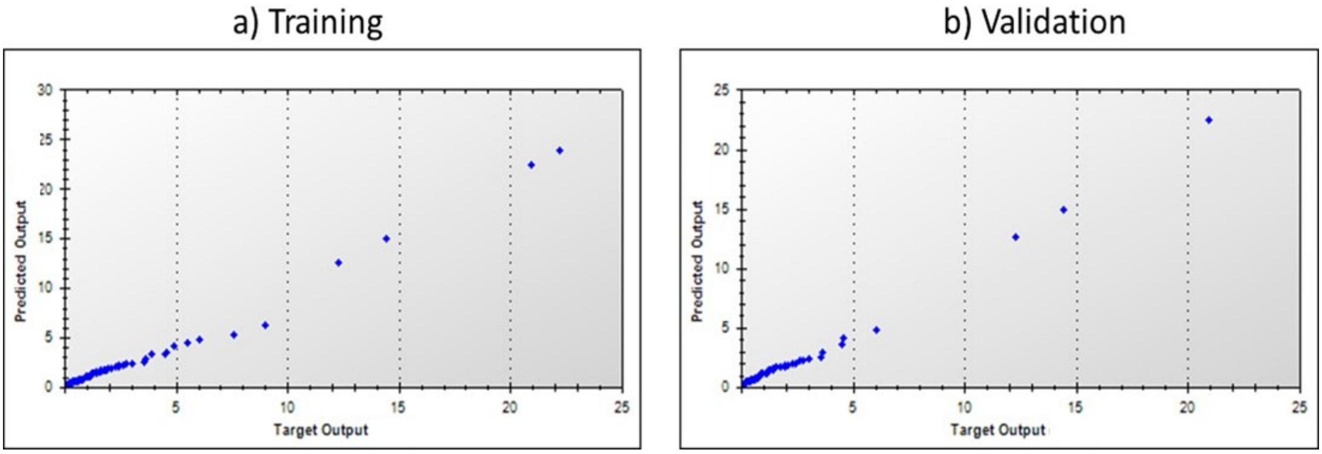

Figure 30: Quantile to Quantile plot for the normalized training and testing data sets. The data from the MODFLOW and surrogate model simulations roughly fall along the 45-degree line indicating that the predictions of model models come from a population with the same distribution

The use of a simplified surrogate model provides a fast and efficient method for approximate estimation of predicted CSG-induced flux impacts for a wide range of (hundreds of thousands) combinations of model parameters within the plausible range. It should be noted that such estimates of flux change also has uncertainties associated with it because of uncertainty in the surrogate models.

However, the purpose of surrogate models in this study is to use them in conjunction with an optimization algorithm to identify the combinations of model parameters and total CSG water production that can lead to maximum flux impacts and evaluate the trade-off between total water extraction for CSG, CSG-induced drawdown in the Pilliga Sandstone and the maximum flux losses form the Pilliga Sandstone. The CSG-induced drawdown and total water extraction by CSG project are more reliably predicted and can later be measured if and when the CSG development actually happens. Thus correlating the maximum flux losses corresponding to maximum values of induced drawdown and CSG water extraction enables to have a better interpretation of maximum flux impacts. The implementation of surrogate-assisted simulation-optimization framework for this purpose is described in the following section.

5.3 Simulation-optimization for identifying potential maximum flux losses

The analysis for identifying potential maximum flux losses corresponding to any level of water extraction considered in the generic scenario of CSG development was formulated as an optimization problem with the following objectives:

$$Max\ Q_{max} = f\{Q_{csg},\ D_{max}, \boldsymbol{p}\} \quad (3)$$

$$Min\ Q_{csg} = f\{\boldsymbol{p}\} \quad (4)$$

$$Min\ \overline{D}_{max} = f\{Q_{csg}, \boldsymbol{p}\} \quad (5)$$

Subject to the following constraints:

$$30 \leq Q_{csg} \leq 110 \quad (6)$$

$$0 \leq \overline{D}_{max} \leq 1 \quad (7)$$

Where Q_{max} is the maximum predicted flux loss from the Pilliga Sandstone aquifer for a given combination of model parameters, total CSG water production and the average of the maximum predicted drawdown in the aquifer ($\overline{D}_{max}$). Q_{csg} is the total volume of water production for CSG development from the coal seams and $\boldsymbol{p}$ is the vector of model parameters that were considered in the surrogate model development. The constraint (6) ensured that the potential maximum flux losses is estimated for the CSG water production rates considered by the generic case of CSG development considered in this study and encompasses the low, base and high cases of water production envisaged by the Narrabri Gas Project. Similarly constraint (7) ensures that the surrogate model is evaluated for flux losses only within the range of $\overline{D}_{max}$ predicted by the MODFLOW model and thus it is not used for extrapolation. It is noteworthy that objectives (3) and (4) are conflicting to each other as maximum flux loss from the Pilliga Sandstone formation often would depend on the volume of CSG water extraction. Similarly objective (3) and (5) are also conflicting to each other because maximum flux loss would usually occur when the drawdown is maximum. The conflicting nature of these objectives helps to explore the trade-off between these objectives using a Pareto-optimal front which is the front along which improvement in the value of one objective function is not achievable without compromising the optimality of another objective function. Constraints (6) and (7) ensure that the CSG water production and flux changes evaluated are within the bounds evaluated in the Monte Carlo runs evaluated using MODFLOW model simulations in order to avoid extrapolation using the surrogate model.

Given that there are three objective functions for the optimization problem, the Pareto-optimal front in this case is a 3D surface. The Pareto-optimal surface is shown in Figure 31.

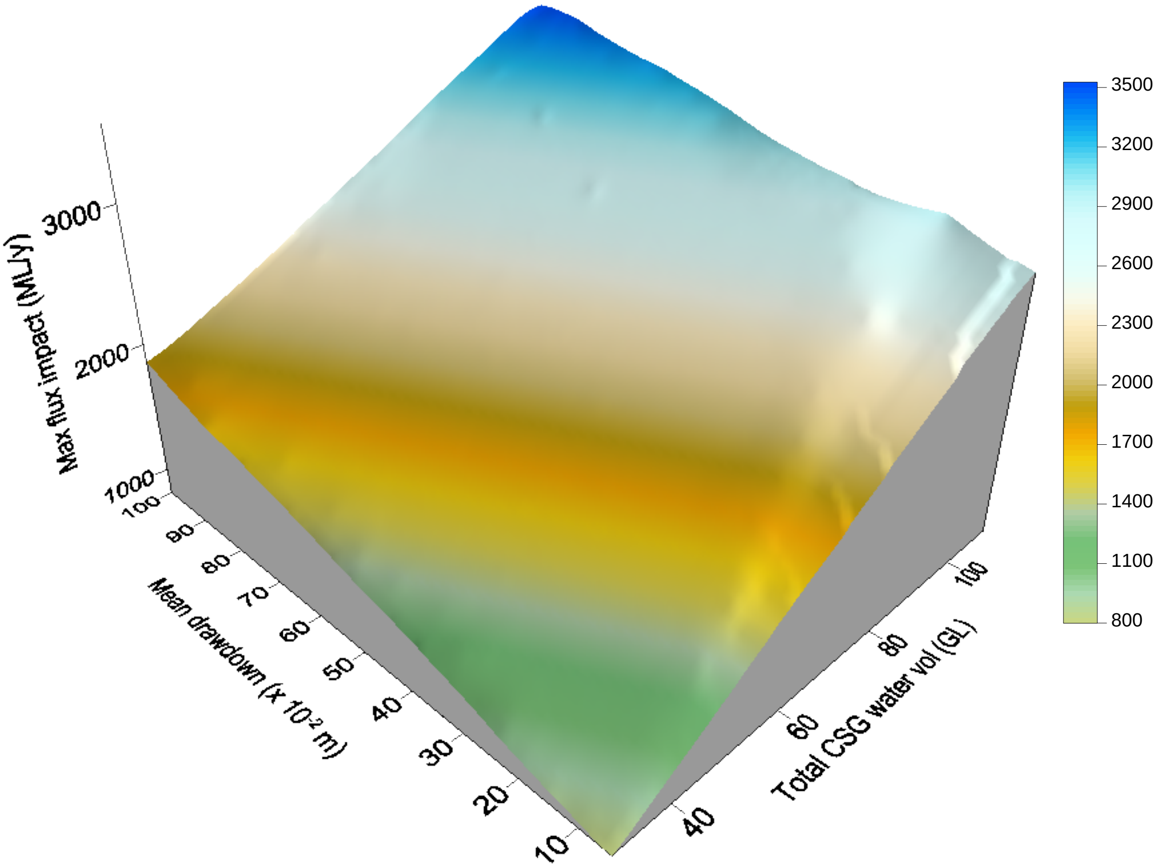

Figure 31: Pareto-optimal surface showing the trade-off between predicted maximum CSG-induced flux impacts, total CSG water production and predicted average drawdown for the Pilliga Sandstone

The Pareto-optimal surface shows that the maximum flux impacts would generally increase linearly with increase in total water production for CSG when other factors like impedance offered by the inter-burden layers are favourable for the propagation of depressurization upward from the coal seams into the Pilliga Sandstone formation. Similarly the flux impact also increases linearly with average of the predicted maximum drawdown for the Pilliga Sandstone formation. It is noteworthy that, while the Monte Carlo simulation predicted a median annual maximum flux loss of 84 ML/year from the Pilliga Sandstone, the simulation optimization analysis shows that the CSG-induced flux losses could be in the range 800 to 3000 ML/year if the model parameter combinations are most conducive for the upward propagation of the depressurization effect.

The predicted flux losses in this range obtained from the Pareto-optimal analysis can be considered as the far-distal end of the distribution of predicted maximum flux losses. This distribution is compared with the distribution of predicted flux changes obtained from the Monte Carlo analysis in Figure 32. It can be observed that the range of flux impacts obtained from the Pareto analysis depicts the probable extreme of the impacts resulting from the generic scenario of coal seam gas development given the current understanding of the groundwater system encapsulated in the conceptual model.

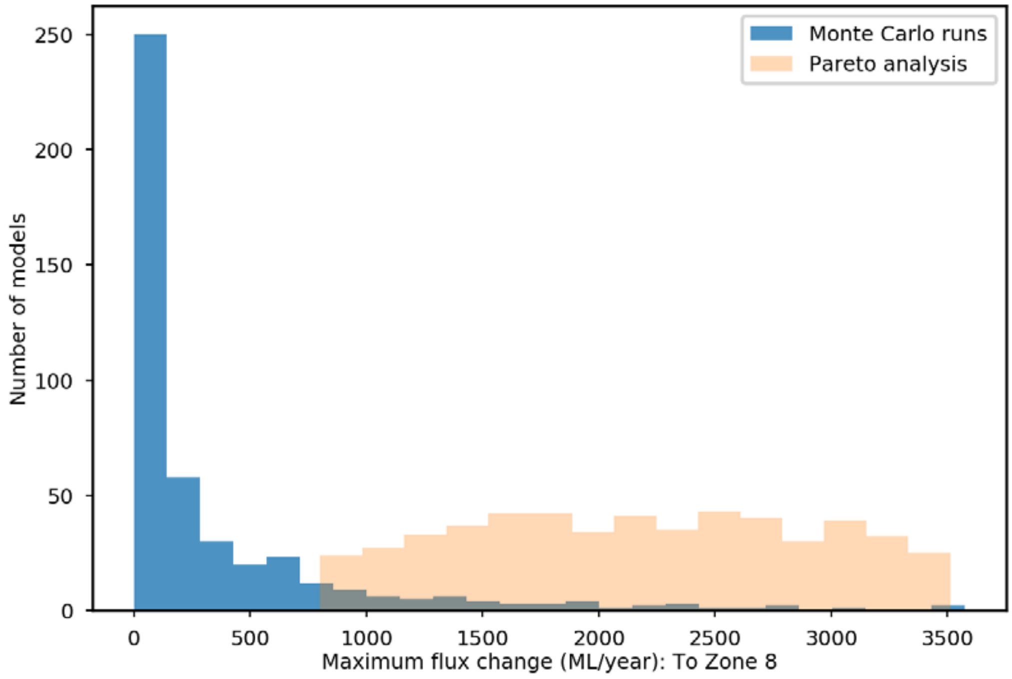

Figure 32: Comparison of the distribution of predicted flux impacts from the Monte Carlo analysis and the Pareto analysis

The distribution of the volumes of CSG water production, $\overline{D}_{max}$ and flux losses from the Pilliga Sandstone obtained from the Pareto analysis is shown in

Figure 33. The trade-off between two each of these three objectives is shown in Figure 34. It is evident from the first sub-plot in this figure that the maximum flux losses from the Pilliga Sandstone increases with increase in the total volume of water produced by the CSG project. It is also noteworthy from this plot that when the total volume of CSG water production is less than 40 GL, the potential maximum flux loss from the Pilliga Sandstone is less than 2000 ML/year. The Pareto-analysis that provides this result has evaluated 1.5 million combinations of model parameters, plausible Dmax and total CSG water production volumes that are within the range prescribed in the Monte Carlo simulations using the parsimoniously parameterized modelling scheme. Thus, the Pareto analysis using the surrogate model and multi-objective optimization framework further validates the results from the Monte Carlo simulation.

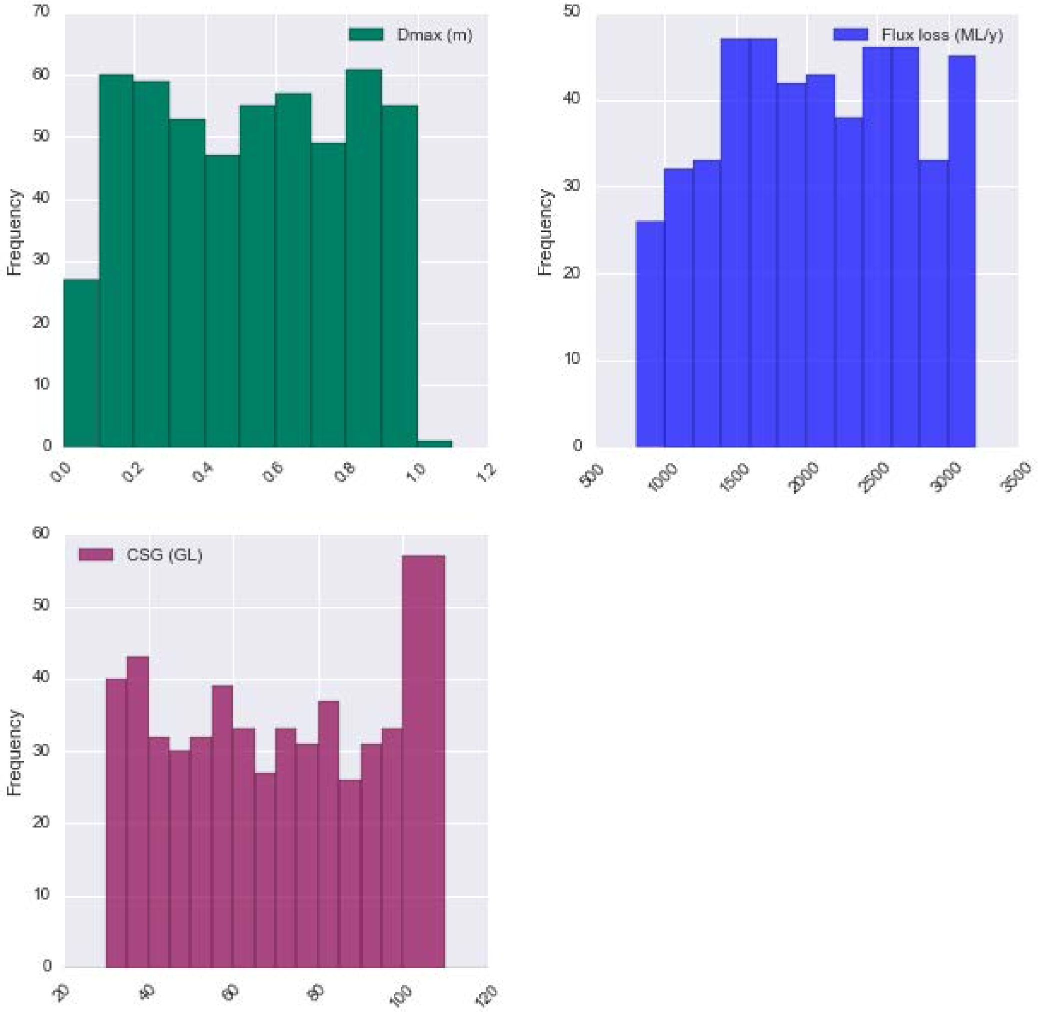

Figure 33: Distribution of $\overline{\mathrm{D}}_{\mathrm{max}}$, CSG water production and flux losses from Pilliga Sandstone obtained from the Pareto analysis

The simulation-optimization analysis that evaluated 1.5 million combinations of sensitive model parameters that are most sensitive to prediction of CSG-induced impacts, CSG water production and predicted maximum drawdown in the Pilliga Sandstone aquifer illustrated that when the realization of the hydraulic characteristics, within the plausible range, are most favourable for maximum flux losses, the CSG-induced flux loss would linearly increase with increase in the total CSG water production. It was also found that, the CSG-induced flux losses would linearly increase with increase in the average of the maximum CSG-induced drawdown observed in the Pilliga Sandstone aquifer.

The simulation-optimization analysis provided the following two important insights. Given the current conceptual understanding of the groundwater system as encapsulated in the numerical groundwater model it is highly unlikely that CSG-induced maximum flux losses from the Pilliga Sandstone aquifer would be more than 2000 ML/year (Figure 34) if the total CSG water production is less than 40 GL, i.e. similar to what is currently predicted for the proposed coal seam gas project. While the flux losses from the relatively deep aquifer is difficult to measure, the analysis shows that the flux losses would be directly proportional to the average of the maximum CSG-induced groundwater head drawdown in the Pilliga Sandstone aquifer. This implies that, measuring of the groundwater head changes in the gas development region using dedicated monitoring network can provide valuable information regarding potential flux losses from the aquifer induced by CSG development. A companion GISERA report on ‘monitoring network design’ (Sreekanth et al., 2018) discusses in detail about potential CSG-induced drawdown and optimal monitoring strategies. Such ongoing monitoring programmes are essential for identifying any changes or deviations from predicted impacts. Future modelling efforts for quantifying CSG-induced impacts should ideally use such monitoring data to improve the conceptual understanding of the groundwater system and refine the prediction of impacts.

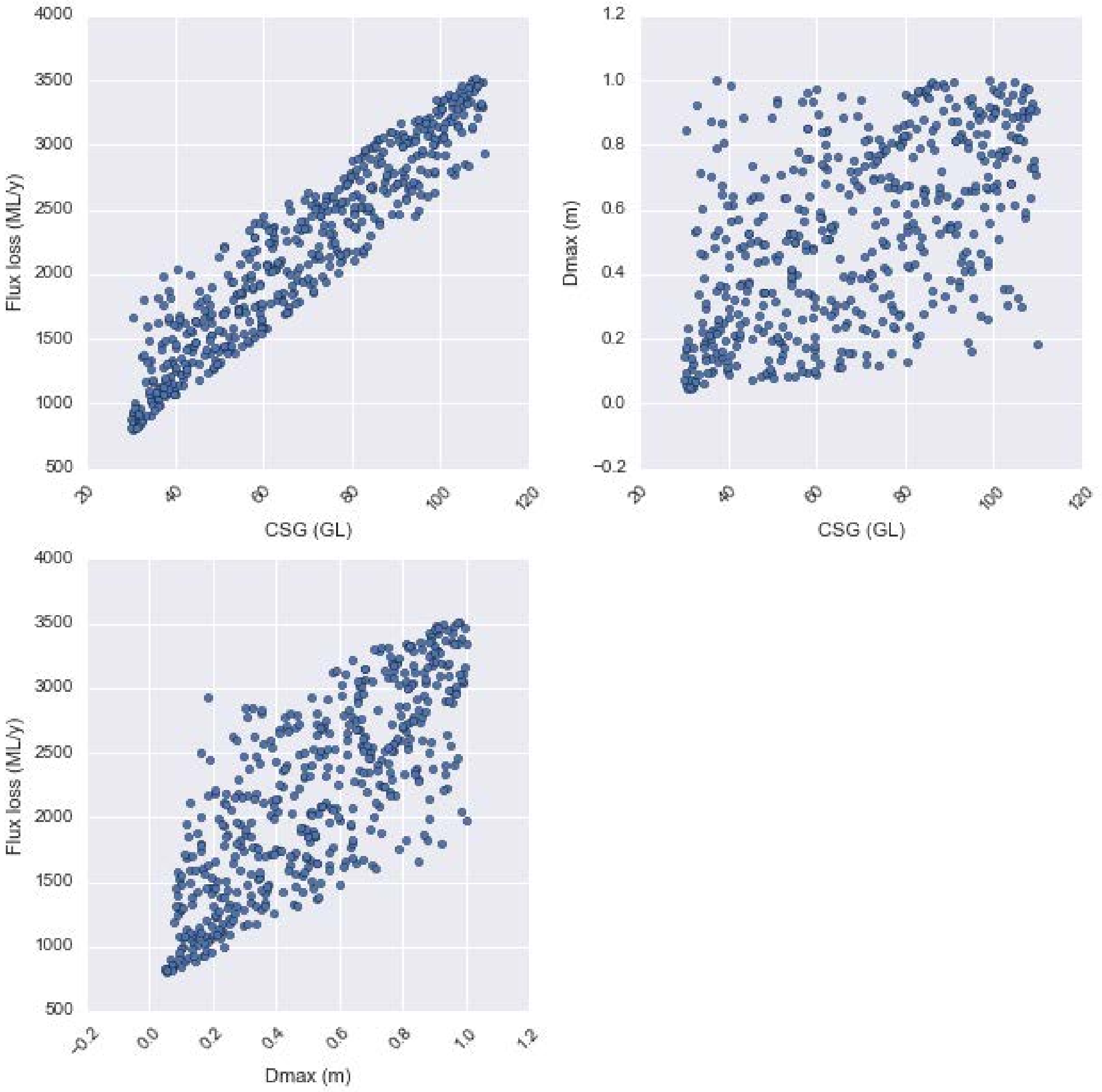

Figure 34: Trade-off between the objectives used in the Pareto analysis

5.4 Utility of the surrogate-based Pareto analysis scheme

The Pareto analysis for evaluating potential maximum flux losses for wide range of combinations of model parameters and total CSG water production was enabled by making use of simpler and fast running surrogate models (response surface approximation) based on Genetic Programming. The fast run-times of the surrogate model enabled to couple it with a multi-objective genetic algorithm code to do millions of model evaluation to identify combinations of hydraulic properties and CSG water productions rates that could result in potential maximum and worst-case flux impacts on GAB flows. The surrogate model used in this study performs a response surface approximation by which it approximates the MODFLOW model's flux responses for a given combination of model parameters. Response surface models performs best when they are used for interpolation, i.e. approximating the responses for combinations of inputs that falls within the range for which the responses were originally evaluated using the MODFLOW model. When the surrogate models are used for extrapolation, reliability of such predictions should be further validated using physically-based models. In this study we used the surrogate model within an interpolation framework only as can be noted from Figure 32. Thus the surrogate model is used in this study to re-iterate the predictive analysis using the MODFLOW model by testing millions of combinations of uncertain model parameters which is otherwise not possible due to exorbitant computational times required by the MODFLOW model.

6 Conclusions

An assessment of potential flux and water balance changes and associated uncertainties in the GAB aquifer – the Pilliga Sandstone caused by depressurisation of coal seams arising from gas development in the Gunnedah Basin 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 gas development and the baseline cases of groundwater flow. Confidence in the underlying impacts was quantified by varying coal seam depressurisation, hydraulic characteristics of the geologic formations and groundwater flow components across broad ranges. 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. Two different model parameterization schemes were employed to evaluate the effects of uncertain hydraulic characteristics of aquifers and aquitards on the prediction of CSG-induced flux changes. The first scheme applied parsimonious parameterization based on depth-dependency of hydraulic properties to quantify the plausible extremes of CSG-induced flux changes. The second scheme applied highly parameterization approach to incorporate spatial variability in observed values of hydraulic properties in aquitards to better constrain the prediction uncertainty.

The results indicated that coal seam depressurisation could potentially induce an 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. 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 predicted by the parsimonious and highly parameterized schemes are respectively 85 ML/year and 60 ML/year. These value are respectively 0.29% and 0.2% of the Long Term Annual Average Extraction Limit of 29.68 GL/year 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. The probabilistic simulation of 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.

6.1 Limitations

The present study applied a probabilistic groundwater modelling approach to quantify a range of potential impacts on flux changes in the Pilliga Sandstone – an important GAB aquifer of the Surat Basin near Narrabri, NSW, for a broad scenario of coal seam depressurisation. 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. (2018). 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 connectivity and recharge 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.
- Recharge from rainfall, irrigation and flood was represented as a specified flux boundary condition in the model for both the baseline and a generic CSG development case. 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.

6.2 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 a generic gas of coal seam depressurisation arising from gas development. 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.

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