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The University of Queensland Surat Deep Aquifer Appraisal Project (UQ-SDAAP)

Scoping study for material carbon abatement via carbon capture and storage

Supplementary Detailed Report

Flow modelling of the managed aquifer recharge areas

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1. Executive summary

Managed Aquifer Recharge (MAR) was investigated as it could provide The project (UQ-SDAAP) a significant dynamic data set that could be used to history match dynamic simulation. A static reservoir model was required to simulate fluid flow in the MAR sector.

A permeability map for the MAR Sector could be determined by either analysing well data where log permeability was derived from the porosity versus permeability regression calibrated to core plug measured values, or from a groundwater model inversion based on the MAR history match.

Having determined two separate permeability maps, water injection was performed for each model and the fluid pressure was monitored across the model. Initial and boundary conditions were identical for all models and simulations.

Having obtained an idea about the local trends of the change in fluid pressure across the model, permeability was *updated* regionally in order to match the pressure prediction with the pressure data (history match). Of the four permeability maps, three were derived from the map obtained by petrophysical analysis and the other came from the groundwater model inversion by using additional input data.

In general, the *updated* groundwater model inversion gave the best prediction of pressure. A notable exception was in the Condabri area, where predictions of the pressure at the well “Contabri-Well-ING2-P” were poor.

2. Introduction

The northern 'depositional centre' of the Blocky Sandstone Reservoir (BSR) was one of the first regions for which a geological model was defined (see La Croix et al. 2019a, 2019b, 2019c). This area was the best constrained by core, well logs, and seismic data compared to areas to the south. It also was the location of a coal seam gas industry, managed aquifer recharge (MAR) activity, which provided UQ-SDAAP a significant dynamic data set that could be used to history match dynamic simulation. As a result, MAR sector model simulations were the first to be performed in UQ-SDAAP's overall workflow. Note that at the time these simulations were performed, concepts of two different BSR depositional centres were still forming (*ibid*).

In order to simulate fluid flow in the MAR sector, a static reservoir model was required. Having characterised the model, we then proceeded to the dynamic flow model and simulated different scenarios. This report starts with discussing the preparation of the static flow model. Different sources of permeability are then used for initialisation and single phase flow is simulated under different scenarios in order to match the field data (history match) across the MAR sector model.

3. MAR sector static reservoir modelling

Regional-scale static reservoir models are the framework upon which simulations of fluid flow behavior in CO_2 storage applications are based. A regional-scale static model was built as part of UQ-SDAAP to improve understanding of the large-scale flow and pressure transmission characteristics of the northern portion of the Surat Basin due to CO_2 injection.

The major data inputs necessary to constrain static reservoir modelling include:

- A stratigraphic framework
- The distribution of facies and/or lithology
- A determination of reservoir properties such as porosity and permeability
- A structural framework describing faults and fractures

These components are essential for understanding the distribution of flow units, as well as their vertical and lateral connectivity relationships. However, data tends to be clustered, and there are commonly large distances between individual wells or groups of wells. This has resulted in a large degree of uncertainty in tracing geological units from location to location across the basin, as well as uncertainty in the most appropriate rock properties (porosity and permeability) to assign grid cells of the model.

The main strategy employed to mitigate uncertainty was to characterise regions with better data constraints and then to use these findings to trace the stratigraphy, facies / lithology, and reservoir properties across the MAR area (Figure 1). The MAR sector area was selected to include the large region where monitoring wells completed in the Precipice Sandstone have shown a pressure response to the MAR injection activities.

Figure 1 Map of the Surat Basin showing the location of the Managed Aquifer Recharge (MAR) sector model area.

3.1 Model structure

A total of 192 wells were used to constrain the data within the MAR area (Figure 2). Of these, 31 wells had petrophysical datasets and formed the basis for populating grid cells with lithology and flow properties (i.e. net to gross, porosity, and permeability). The wells were primarily located along the eastern and western margins of the MAR sector model area with a large gap in data existing through the central portion of the MAR, especially in the southern half.

The sequence stratigraphic framework for the UQ-SDAAP project was applied to static modelling of the MAR area (Figure 3). Since the MAR area was the first dynamic simulation for the UQ-SDAAP project, its focus was to determine the regional-scale bulk behaviour of the Blocky Sandstone Reservoir to the MAR activities. Therefore, only the regionally defined stratal surfaces that define the Blocky Sandstone Reservoir were utilised. These are the J10 and TS1 surfaces (see La Croix et al. 2019b, 2019c).

The model used 10 m, equal-thickness layering, following the horizon that defined the top of each zone. Grid cells in the 'j' and 'k' directions (i.e. both horizontal directions) are 500 m x 500 m. This resulted in a model consisting of 268 cells x 708 cells x 9 cells (1,707,696 cells in total).

Twelve main faults were included in the static model to represent the main structural features in the MAR region. These were derived from The University of Queensland Centre for Coal Seam Gas (UQ-CCSG) Faults and Fractures project (Copley et al. 2017, Figure 2). The model grid honoured the faults by using a "stair-step" pattern to avoid cells with odd geometries. All faults dip vertically and they propagate through all model layers.

Figure 2 (A) 192 wells within the MAR area. (B) Faults used in the MAR static model, derived from the SEES Faults and Fractures Project.

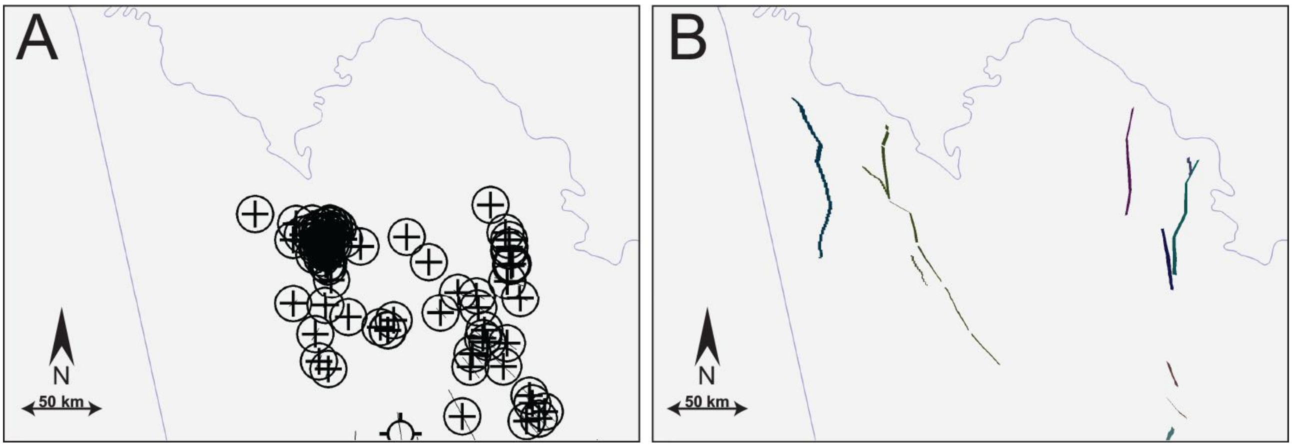
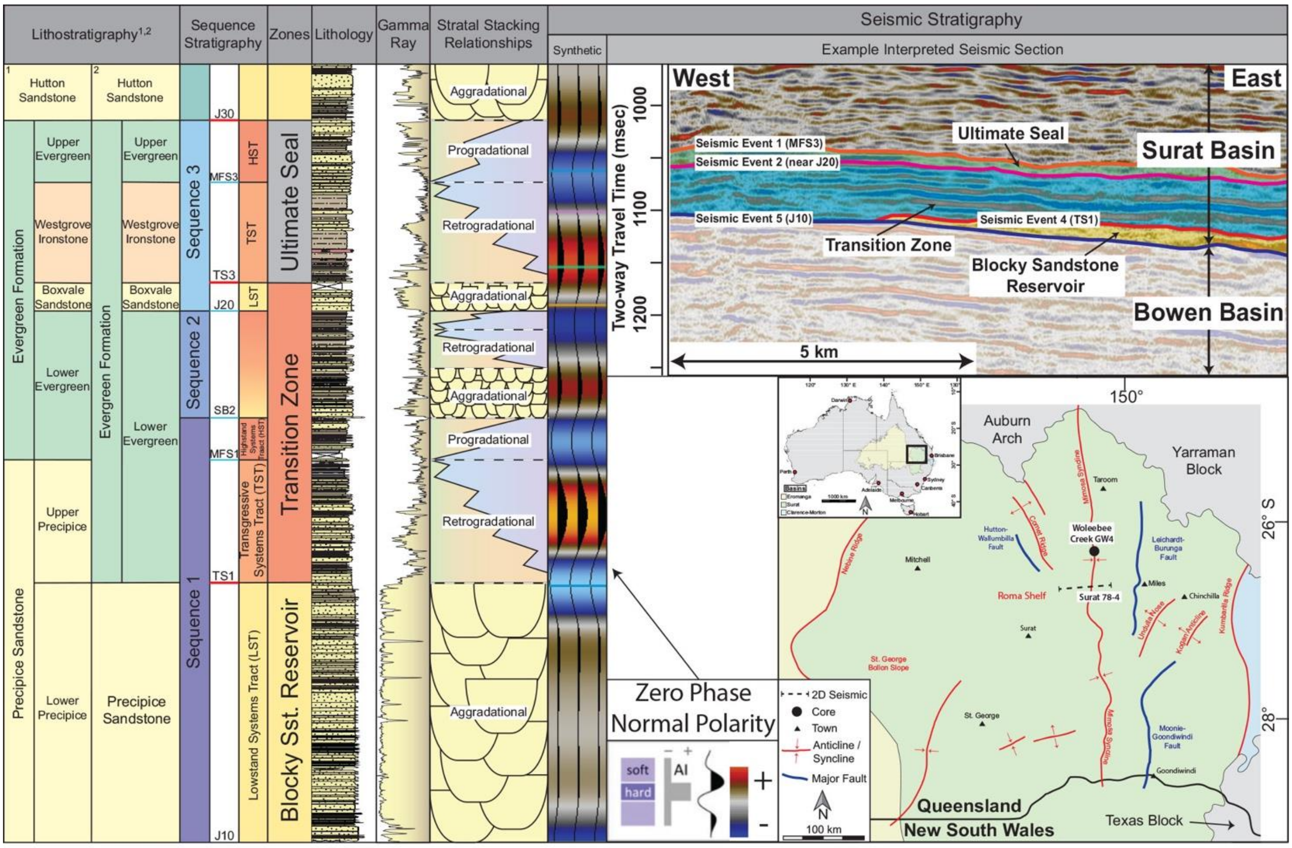


Figure 3 Comparison of stratigraphic nomenclature, zones, lithology, wireline log signature, stratal stacking patterns, and seismic stratigraphy that form the basis of the UQ-SDAAP project framework.



1after Exon et al. 1967, Gray 1968, Rigby and Kanstler 1987, Martin et al. 2018
2after Mollan et al. 1972, Green et al. 1997, Wang et al. in press

3.2 Property modelling

Flow unit terminology was used for cell classification to help control the distribution of porosity and permeability. Three classifiers were modelled: Blocky Sandstone, Other Sandstone, and Less Flow. The Blocky Sandstone classifier corresponds to the wireline log facies SA (La Croix et al. 2019c). The Other Sandstone classifier consisted of wireline log facies SB, SC, SD, SMA, and SMB (La Croix et al. 2019c). Finally, the Less Flow classifier comprised wireline log facies MA, MB, OA, and OB (La Croix et al. 2019c).

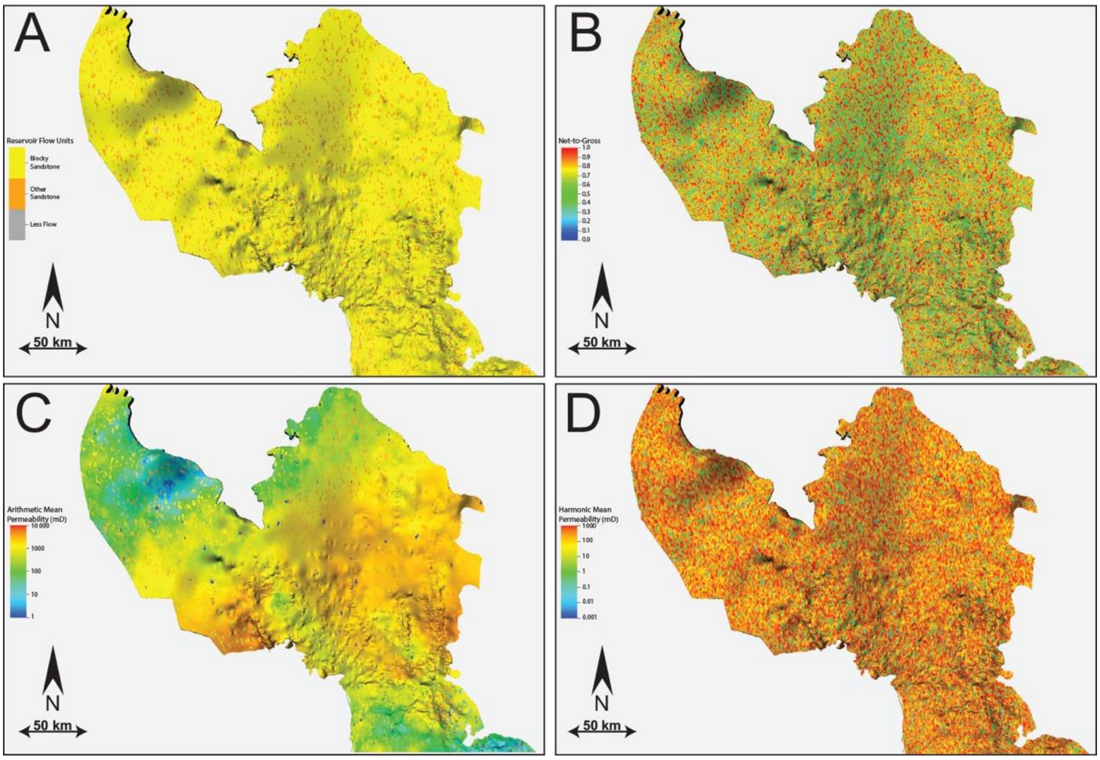
By and large, the reservoir model consisted predominantly of Blocky Sandstone, with subordinate Other Sandstone, and rare Less Flow. Flow units were derived from well data, and then distributed throughout the model using Sequential Indicator Simulation (SIS; Journel, 1983, Journel and Issaks, 1984, Journel and Alabert, 1988, Deutsch, 2006).

Modelling of net-to-gross (NTG) used a simple V_{shale} and porosity cut-off derived from petrophysical logs (Harfoush et al. 2019a). These were 0.4 V_{shale} and 0.06 porosity, respectively. NTG was distributed to model cells using Sequential Gaussian Simulation Figure 4 (SGS; Deutsch and Journel, 1992, Lee et al., 2007, Verly, 1993) and was conditioned to the flow unit classifiers.

Porosity was determined with the neutron-density method as discussed in Harfoush et al. 2019a. The property was modelled using SGS, conditioned to the V_{shale}-based lithology that characterised model cells Figure 4. Overall, the porosity had a normal distribution with a mean of ~0.23 in the Blocky Sandstone Reservoir interval.

Permeability was determined using well data where log permeability was derived from the porosity versus permeability regression calibrated to core plug measured values (see Harfoush et al. 2019a, 2019b). Permeability was modelled using SGS, conditioned to the V_{shale}-based lithology that characterised model cells (Figure 4). The arithmetic and harmonic means of permeability were also modelled using SGS. These were intended to capture the possible range of vertical permeability (cf., Freeze and Cherry, 1979).

Figure 4 (A) Reservoir flow unit designation for the model of the MAR sector area. (B) Net-to-Gross model for the MAR sector area. (C) Arithmetic mean of permeability for the MAR sector area. (D) Harmonic mean of permeability for the MAR sector area.



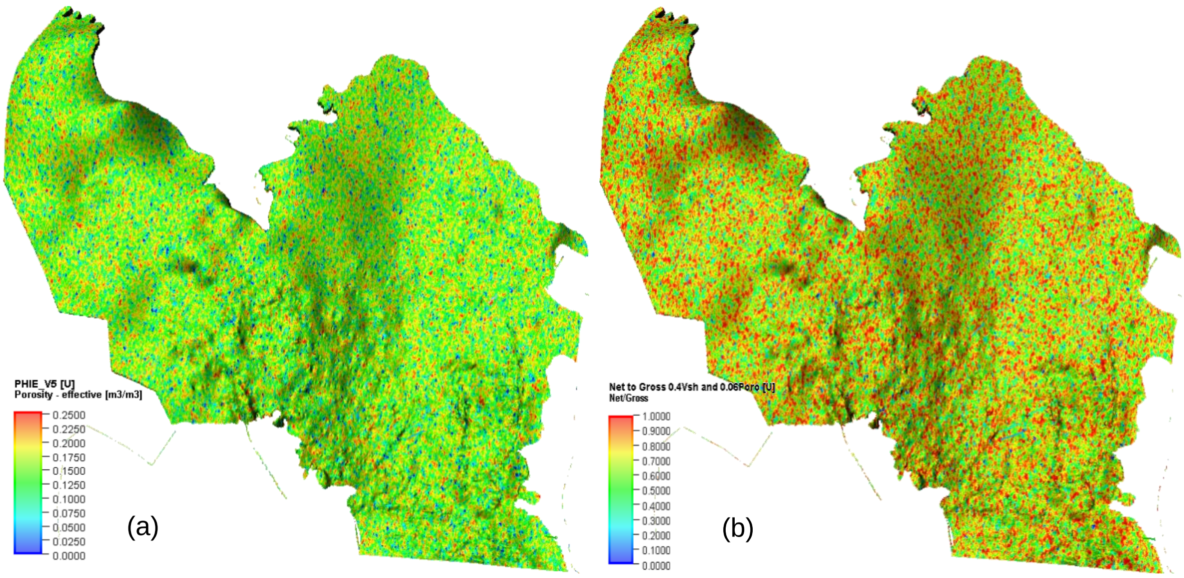
4. Petrophysics versus MAR inversion derived permeability

This section compares the results of the MAR Sector flow analysis between static models parameterised either from the petrophysics workflow described previously, or from a groundwater model inversion based on the MAR history match (Hayes et al. 2019a). Both models have identical physical geometries for the MAR sector static geological model (Figure 4). The models also have identical initial and boundary conditions; however, the assigned permeability values are different in between them. The permeability map in the first model is generated based on the log analysis of several wells in MAR sector as previously described (details in Harfoush et al. 2019a, 2019b, 2019c and 2019d). However, permeability in the second model is generated based on the analysis of the water level data gathered at various monitoring wells (completed in the Precipice Sandstone) during the MAR operations at Reedy Creek and Spring Gully areas (see Hayes et al. 2019a). Having compared the pressure response of both models with the data at the bores across the model (i.e. in the Spring Gully, Coochiemudlo, Woleebee Creek, Charlotte, Charlie, and Condabri areas), a few sensitivity cases for permeability were analysed in order to match the observed water level data.

5. Model initialisation

The UQ-SDAAP used the well log and facies analysis (La Croix et al. 2019a, 2019c) along with the SGS techniques to distribute porosity and net-to-gross over the entire Surat Basin (see Harfoush et al. 2019d and Gonzalez et al. 2019b). The porosity and net-to-gross maps of the MAR section were clipped form the regional Surat Basin model, shown in Figure 5 (A) and Figure 5 (B), respectively.

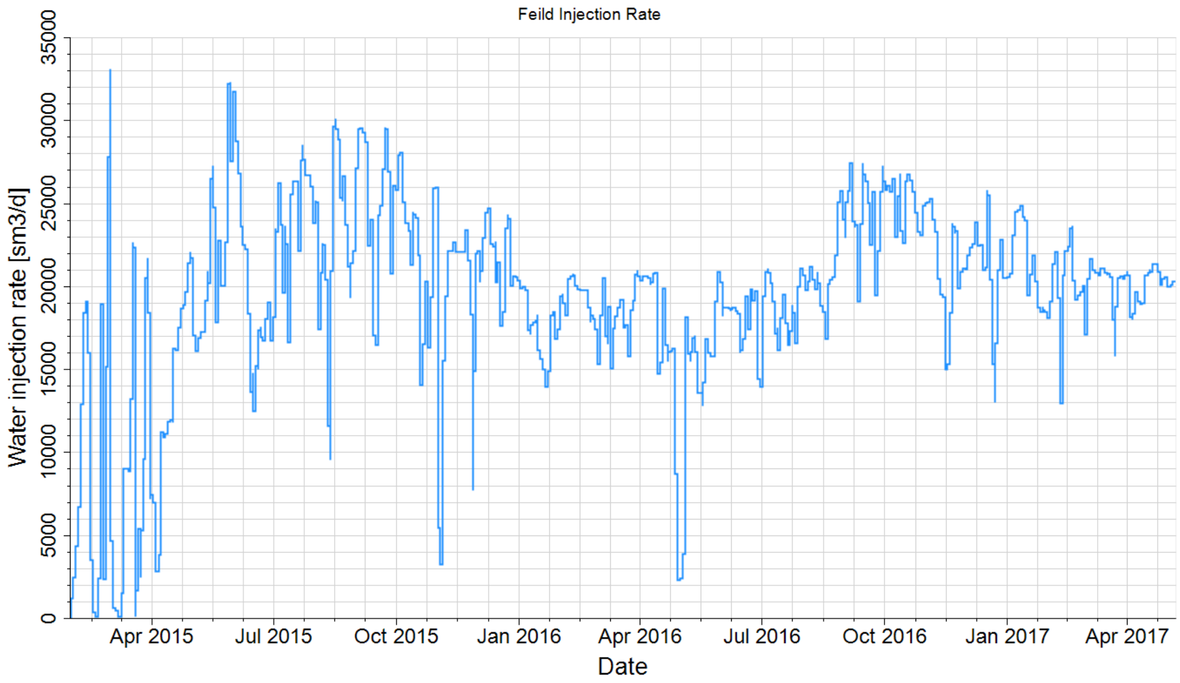
Figure 5 (A) Porosity (B) Net-to-gross distributions for MAR sector area.



Using ECLIPSE software, we initialised the model with the equilibrium pressure of 134.12 bar at the depth of 1106 m. We assigned infinite aquifer (constant water pressure) to the edge of the Blocky Sandstone Reservoir, so the boundary is open unless it geologically pinches out. We assumed the Blocky Sandstone Reservoir is sealed at the top and bottom. We assume the model is fully saturated with water, having a salinity of 800 mg/L at its initial state. Injecting water with an average rate of 21,000 m^3/day, we modelled the resulting single phase flow. Starting from January 2015, for 28 months, water was injected via eleven wells in the Reedy Creek area and three wells in the Spring Gully area. The total flow rate is shown in Figure 6.

Assuming isothermal conditions, we ignore the thermal effects from relatively cold water being injected into a relatively hot formation.

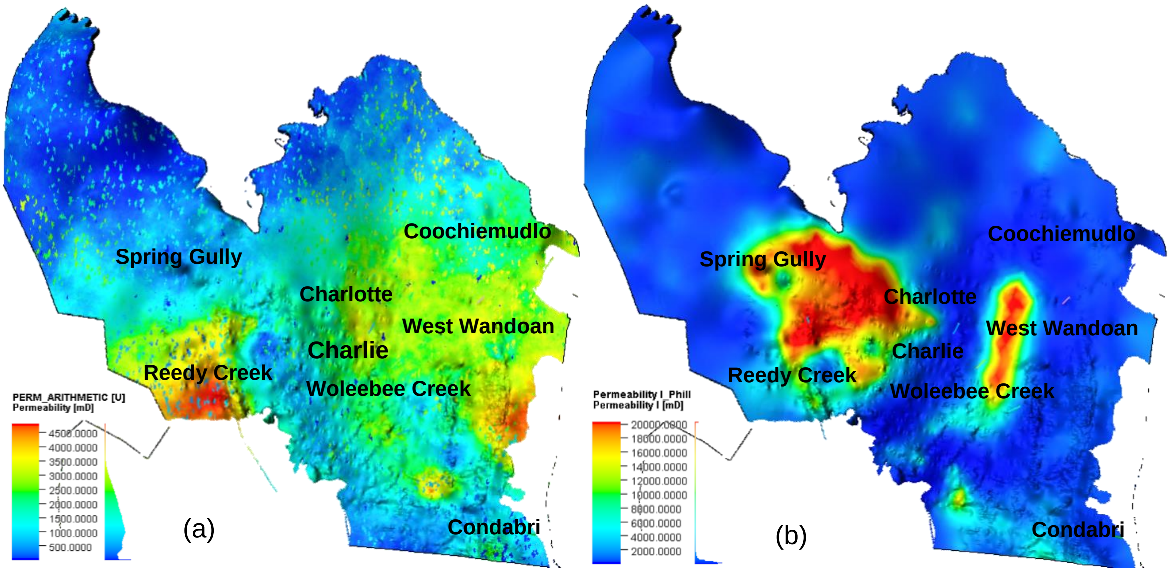
Figure 6 Water injection rate into the MAR sector model (MAR area) for Reedy Creek and Spring Gully combined.



5.1 Distribution of permeability

As mentioned earlier, two permeability distribution maps were available from different sources. One was derived from petrophysical log analysis calibrated with measured core data and DST analysis and the other was derived from inverse groundwater modelling of the MAR observation bore data, shown in Figure 7 (A) and 4b, respectively. The maps are entirely different, not only regarding the magnitude of permeability values but also regarding its distribution. In the map provided sourced from petrophysical analysis, the maximum permeability is less than 5 Darcy, and the highest permeability values occur in the in Reedy Creek area. The permeability distribution from the groundwater inversion model of the MAR observation wells (Figure 7 (B)) shows a broad region of high permeability of up to 200 Darcy around Spring Gully. There is also a narrow but long region (~40 km long) of high permeability from West Wandoan to southern Woleebee Creek. It is speculated that the presence of natural fractures is an explanation for the discrepancy of the two methods since the petrophysical analysis would only “see” the matrix permeability while the groundwater inversion model will “see” the bulk permeability at a larger scale (see Harfoush et al. 2019d for details).

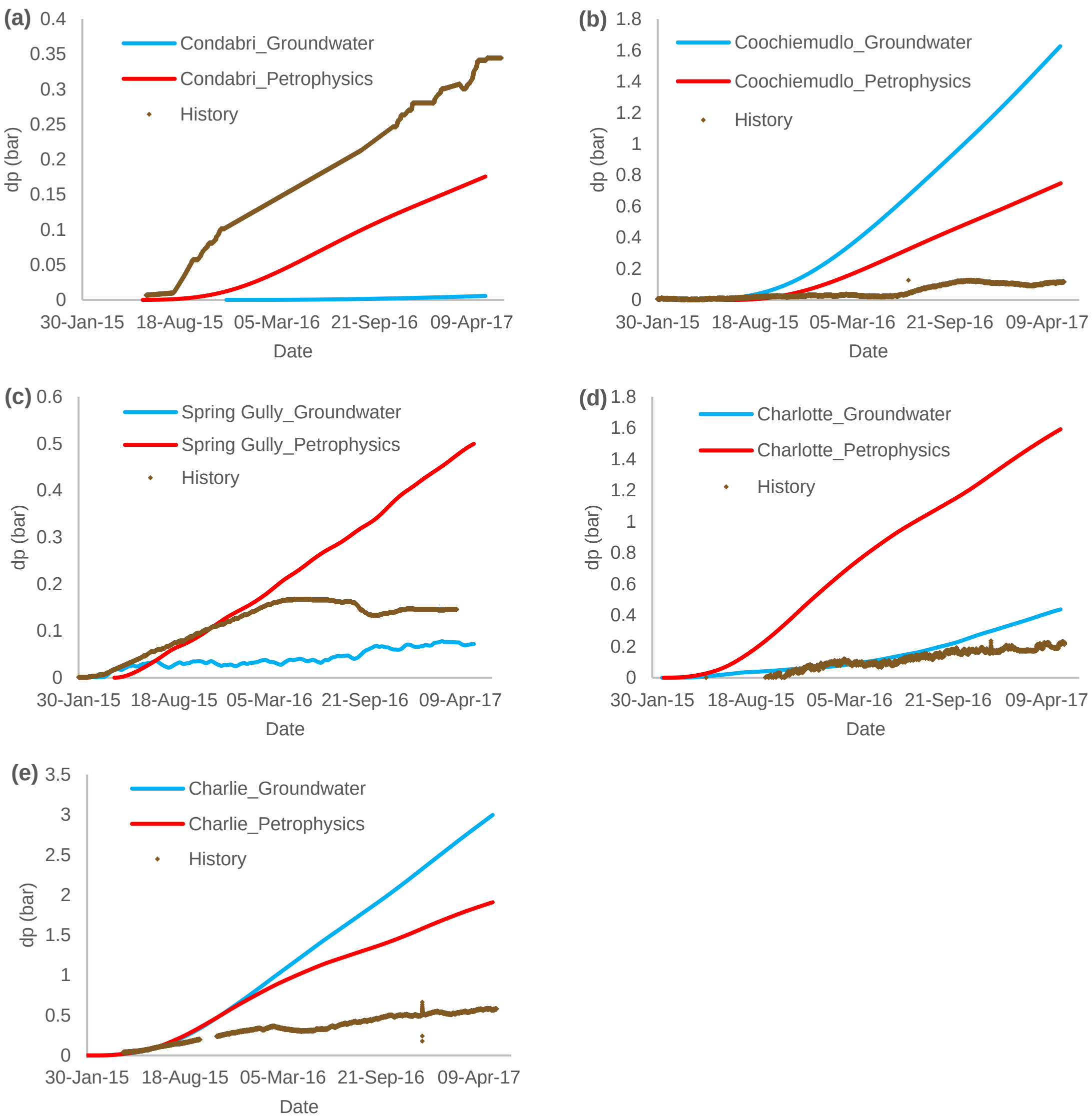
Figure 7 MAR sector permeability distributions provided by (A) petrophysical analysis and (B) groundwater model inversion of MAR observation well data.



5.2 Pressure response prediction

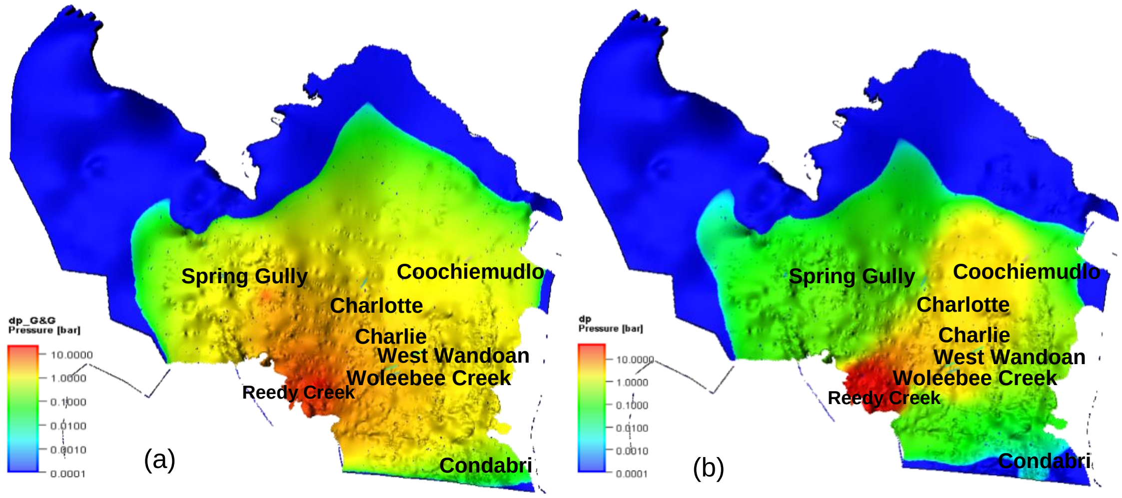
The MAR sector dynamic simulation was run using each of the two alternative permeability distributions described in the previous section. Figure 8 shows the prediction of fluid pressure as well as the available pressure data (history) at five locations in MAR area as a comparison for each permeability distribution scenario. According to the results, using the permeability distribution calculated from the petrophysical analysis has led to a better prediction of pressure in Condabri (south-east), Coochiemudlo (north-east), and Charlie (middle) areas of the MAR sector model. However, the permeability map determined from the groundwater inversion model gives a better prediction of pressure in Spring Gully (North-West) and Charlotte (middle-north) areas of the MAR sector model. The highest increase in pressure (dp) happens at the Charlie area, where the pressure is 1.9 and 3 bar for the petrophysics and groundwater inversion models, respectively. However, both values are far above the field data (history) which is only 0.5 bar change.

Figure 8 MAR Sector dynamic model pressure increase due to MAR injection at Reedy Creek and Spring Gully.



Looking at the distribution of pressure change (dp), the MAR sector dynamic model based on the petrophysical analysis, permeability gives a more homogenous dp over the MAR sector model area (Figure 9). For this model, dp gradually decreases with distance from the main injection location at Reedy Creek (Figure 9 (A)). However, in the model based on the groundwater inversion permeability (Figure 9 (B)), results in a dp distribution chiefly localised in Reedy Creek area, where it gradually decreases along the North-East direction towards Charlie, Charlotte, and Coochiemudlo areas. It significantly drops along the North-West and South-West directions towards Spring Gully and Condabri, respectively.

Figure 9 The distribution of the pressure increase (dp) due to MAR injection in MAR sector area. (A) based on petrophysical analysis permeability distribution and (B) based on groundwater model inversion permeability distribution.



5.3 Sensitivities and modifications

Figure 8 demonstrates that neither model was able to completely history match the pressure prediction with the observed monitoring well data during MAR operations. Thus, a few sensitivity analysis cases on permeability were defined to get a general idea about the trend of the change in pressure prediction as we changed the permeability locally. Comparing the permeability maps determined from petrophysics and groundwater model inversion (Figure 6) reveals that the north-west (Spring Gully) and the middle regions (Charlie/Charlotte) of the MAR sector model have the most discrepancies. We changed the permeability of these two regions for the first map (determined by petrophysics), and compared it with the second one (determined from groundwater model inversion). In one case we multiplied the permeability of Spring Gully and Charlie/Charlotte/Reedy Creek regions to five (Figure 10 (A)), and in the other case we multiplied the permeability of Spring Gully to 10, however we halved the permeability of the middle areas, i.e. Charlie, Charlotte, and Reedy Creek (Figure 10 (B)). Since there might be faults located beyond the Spring Gully and Condabri region to the east (see Gonzalez et al. 2019b), we also defined a case for which the model is sealed in these regions (Figure 10(C)). Adding more pressure field data for further analyses, the hydrogeologists provided an updated permeability map (Figure 10(D)). This is considered as another case.

Table 1 A list of the permeability maps considered for the MAR sector dynamic model sensitivity analysis.

Case	Source of the model (UQ-SDAAP team)	Notation	Remarks	Figure
1	petrophysics	petrophysics	Original	Figure 7 (a)
2	petrophysics	petrophysics _Modified_1	Permeability in Spring Gully, Charlie, Charlotte, Reedy Creek is multiplied to 5	Figure 10 (a)
3	petrophysics	petrophysics _Modified_2	Permeability in Spring Gully is multiplied to 10. However, permeability in Charlie, Charlotte, Reedy Creek is multiplied to 0.5	Figure 10 (b)
4	petrophysics	petrophysics _Modified_3	The model is sealed in upper Spring Gully and lower Condabri	Figure 10 (c)
5	Groundwater	Groundwater	Original	Figure 10 (d)
6	Groundwater	Groundwater_2	Updated by the hydrogeologists by including more pressure field data	Figure 7 (a)

Figure 10 Permeability modifications in the MAR sector area sensitivity analysis: (A) increasing the permeability determined by petrophysics moderately in Spring Gully, Reedy Creek, Charlie, Charlotte, Woleebee Creek; (B) increasing the permeability significantly in Spring Gully, however decreasing it moderately in the Reedy Creek, Charlie, Charlotte, Woleebee Creek areas; (C) sealing the modelled faults in the upper Spring Gully and southern Condabri areas; and (D) modifying the permeability of the groundwater model inversion by using more data as input.

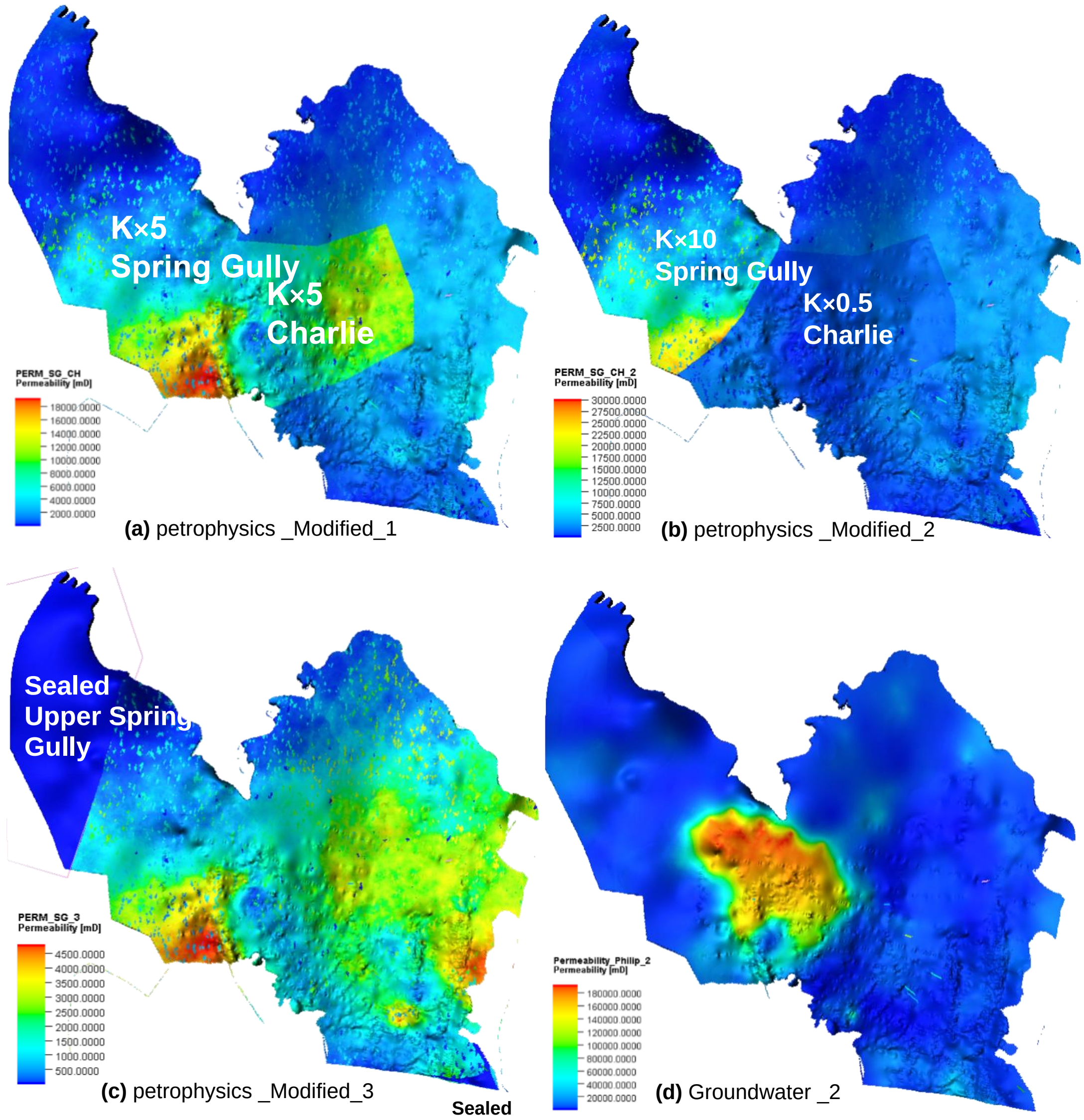
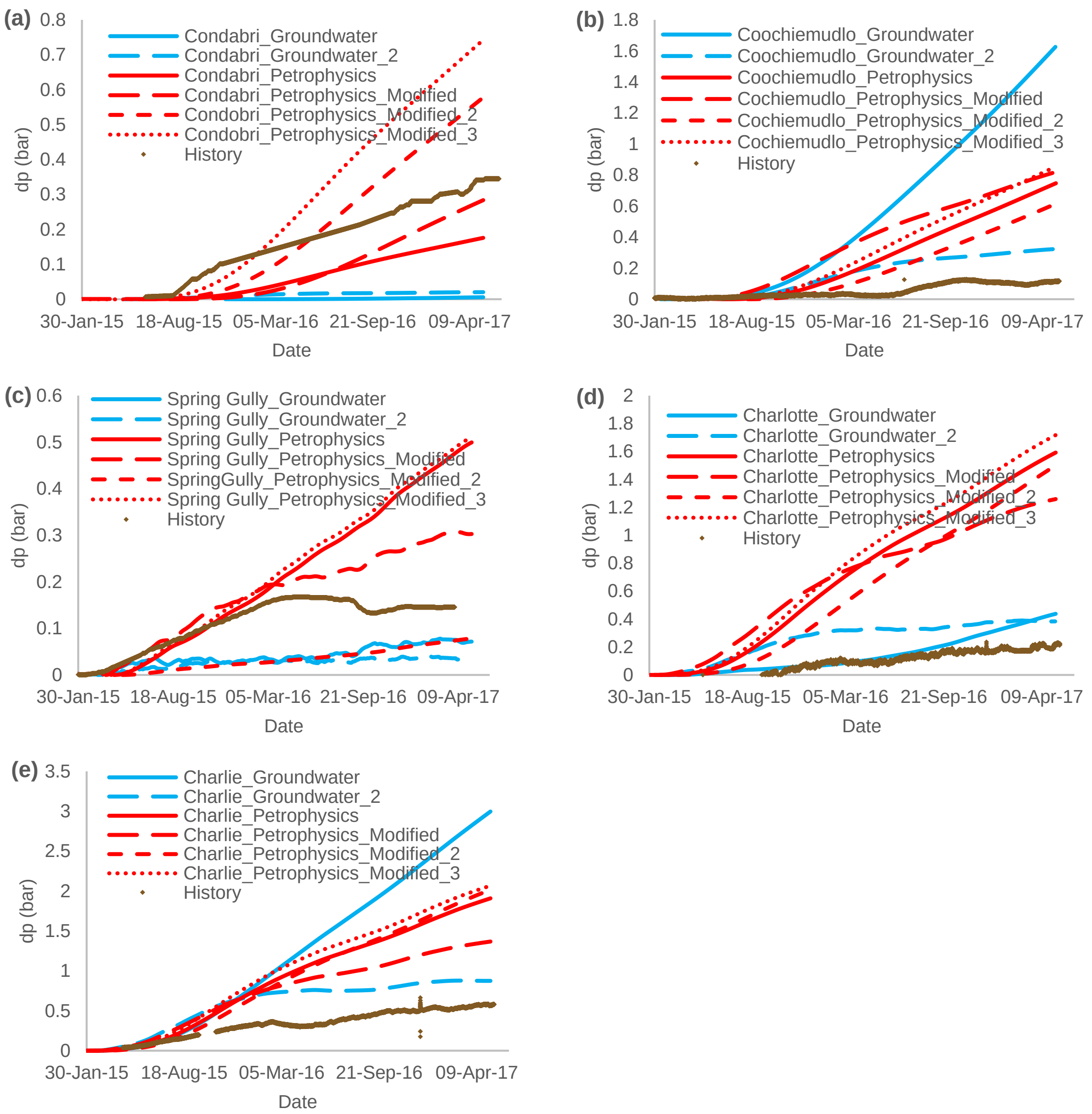


Figure 11 shows the results of the sensitivity analysis done on the MAR sector area at the same locations as before. At Condabri-Well-INJ2-P, the first modified permeability map gives the closest prediction to the actual measured history at observation bores. However, the original permeability map gives a better trend. Both original and updated models provided by the groundwater model inversion gave the worst prediction of pressure. At Coochiemudlo-Well-GW2, the updated permeability map (Figure 10 (D)) gave the best prediction in terms of both pressure values and its general trend with time at specific well locations (Figure 11 (B)). The original groundwater model inversion gave the worst prediction. At Spring Gully-Well-Precipice Bore-1, none of the cases could predict the observed pressure history accurately. In early time the first modified map of the petrophysics determined that permeability gives a good prediction. However, in late time, the original model of the groundwater model inversion gives a better prediction (Figure 11 (C)). In general, increase in pressure in the Spring Gully area is low (<0.8 bar) and the inclusion of a long sealing fault did not improve the prediction of pressure. In the Charlotte area, neither the original nor the modifications of the petrophysics determined permeability models gave good results (Figure 11 (D)). Here, the original groundwater model inversion gave a good prediction of pressure in early time, however, the modified groundwater model inversion gave a better trend in late time. In the Charlie area (at Charlie-Well-GW2), quite like in the Coochiemudlo area, the difference between the predictions made by the original and the updated models of the groundwater model inversion was huge. However, the original and the modified petrophysics models gave similar results (Figure 11 (E)). The best prediction of pressure has been achieved by the updated groundwater model inversion (Figure 10 (E)).

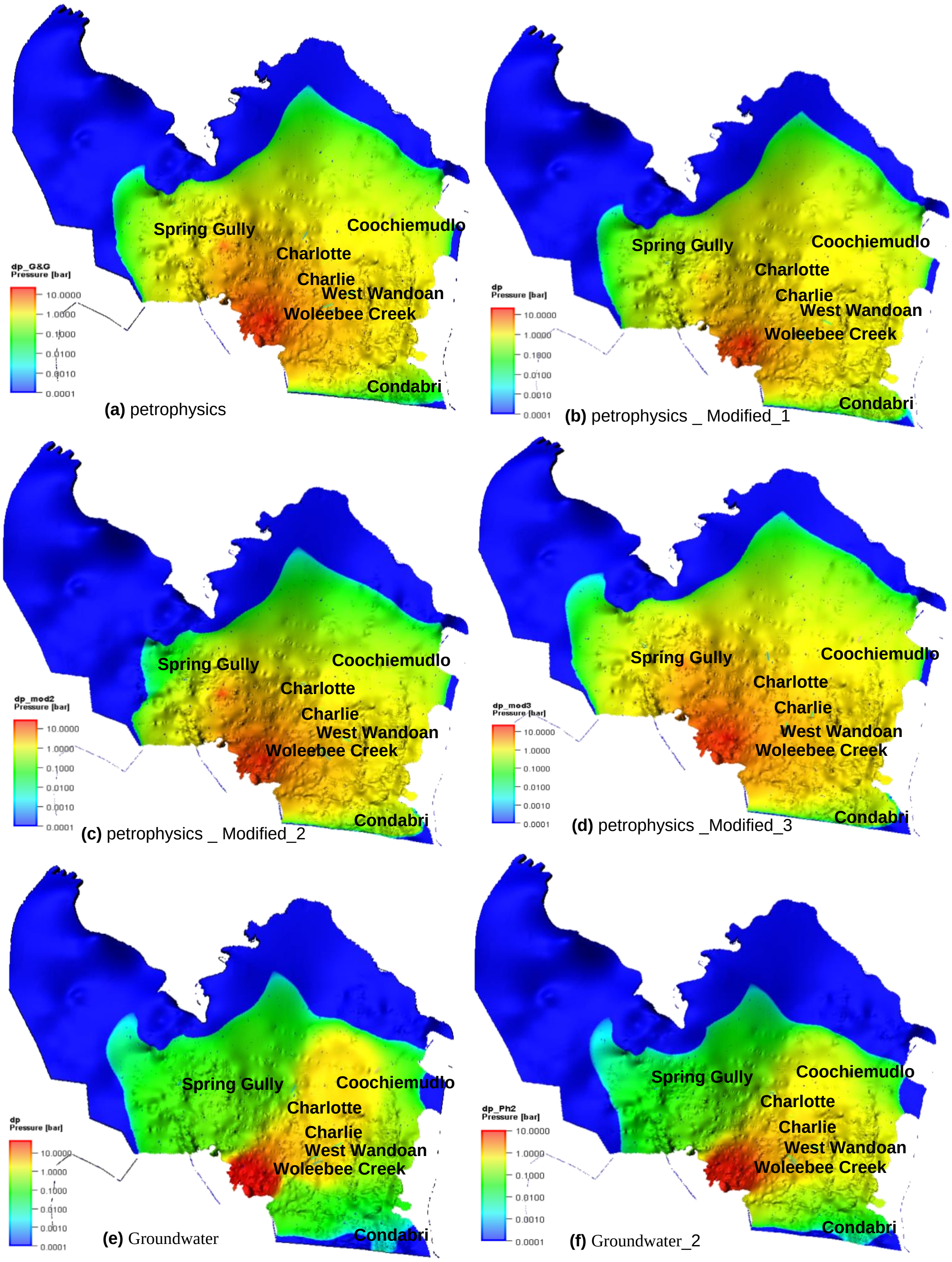
In conclusion, among all the cases, the updated groundwater model inversion (Figure 10 (D)) gave the best prediction of pressure. It only failed to closely predict the pressure in the Condabri area (at Contabri-Well-ING2-P). Low values of dp in this location could be related to the open boundary condition. This could be improved by assigning a closed boundary condition. The results could also be improved if we sealed the north-west boundary at Spring Gully. However, sealing a wider area of the model boundary would also lead to a general increase in pressure across the model, and this might lead to a deterioration of the history match in the central areas.

Figure 11 Sensitivity analysis results: pressure increase due to MAR injection in the MAR sector area.



The distribution of dp across the MAR sector model area is similar between the petrophysics derived permeability scenario models (Figure 12 (A-D)). In general, the highest dp is achieved in the third modification of the petrophysics derived permeability model. The dp distribution is totally different between the groundwater model inversion and the updated groundwater model inversion scenarios where dp is high in the middle and the north-east, but it is low in the north-west and the south-east (Figure 12 (E-F)). The updated groundwater model inversion gives high dp values in a wider area in the middle of the MAR sector area and increase in fluid pressure in eastern areas such as West Wandoan which has become ten times higher (Figure 12 (E)).

Figure 12 Sensitivity analysis: the distribution of the pressure increase (dp) due to MAR injection in the MAR sector area.



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