Les Rencontres scientifiques d'IFP Energies nouvelles

Flows and mechanics in natural porous media from pore to field scale. *Pore2Field*
16-18 November 2011, IFP Energies nouvelles (France)

Challenges of modelling the impact of multi-purpose aquifer utilization on variable-density groundwater flow

Karsten Michael[1*], Sunil Varma[1], Elise Bekele[2]

1 CSIRO Earth Science & Resource Engineering, 26 Dick Perry Avenue, Kensington WA 6151, Australia, karsten.michael@csiro.au
2 CSIRO Land & Water, Underwood Avenue, Floreat Park WA 6014, Australia
** Corresponding author*

Abstract — Challenges of modelling the impact of multi-purpose aquifer utilization on variable-density groundwater flow — *The Latrobe aquifer in the Gippsland Basin in southeastern Australia is a prime example for emerging resource conflicts in sedimentary basins. The Latrobe Group forms a major freshwater aquifer in the onshore Gippsland Basin and is an important reservoir for oil and gas in the offshore parts of the basin. The Latrobe Group and overlying formations also contain substantial coal resources and the basin is considered prospective for its geothermal energy and* CO_2 *storage potential. The freshwater-saltwater interface in shallow aquifers closely follows the present-day shoreline in the form of a conventional seawater wedge. However, in the Latrobe aquifer a wedge of freshwater displaces saline water downdip, several kilometres offshore. Basin-scale simulations of formation water flow in the Gippsland Basin were performed for this study using two numerical codes capable of modelling density dependent flow. As the Latrobe aquifer extends from the shallow "groundwater model" to the deep "petroleum reservoir simulator" domain, comparative simulations were run with Visual MODFLOW/SEAWAT as well as with PetraSim5 (TOUGH2). So far, the large scale and computation requirements posed problems with running SEAWAT for variable salinity and temperature conditions, and only TOUGH2 simulations were completed successfully for an un-stressed system and simplified parameterization. Future modelling efforts will involve more realistic permeability distributions and including pumping stresses to significantly improve the model accuracy. It remains to be demonstrated whether this type of modelling can adequately predict the* relative balance between the impact of onshore coal mine dewatering and agricultural use and offshore petroleum production *on water levels in shallow, unconfined aquifers, or if there is a need for better integration of groundwater model and reservoir simulator capabilities.*

INTRODUCTION

With an increase in demand for energy and groundwater resources, potential exists for future resource conflict in sedimentary basins. Groundwater extraction from relatively shallow aquifers and the production of deeper petroleum resources are generally independent. However, with increasing exploration in emerging sectors such as unconventional gas (i.e. coal seam and shale gas), this spatial divide will decrease creating multiple use zones.

In the Gippsland Basin of southeastern Australia, such zones already exist. For example, petroleum is produced from the offshore Latrobe Group, whilst coal mine dewatering and groundwater is extracted from the same stratigraphic unit in the onshore parts of the basin, (Figure 1). Future activities such geological carbon storage and geothermal energy production are also likely to further impact fluid flow in the basin.

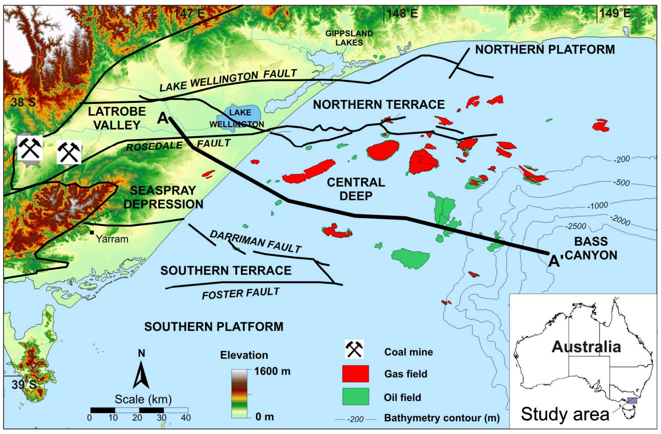

Figure 1. Location of the Gippsland Basin in southeastern Australia. Line AA' refers to location of cross-section in Figure 2.

1 GIPPSLAND BASIN GEOLOGY AND HYDROGEOLOGY

The regional geology and hydrogeology of the Gippsland Basin is summarized in Figure 2. Pliocene to Pleistocene sediments form the shallow aquifer system, which is largely unconfined in the onshore Gippsland Basin. Its thickness varies from <20 m onshore to around 300 m offshore. The underlying Seaspray Group forms an aquifer-aquitard system. In the onshore area, sandy horizons form aquifers between the adjacent coal seams and shale beds of the Latrobe Valley Subgroup. Offshore, the time-equivalent Gippsland Limestone consisting of limestone, silt and marl forms a low-permeability aquitard system. The shale and marls of the Lakes Entrance Formation form a major regional aquitard, confining the underlying regional Latrobe Group aquifer system (the Latrobe aquifer). The Lakes Entrance Formation is absent in the western half of the onshore Gippsland Basin and is commonly around 400 m thick across the central offshore part of the basin. The Latrobe Group consists of interbedded marginal marine to deltaic sandstone, siltstone, shale and coal [1]. The Latrobe Group crops out in the onshore parts of the Gippsland Basin and its thickness increases to more than 2000 m in the Central Deep. Along the eastern edge of the basin, the Latrobe aquifer subcrops beneath recent sediments at the seafloor. It pinches out along the northern and southern margins of the basin.

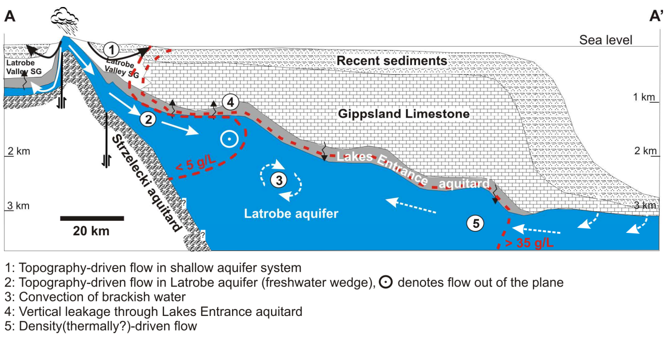

Figure 2. Conceptual flow patterns in the Gippsland Basin. See Figure 1 for line of cross-section.

The salinity of the formation water in the Latrobe aquifer varies from less than 0.5 g/l in the onshore area to more than 35 g/l total dissolved solids in the Central Deep region of the offshore Gippsland Basin. The transition from freshwater to saltwater varies throughout the sedimentary succession. In the shallow aquifers, the transition zone is relatively narrow and closely follows the present-day shoreline, whereas in the deeper Latrobe aquifer a lower salinity gradient and wider zone of brackish formation water extends to about 20 km offshore. In the centre of the Latrobe aquifer, the overlying aquitard impedes freshwater discharge vertically upward, and the density contrast forces most freshwater to flow laterally along the freshwater-seawater transition zone before it discharges at shallower depths offshore along the southern and northern aquifer edges [2]. The large-scale petroleum and groundwater extractions have modified the natural flow systems in the Gippsland Basin. The largest drawdowns, of up to 130 m, are estimated in the offshore region near petroleum fields and onshore in the coal mining areas.

2 NUMERICAL SIMULATIONS

The impacts of large scale groundwater extraction related to open pit coal mine dewatering, public water supply, and petroleum production on the flow of variable density formation water in the Latrobe aquifer were assessed previously using equivalent freshwater hydraulic heads [3] and freshwater, isothermal flow simulations [4]. However, impelling force vector analysis suggests that these model results have varying degrees of inaccuracy due to the neglect of density effects, particularly in the deep parts of the aquifer [2]. Consequently, basin-scale simulations of formation water flow in the Gippsland Basin are underway for this study, using two numerical codes capable of modelling density dependant flow. As the Latrobe aquifer extends from the shallow "groundwater model" to the deep "petroleum reservoir simulator" domain, comparative simulations were run with Schlumberger's Visual Modflow based on the MODLFOW/SEAWAT from the USGS, as well as PetraSim5, a commercial interface using the TOUGH2 code developed by Lawrence Berkeley National Laboratories.

2.1 Model codes

Work on these simulations is progressing, particularly those involving the SEAWAT modelling. The capabilities of both codes are shortly described in this section, but only the TOUGH2 simulations are presented in more detail here.

2.1.1 SEAWAT

The SEAWAT (v.4) program is a coupled version of MODFLOW and MT3DMS for simulating three dimensional, variable-density, non-isothermal, saturated groundwater flow (http://water.usgs.gov/ogw/seawat/). It includes all MODFLOW capabilities (e.g. modelling unconfined aquifers and applying various boundary conditions to represent areal recharge, evapotranspiration, and flow through river beds) [5]. Although not explicitly designed to simulate heat transport, temperature can be simulated as one of the species by entering appropriate transport coefficients. Heat conduction can be represented by assigning a thermal diffusivity for the temperature species. Heat exchange with the solid matrix can be treated in a similar manner by using the mathematically equivalent process of solute sorption.

2.1.2 TOUGH2 (ECO2N)

TOUGH2 is a reservoir simulator for non-isothermal multiphase flow in fractured porous media (http://esd.lbl.gov/research/projects/tough/). In view of the potential future application to geological carbon storage assessments, the ECO2N module was used in this project. It includes a comprehensive description of the thermodynamics and thermophysical properties of H_2O - $NaCl$-CO_2 mixtures, that reproduces fluid properties largely within experimental error for the temperature, pressure and salinity conditions of interest (10 °C ≤ T ≤ 110 °C; P ≤ 600 bar; salinity up to full halite saturation) [6]. Flow processes can be modelled isothermally or non-isothermally, and phase conditions represented may include a single phase, as well as two-phase mixtures. Fluid phases may appear or disappear in the course of a simulation, and solid salt may precipitate or dissolve. Heat transport occurs by means of conduction (with thermal conductivity dependent on water saturation), convection, and binary diffusion.

2.2 Model set-up (TOUGH2)

Simulations of undisturbed formation water flow in the Gippsland Basin accounting for salinity and temperature effects were performed using the PetraSim5 (TOUGH2) code. The PetraSim5 model grid is based on a simplified hydrostratigraphy using stratigraphic surfaces provided by GeoScience Victoria: 1) seafloor topography, 2) top of Lakes Entrance Formation, 3) top of Latrobe Group and 4) top of Strzelecki Group. The 10 layer model consists of approximately 50,000 cells with 3 km x 3 km cells of variable thickness (Figure 3).

All vertical model boundaries are modelled as no-flow boundaries, whereas the top and bottom layers are set to fixed pressure, salinity and temperature conditions. Initial conditions consist of a) hydrostatic pressure, b) constant temperature gradient of 20°C/km, and c) varying salinity (35 g/l in the offshore Lakes Entrance and Gippsland Limestone layers, 0 g/l in the onshore cells and salinity increasing eastwards from 0 – 35 g/l in the Latrobe aquifer layers).

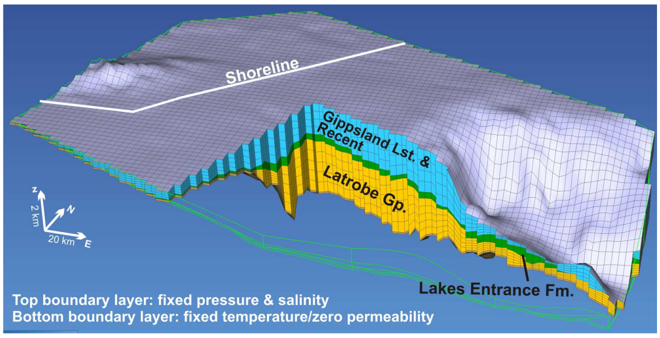

Figure 3. Model grid along two cross-sections for the PetraSim5 (TOUGH2) simulations. The grid consists of approximately 50,000 active 3 km x 3 km cells.

2.3 Simulation results

The model was run over a period of one million years by which time it was assumed quasi-steady-state conditions were reached. After a few thousand years, pressures do not change significantly, while salinity and temperature fields continue to change (Figure 4). Nevertheless, comparing modelled versus observed pressures in selected oil wells indicates that the modelled pressure and salinity distributions resemble closely the undisturbed hydrodynamic conditions in the Gippsland Basin. The results provide evidence for two formation water flow systems, each with a distinct flow-driving mechanism:

1. Cold, high-density seawater in the ocean and Gippsland Limestone overlying warm, fresh-brackish, lower density formation water in the Latrobe Group causes instability and density-driven flow. This results in westwards (shorewards) displacement of Latrobe aquifer connate waters.
2. Gravity-driven flow with recharge of meteoric water in areas of topographic highs and discharge into lakes and along the fresh-seawater interface. This results in eastward flow in the Latrobe aquifer and forms a freshwater wedge that pushes seawards.

A number of limitations apply to this model, which include: a) simplified permeability distribution (resulting in unrealistically extensive convection cells), b) low temperature gradient, c) simplified boundary conditions (particularly with respect to recharge of meteoric water in the onshore area), d) uncertainty in initial salinity distribution, and e) faults not represented as distinct features. Future simulation efforts will address these limitations and will assess the impact of production activities on the basin-scale flow regime in the Gippsland Basin.

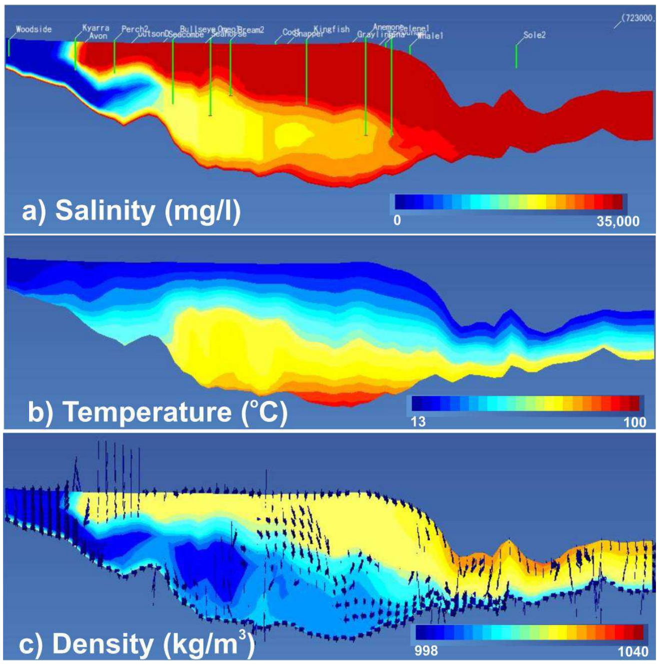

Figure 4. Initial simulation results along a W-E cross-section (10x vertical exaggeration) for quasi-steady state conditions. Green lines in a) depict well locations and blue arrows in c) represent flow direction and magnitude.

3 SUMMARY & CONCLUSIONS

With the ever increasing demand for water and energy, there is a need for managing the growing overlap between groundwater, petroleum and geothermal resources. Numerical flow models are an important tool for the assessment and management of resource conflicts in the subsurface. These models must be capable of simulating coupled processes such as multiphase fluid and heat flow, chemical diffusion and geomechanics, as well as accounting for interactions between groundwater and surface water bodies. Both, groundwater models and reservoir simulators, have been used successfully for simulating multiphase flow phenomena related to either groundwater contamination or petroleum production. However, groundwater models of the MODFLOW family of codes provide advantages in representing the interaction between surface and subsurface water; whereas (petroleum) reservoir simulators are more efficient in modelling processes that involve variable salinity and heat flow.

Variable-density modelling using PetraSim5 (TOUGH2) resulted in a relatively coarsely-calibrated model of the pressure and salinity distributions of the pre-stress flow system in the Gippsland Basin. Additional simulations currently underway, using more realistic permeability distributions and including pumping stresses, will significantly improve the model accuracy. It remains to be demonstrated whether this type of modelling can adequately predict the potential impact of petroleum production on water levels in shallow, unconfined aquifers, or if there is a need for better integration of groundwater model and reservoir simulator capabilities.

ACKNOWLEDGMENTS

The authors are grateful to the Victorian Department of Primary Industries for the funding and data support received for this project.

REFERENCES

1. Goldie Divko, L.M., O'Brien, G.W., Harrison, M.L., and Hamilton, P.J., 2010. Evaluation of the regional top seal in the Gippsland Basin: Implications for geological carbon storage and hydrocarbon prospectivity. APPEA Journal, v. 50, p. 463-486.
2. Varma, S. and Michael, K., in press. Impact of multi-purpose aquifer utilisation on a variable-density groundwater flow system in the Gippsland Basin, Australia: Hydrogeology Journal.
3. Gibson-Poole, C., Svendsen, L., Underschultz, J., Watson, M., Ennis-King, J., van Ruth, P., Nelson, E., Daniel, R., and Cinar, Y., 2008. Site characterisation of a basin-scale CO_2 geological storage system: Gippsland Basin, southeast Australia: Environmental Geology, v. 54, p. 1583-1606.
4. Schaeffer, J., 2008. Scaling point based aquifer data for developing regional groundwater models: application to the Gippsland groundwater system. PhD Thesis (unpublished). Department of Civil and Environmental Engineering, University of Melbourne, Australia, 331 p.
5. Harbaugh, A. W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000. MODFLOW-2000, the U.S. Geological Survey modular ground-water model - User guide to modularization concepts and the Ground-Water Flow Process: U.S. Geological Survey Open-File Report 00-92, 121 p.
6. Pruess, K., and Spycher, N., 2007. ECO2N - A fluid property module for the TOUGH2 code for studies of CO_2 storage in saline aquifers: Energy Conversion and Management, v. 48, p. 1761-1767.