Simulation of Coastal Subsidence and Storm Wave Inundation Risk in the Gippsland Basin

Reem Freij-Ayoub, Jim Underschultz, Fangjun Li, Christine Trefry, Alison Hennig, Claus Otto, Kathleen McInnes

CSIRO Petroleum Report 07-003
November 2007
Enquiries should be addressed to:
Reem Freij-Ayoub       Jim Underschultz
reem.freij-ayoub@csiro.au   james.underschultz@csiro.au

PO Box 1130, Bentley WA 6102, Australia
T: +61 8 6436 8500
F: +61 8 6436 8555
W: www.csiro.au/WealthFromOceans

Copyright and Disclaimer
© 2007 CSIRO To the extent permitted by law, all rights are reserved and no part of this publication covered by copyright may be reproduced or copied in any form or by any means except with the written permission of CSIRO.
# TABLE OF CONTENTS

**EXECUTIVE SUMMARY** .......................................................................................................................... 1

1 **INTRODUCTION AND BACKGROUND** ......................................................................................... 3

2 **GIPPSLAND HYDRO_DYNAMIC SYSTEMS** .................................................................................. 4
   2.1 Pre production hydrodynamic system ................................................. 4
   2.2 Post production hydrodynamic system ............................................... 5
   2.3 Hydraulic scenario models input in the Geomechanical subsidence model. .............................................................. 5
      2.3.1 Offshore sinks ............................................................................. 5
      2.3.2 Onshore sinks ............................................................................. 6
      2.3.3 Aquifer recharge estimates ......................................................... 6
      2.3.4 Compaction dewatering ............................................................. 6
      2.3.5 Hydraulic head modelling scenarios ........................................... 7
      2.3.6 Other possible hydraulic head scenarios ..................................... 7

3 **COASTAL SUBSIDENCE** .................................................................................................................. 14
   3.1 Background ..................................................................................... 14
   3.2 Objectives ...................................................................................... 14
   3.3 Model assumptions .......................................................................... 14
   3.4 Water level prediction scenarios ..................................................... 16
   3.5 Geomechanical modelling approach ................................................. 16
      3.5.7 The mechanical parameters ....................................................... 17
      3.5.8 Reducing the uncertainty in the mechanical parameter ............... 17
      3.5.9 Vic DPI ground elevation measurements .................................. 18
      3.5.10 Comparison of Vic DPI measurements and the model predictions 19
   3.6 Subsidence prediction results and conclusions .................................. 20

4 **EXTREME WAVE CONDITIONS AND SEA LEVEL PREDICTION IN THE NEXT 50 YEARS** .... 41
   4.1 Objective .......................................................................................... 41
   4.2 Extreme sea level projections to 2056 under climate change .......... 42
   4.3 Extreme wave analysis for the region .............................................. 43
      4.3.11 Data selection ........................................................................... 43
      4.3.12 Extreme wave analysis ............................................................. 43
      4.3.13 Wave direction .......................................................................... 45
      4.3.14 Wave transformation over shallow waters ............................... 45
4.4 50-year-return wave heights across Gippsland Coast 47
   4.4.15 Current Climate 47
   4.4.16 2031 Climate with high sea level rise 47
   4.4.17 2056 Climate with high sea level rise 47

4.5 Conclusions of extreme wave height calculations 49

5 INUNDATION RISK MAPS 54
   5.1 Inundation risk due to land subsidence 54
   5.2 Inundation risk due to storm tide and extreme wave 54
   5.3 Inundation risk due to the combined effect 55

6 FINAL CONCLUSIONS AND RECOMMENDATIONS 80

7 ACKNOWLEDGMENTS 83

8 REFERENCES 83

9 ADDENDUM: DPI HIGH RESOLUTION GPS PROGRAM- EPOCH 3- 2007 85

10 APPENDIX A: VARIOUS FACTORS AFFECTING SETTLEMENT PREDICTIONS 87
# List of Tables

Table 1. Predicted subsidence for years 2031 and 2056 at various wells with the respective aquifer thickness.............................................................................................................. 24

Table 2. Calculation of the confining pressures at centre or top of aquifer. ...................... 28

Table 3. Scaled mechanical parameters using two methods. ............................................... 29

Table 4. Calibration of the compressibilities based on comparisons between measured and calculated subsidence using unscaled and scaled mechanical parameters......................... 30

Table 5. Final predicted subsidence in years 2031 and 2056 for both the pessimistic and realistic hydraulic head scenarios.................................................................................... 35

Table 6. Predicted total head and water pressure head change for the pessimistic and realistic scenarios for both years 2031 and 2056 ................................................................. 36

Table 7. Summary of subsidence results at various regions of the coastline. Pessimistic and realistic scenarios coincide between the Lake Wellington and Rosedale Fault System. 41

Table 8. Extreme storm tide level for selected locations around the Gippsland Lakes under current climate, 2031 and 2056 high mean sea level rise scenarios (after McInnes, et al., 2005, 2006). ...................................................................................................................... 42

Table 9. Wave sampling locations ........................................................................................... 43

Table 10. Extreme wave climate estimates for deep water boundary. ................................. 44

Table 11. Wave parameters of the top 50 storms in 5 years (1997-2002) for the deep water-Gippsland region. ............................................................................................................ 45

Table 12. Summary of storm tide and wave heights within three examined mean sea level scenarios .......................................................................................................................... 50

Table 13. Summary of subsidence contribution to the total inundation risk predicted at the coastline. Pessimistic and realistic scenarios coincide between the Lake Wellington and Rosedale Fault System. .......................................................................................................................... 55

Table 14. Comparison of predicted subsidence limits to predicted extreme wave height levels for the years 2031 and 2056. .................................................................................. 55
List of Figures

Figure 1. Gippsland Basin Risk Study: topography and bathymetry ........................................ 8
Figure 2. Gippsland Basin Risk Study: mines and oil and gas fields in the study area ............ 9
Figure 3. Pre-Production hydraulic head distribution for the Upper Latrobe Aquifer System (after Hatton et al., 2004) ................................................................. 10
Figure 4. Mid 1980s hydraulic head distribution for the Upper Latrobe Aquifer System (after Underschultz et al., 2006) ................................................................. 11
Figure 5. Mid 1990s hydraulic head distribution for the Upper Latrobe Aquifer System (after Underschultz et al., 2006) ................................................................. 12
Figure 6. Estimated hydraulic head for the Upper Latrobe aquifer in 2004 (after Underschultz et al., 2006) ................................................................. 13
Figure 7. Locations modelled for subsidence. Circles in blue indicate wells where pore pressure measurements were taken. Circles in red indicate wells where aquifer thickness data is available from well completion reports (after Hatton et al., 2004) ... 22
Figure 8. Gippsland Basin Risk Study, subsidence data extent for the subsidence model. ..... 23
Figure 9. Gippsland Basin Risk Study: A map of the Latrobe Aquifer thickness from Mehin (1995) ........................................................................................................ 25
Figure 10. Gippsland Basin Risk Study: Cross-sections of the Gippsland Basin from Mehin (1995) ........................................................................................................ 26
Figure 11. Gippsland Basin Risk Study: Vic DPI high resolution GPS monitoring sites (red dots) and some other reference well locations ........................................ 27
Figure 12. Comparison between measured (by Vic. DPI) and predicted scaled calculated subsidence values (model prediction) for the period between June 2004 and November 2006 plotted from south to north along the Gippsland coastline ................................ 31
Figure 13. Predicted subsidence based on the pessimistic and realistic extraction scenarios. 34
Figure 14. Gippsland Basin Risk Study 2031 realistic scenario predicted subsidence data and contours. Pessimistic and realistic scenarios coincide between the Lake Wellington and Rosedale Fault System, Figure 15 ......................................................... 37
Figure 15. Gippsland Basin Risk Study 2031 pessimistic scenario predicted subsidence data and contours .................................................................................................... 38
Figure 16. Gippsland Basin Risk Study: 2056 realistic scenario predicted subsidence data and contours. Pessimistic and realistic scenarios coincide between the Lake Wellington and Rosedale Fault System, see Figure 17 ......................................................... 39
Figure 17. Gippsland Basin Risk Study: 2056 pessimistic scenario predicted subsidence data and contours .................................................................................................... 40
Figure 18. Study area map for the extreme wave prediction model ........................................ 41
Figure 19. The contributions to sea level extremes at the coast (after McInnes, et al., 2005) .... 42
Figure 20. Extreme wave heights and their return periods by CSIRO wave data .................... 44
Figure 21. Relation between significant wave height and wave period ................................ 45
Figure 22. Regional bathymetry derived from the Geoscience Australia GA 0.0025 (250 m) resolution digital elevation model. ................................................................. 47

Figure 23. 50-year-return wave height distribution under the current climate; highest wave path is from the southeast direction=120° (shown in the white arrows).............. 48

Figure 24. 50-year-return wave height distribution under the 2031 high sea level rise scenario; highest wave path is from the southeast direction=120° (shown in the white arrows). 48

Figure 25. 50-year-return wave height distribution under the 2056 high sea level rise scenario; highest wave path is from the southeast direction=120° (shown in the white arrows). 49

Figure 26. Gippsland Basin Risk Study, present day combined extreme sea level/storm tide/wave height contours (m)..................................................................................... 51

Figure 27. Gippsland Basin Risk Study; 2031 combined extreme sea level/storm tide/wave height contours (m). ......................................................................................... 52

Figure 28. Gippsland Basin Risk Study; 2056 combined extreme sea level/storm tide/wave height contours (m). ......................................................................................... 53

Figure 29. Gippsland Basin Risk Study: extents of data input to the subsidence model......... 56

Figure 30. A 3 arc second (90 m) DEM is used on shore. White colour indicates gaps in the elevation data............................................................................................................ 57

Figure 31. Area covered by the 0.1 arc second (90 m) DEM zoomed to the southern part of the cost line. White colour indicates gaps in the elevation data................................. 58

Figure 32. Area covered by the 3 arc second (90 m) DEM zoomed to the central part of the cost line. White colour indicates gaps in the elevation data..................................... 59

Figure 33. Area covered by the 3 arc second (90 m) DEM zoomed to the northern part of the cost line. White colour indicates gaps in the elevation data..................................... 60

Figure 34. Gippsland Basin risk study. Inundation risk due to predicted subsidence due to both scenarios for various times................................................................. 61

Figure 35. Gippsland Basin risk study. Inundation risk due to predicted subsidence under both hydraulic head scenarios for year 2031 zoomed to the southern part of the study area. .......................................................................................................................... 62

Figure 36. Gippsland Basin risk study. Inundation risk due to predicted subsidence under both hydraulic head scenarios for year 2031 zoomed to the central part of the study area. 63

Figure 37. Gippsland Basin risk study. Inundation risk due to predicted subsidence under both hydraulic head scenarios for year 2031 zoomed to the northern part of the study area. .......................................................................................................................... 64

Figure 38. Gippsland Basin risk study. Inundation risk due to predicted subsidence under both hydraulic head scenarios for year 2056 zoomed to the southern part of the study area. .......................................................................................................................... 65

Figure 39. Gippsland Basin risk study. Inundation risk due to predicted subsidence under both hydraulic head scenarios for year 2056 zoomed to the central part of the study area. 66

Figure 40. Gippsland Basin risk study. Inundation risk due to predicted subsidence under both hydraulic head scenarios for year 2056 zoomed to the northern part of the study area. .......................................................................................................................... 67
Figure 41 Gippsland Basin Risk Study sea level/storm tide/wave inundation risk predicted for various times. ................................................................. 68
Figure 42. Gippsland Basin Risk Study sea level/storm tide/wave inundation risk predicted for various times and zoomed to the southern coast part of the study area. ..................... 69
Figure 43. Gippsland Basin Risk Study sea level/storm tide/wave inundation risk predicted for various times and zoomed to the central coast part of the study area. .................... 70
Figure 44. Gippsland Basin Risk Study sea level/storm tide/wave inundation risk predicted for various times and zoomed to the northern coast part of the study area. ................... 71
Figure 45. Gippsland Basin Risk Study 2031 sea level/storm tide/wave plus subsidence inundation risk. Pessimistic and realistic scenarios coincide between the Wellington and Rosedale Fault System. ................................. 72
Figure 46. Gippsland Basin Risk Study: 2031 sea level/storm tide/wave plus subsidence inundation risk zoomed to the southern coast part of the study area. .......................... 73
Figure 47. Gippsland Basin Risk Study: 2031 sea level/storm tide/wave plus subsidence inundation risk zoomed to the central coast part of the study area. ............................ 74
Figure 48. Gippsland Basin Risk Study: 2031 sea level/storm tide/wave plus subsidence inundation risk zoomed to the northern coast part of the study area. Pessimistic and realistic scenarios coincide between the Wellington and Rosedale Fault System. .... 75
Figure 49. Gippsland Basin Risk Study: 2056 sea level/storm tide/wave plus subsidence inundation risk. Pessimistic and realistic scenarios coincide between the Wellington and Rosedale Fault System. ........................................ 76
Figure 50. Gippsland Basin Risk Study 2056 sea level/storm tide/wave plus subsidence inundation risk zoomed to the southern coast part of the study area. .......................... 77
Figure 51. Gippsland Basin Risk Study 2056 sea level/storm tide/wave plus subsidence inundation risk zoomed to the central coast part of the study area. ............................... 78
Figure 52. Gippsland Basin Risk study. 2056 sea level/storm tide/wave plus subsidence inundation risk zoomed to the northern coast part of the study area. Pessimistic and realistic scenarios coincide between the Wellington and Rosedale Fault System. ...... 79
Figure 53. DPI high resolution GPS subsidence measurement results. .............................. 86
Figure 54. Assume K=1.12x10^{-4} m/yr, aquifer thickness=1102 m, all compressible-overconsolidated sediments................................................................. 87
Figure 55. Ultimate settlement achieved by using a high permeability. K=1 m/yr, aquifer thickness=1102 m, consists of compressible and overconsolidated sediments. ......... 88
Figure 56. K=1 m/yr, aquifer thickness=570 m and compressible clay lenses thickness 299.5 m-overconsolidated sediments. Sands are given one tenth of clay compressibility. ... 88
Figure 57. K=1.12x10^{-4} m/yr, aquifer thickness=570 m and clay lenses thickness 299.5 m-overconsolidated sediments. Sands are given one tenth of clay compressibility. ....... 89
Figure 58. K=1.12x10^{-4} m/yr, aquifer thickness=570 m and clay lenses thickness 299.5 m. The pre-consolidation stress =100 m. Sands are given one tenth of clay compressibility.. 89
Executive Summary

The Latrobe Aquifer of the Gippsland supports a number of water related industries. Falling water levels in this region have been observed since the late 1960’s with associated impacts on irrigators and possibly the wider community through potential land subsidence. The “Hatton Report” conducted by the CSIRO Wealth From Oceans Flagship program (Hatton et al., 2004) concluded that these fluid extraction activities have geographically variable impact on the Latrobe Aquifer water levels. The Hatton report noted community concern regarding the related risk of coastal subsidence and inundation stemming from subsidence measurements at the Latrobe Coal Mines and a series of studies of subsidence risk in the Gippsland coast by SKM (Sinclair Knight Merz (2001a, b&c)). Limited rock property data and pore pressure depletion data was used in these studies. In an effort to reduce the resulting uncertainty and address the geographic variability of the subsidence along the coastline, the CSIRO Wealth From Oceans flagship program conducted this modelling that includes results from Hatton et. al. (2004) and Underschultz et. al. (2006). The Victoria Department of Primary Industries (Vic DPI) high resolution GPS ground level elevation monitoring program results were examined and contributed to constraining subsidence predictions. This study specifically incorporates the geographic variability of properties affecting subsidence along the coastline. In order to put coastal inundation risk due to subsidence in perspective with other coastal risks, this report also examines the risk of coastal inundation due to the 50-year-return storm tide and extreme wave in the context of climate change and rising sea level. A series of coastal inundation risk maps for the Gippsland Basin are the result of this study.

The decline of ground water levels implies increasing the stresses borne by the solid grains of the sediments –the effective stresses- resulting in a subsequent settlement. Due to their high permeability, sands respond almost immediately to fluid pressure gradients creating fluid withdrawal (pressure drop) and increasing effective stresses. Low permeability compressible clays and coals on the other hand, respond to the resulting pore pressure decrease and effective stress increase in the surrounding sands by larger deformations taking place over a longer period of time. Previous subsidence calculations by CSIRO have been expanded in this study to incorporate pore pressure and lithology data from a large coastal region of the Gippsland Basin. Two hydraulic head profiles that bracket a range of possible scenarios for aquifer depletion (a “realistic” and a “pessimistic” scenario) have been used for the subsidence prediction calculations. These subsidence predictions are “ultimate settlements” calculations that are sensitive to many parameters that are constrained by the best knowledge at the time.

Deterministic rock properties proposed by Sinclair Knight Merz (2001a) for the Yarram area have been adjusted in this study to account for aquifer thickness and confinement that vary along the coastline. The maximum subsidence predicted under the pessimistic hydraulic head scenario (extreme aquifer depletion scenario) was at the well where the aquifer is thickest and the pressure depletion is largest, Golden Beach West 1, and was 1208 mm by the year 2056. The subsidence predicted at the same location and time within the realistic depletion scenario was 480 mm. Such values for the regional subsidence might impact on the serviceability of pipelines and infrastructure.

Land subsidence measurements produced by the Victorian DPI high resolution GPS study between June 2004 and November 2005 have been examined. Both the predicted realistic subsidence values modelled here, and the DPI measurements, were within the error of the measuring gauges. Although, this fact together with the type of subsidence predicted (ultimate subsidence) prohibits the use of these measurements to back estimate (further refine) the mechanical parameters at various locations, these measurements confirmed the assumption that the aquifer is overconsolidated. Further GPS measurements over a longer period would be valuable for calibrating the mechanical parameters and detecting the transition to the normal consolidation behaviour.
Subsidence predictions have been linked in a Geographic Information System and overlain with SRTM Digital Elevation Model (DEM) of the land surface. Inundation resulting from the predicted subsidence alone was of negligible spatial extent.

The Gippsland extreme wave conditions are simulated. It is concluded that parts of the Gippsland coastline will be inundated due to the modelled 50-year-return storm tide and extreme wave. The simulations include the sea level rise in the future resulting from climate change. The risk of inundation will increase from present time to year 2056. The predicted inundation is located mainly at the borders of the existing lakes between the lakes and the coastline. The width of the inundated regions, in many areas, exceeds one km even within the current mean sea level scenario. Inundated regions > 2 km width are identified as a risk within the 2056 mean sea level scenario particularly in the area north of the Lake Wellington Fault System. These calculations have a significant degree of uncertainty particularly due to the limited duration of the historical data used in the simulation.

Both the subsidence model results and the predicted future sea level changes and extreme storm wave height data have been linked in a Geographic Information System (GIS) and overlain with the same Digital Elevation Model of the land surface, to produce inundation risk maps.

The risk maps suggest that the risk of coastal inundation due to subsidence is small compared to that of storm wave and tide. Subsidence contribution to inundation (in value not spatial extent) does not exceed 20% in most of the regions. In the areas at higher inundation risk, between the Lake Wellington and the Rosedale Fault Systems, this contribution is about 1% which is minimal compared to the sea level contribution. Whilst it would be possible to further reduce the uncertainty in expected subsidence with rock property measurements and a better stratigraphic model, it is expected that these would only lead to marginal gains in improving inundation risk prediction. This is mainly due to the large uncertainty in the coastal digital elevation model.

Reduction in the uncertainty of the predicted subsidence can be achieved by obtaining a more accurate characterisation of the stratigraphy and rock properties at various boreholes along the coastline. A three-Dimensional (3-D) numerical subsidence simulation model would be needed instead of the calculations conducted at numerous discrete wells along the coastline. The coastal subsidence risk map produced in this study could be used to guide the sample collection to areas of highest risk. The actual 3-D pressure depletion profile - characterized in the first phase of this research- and an improved stratigraphic and structural geology model - with details of interbedded soft layers - could be built into the model. The area of the numerical simulation of the subsidence would need to be extended to include the region north of the Lake Wellington Fault System. It could include the possible mitigating impact of offshore CO2 geosequestration that might allow a faster recovery of aquifer pressure.

After the completion of this report a new set of ground surface elevation measurements were made available to us by the Victorian DPI high resolution GPS program Epoch 3 (2007) (see Addendum). The survey showed that there is no statistically significant subsidence measured. As the subsidence predicted between June 2004 and May 2007 will not exceed the measured values. It was not possible to calibrate the mechanical parameters used in the modelling based on these measurements (considering the realistic scenario). The high resolution GPS measurements program needs to continue until measurements within the accuracy range of the gauges are obtained. These measurements combined with detailed knowledge of the stratigraphy along the coastline can generate more accurate predictions to the subsidence.
1 INTRODUCTION AND BACKGROUND

An investigation and overview of previous work on the falling water levels in the Latrobe Aquifer system of the Gippsland Basin was described by the “Hatton Report” in 2004 (Hatton et al., 2004). It concluded that significant withdrawal of fluid resulted in a complex pattern of pressure decline in the Latrobe aquifer. This pattern reflects both the structural complexity of the basin as well as the impacts of withdrawals by the mining, irrigation and offshore oil and gas industry. A review of subsidence modelling and monitoring indicated unclear history of subsidence except the well-documented subsidence around the coal mines of the Latrobe Valley. To further understand the controls on falling water levels and risks of subsidence and to move towards a mitigation strategy, the Hatton Report made the following recommendations.

1. Expand the preliminary analysis and conduct a detailed pressure decline study of the Gippsland Basin using all relevant onshore and offshore wells and historical production and pressure data. A better appreciation of the basin’s structural and lithological complexity is required, followed by a regional modelling study that incorporates this added detail.

2. Review the current groundwater level and formation pressure monitoring network, including an assessment of required refurbishment of wells.

3. Identify critical monitoring wells and install pressure transducers and loggers to measure water levels and pressures at more frequent and regular intervals.

4. Conduct a more comprehensive risk assessment study of potential subsidence in the coastal region, including petrophysical measurements on core linked with further subsidence modelling.

5. Review the option to use satellite-based subsidence monitoring technology.

6. Development of an integrated decision support and groundwater management system for the Gippsland Basin.

The Victorian Department of Primary Industries (Vic DPI) has reviewed point 5 and concluded that the satellite-based technology would not work satisfactorily in this situation because insufficient large fixed objects (such as buildings) occur across the region of interest to achieve the desired precision of measurement. Alternatively Vic DPI has embarked on a 5 year monitoring program using high resolution GPS technology.

At the time of writing this report, the Victorian Department of Sustainability and Environment has put out to tender a project designed to address point 2 of the Hatton Report recommendations above.

After the completion of the Hatton Report, the study by Underschultz et. al. (2006) focused on three issues:

1. Uncertainty in certain aspects of the hydrodynamic analysis in the Hatton Report due to lack of formation pressure data.

2. Uncertainty in the location and vertical extent of basin forming faults.

3. Uncertainty in previous subsidence models.

Results of the study are summarized as follows.

1. Additional pressure data collected for the offshore has both confirmed and better defined the region and extent of aquifer pressure depletion. This now includes the area of Kingfish and West Kingfish. While no additional data for the time since 1990 was publicly available, an extrapolation of historic data in two key areas (Fortescue and Kingfish) was conducted to estimate the possible severity of present day depletion.

2. Examination of onshore seismic data has confirmed the location and extent of basin forming fault systems on the boundaries of the Seaspray Depression. Previously, these were suspected to be responsible for compartmentalizing parts of the Latrobe Aquifer system (Hatton et. al., 2004).
This confirms that the geographic variation in the degree of pressure depletion observed in the Hatton Report is likely related to faulted domains of the Latrobe aquifer. Within each domain, the relative cause of depletion is different. However, seismic data frequency and quality is insufficient to perform a complete shale gouge ratio determination on the fault zones for independent quantification of each faults seal capacity.

3. First stage simulations of subsidence, with parameters identical to the previous deterministic model (Sinclair Knight Merz, 2001a), produced similar but not identical results (the CSIRO model predicted only half the subsidence reported in the SKM report). The most likely reason for the discrepancy is ambiguity with respect to the preconsolidation stress. Sensitivity analysis has shown that uncertainty in the preconsolidation stress creates the most variation in predicted total subsidence. This uncertainty may be reduced if burial history curves for the basin can be determined.

Within the project reported here, the recommendations in point 1 and parts of point 4 in the above list from the Hatton Report, have been addressed. In this phase of the research, the numerical subsidence model (from Underschultz et al. 2006) will be expanded to incorporate the entire coastal region described in the Hatton Report, Figures 1 and 2. Two pressure depletion profiles bracketing the possible scenarios of pressure depletion will be input to the numerical simulation. Mean mechanical rock properties proposed by Sinclair Knight Merz (2001a) will be scaled to account for varying aquifer thickness and confinement along the coastline. In order to put the inundation risk due to subsidence in perspective with other coastal inundation risks, the simulations of subsidence will be conducted in conjunction with storm tide and extreme wave conditions in the context of climate change and mean sea level rise scenarios. The subsidence and storm tide and extreme wave modelling results were linked in a Geographic Information System (GIS) and overlain with a Digital Elevation Model (DEM) of the land surface. This resulted in the development of coastal subsidence and inundation risk maps.

2 GIPPSLAND HYDRODYNAMIC SYSTEMS

The hydrodynamic systems of the Gippsland Basin were described in detail by Hatton et al. (2004) and Underschultz et al. (2006). No further hydrodynamic work is conducted in the stage of work reported on here, however, a summary of the pre-production and post-production hydrodynamic systems is provided for the reader in brief. All hydraulic heads are calculated as fresh water relative to mean sea level elevation.

2.1 Pre production hydrodynamic system

There are competing basin-scale driving forces causing flow in the Latrobe Aquifer system in the Gippsland Basin. High hydraulic head extending eastwards from onshore subcrop reflects gravity driven freshwater recharge from the west (Figure 3). Higher hydraulic heads are particularly prominent within the boundaries of the Seawpray Depression and the western part of the offshore Central Deep. Compaction driven dewatering of the offshore sedimentary pile is expressed as regions of high hydraulic head (roughly those areas greater than 50m head) in the eastern part of the study area. In the central part of the Central Deep, there is a region of less than 30m of hydraulic head that forms a groundwater sink into which the formation water flows. It appears that this sink is connected to the Darriman Fault System on the southern edge of the Central Deep. The sink has several “arms” or “troughs” of low hydraulic head which extend to the north and east. These tend to pass between the main hydrocarbon pools. A major trough extends northwards between the Snapper and Marlin fields and a second one extends eastwards between the Fortescue and Kingfish fields. It is postulated that this sink directs formation water to discharge from the Latrobe aquifer up along the Darriman Fault System either to an upper aquifer or even to the seabed.
2.2 Post production hydrodynamic system

The distribution of hydraulic head for the Upper Latrobe Aquifer System in the mid 1980s (Figure 4) shows that by this time, production from the Halibut, Fortescue, Cobia, Mackerel and Kingfish fields has resulted in a localized decrease in the hydraulic head surface for the Upper Latrobe Aquifer System. In the area of Fortescue, this hydraulic head reaches about -50 m, and about -20 m at Kingfish. At this time, the most intense part of the depression is localized, with the Selene 1, Angler 1 and Anemone 1A wells to the southeast being relatively unaffected, having hydraulic head still at about 50 m.

The area on the southern edge of the Central Deep previously described as a possible discharge region (Figure 3) is of particular interest. By the mid 1980’s the flow direction in this region is reversed. As this trend of aquifer depletion and dropping hydraulic head continues, the previously discharge related zone along the Darriman fault bend may reverse and eventually be contributing as recharge to the Latrobe Aquifer system.

The distribution of hydraulic head for the Upper Latrobe Aquifer System in the mid 1990s is shown in Figure 5. The dashed hydraulic head contours in Figures 4 and 5 indicate that data control is limited and consequently uncertainty in the hydraulic head distribution is high. Whilst there is less data control in the mid 1990s than the mid 1980s, the mid 1980s map can be used as a guide for the general shape of the hydraulic head distribution in the mid 1990s. This is used in combination with a few control points from Halibut and Kingfish development wells, to estimate the mid 1990s hydraulic head distribution.

With continued oil production, the hydraulic head depression centred near the Fortescue to Kingfish fields becomes greater. In the Fortescue area, the hydraulic head is below -70 m and less than -40 m in the Kingfish area. The area of low hydraulic head also now extends north and west to include the Marlin, Snapper and Barracouta fields. Regionally, there is a continued gradual decline in the hydraulic head of the Upper Latrobe Aquifer System with data at locations such as Dolphin dropping from 26 m in 1989 to 7 m of hydraulic head in 1997.

There are almost no present-day offshore pressure data available in the public domain. In the absence of evidence to the contrary, it is reasonable to assume that the trend of decreasing hydraulic head with time observed during the first 20 years of hydrocarbon production continues to the current day. It is then possible to estimate the present day hydraulic head distribution using the mapped distribution for the mid 1990’s and the observed trend in decreasing hydraulic head with time during the 1990’s. Using the procedures, outlined in Underschultz et al. (2006), the estimated hydraulic head distribution for year 2004 is shown in Figure 6. The map in Figure 6 shows a continued decrease of hydraulic head particularly around the Kingfish and Fortescue areas. Contours in the offshore are displayed as dashed lines to indicate that the hydraulic head distribution is only an estimate based on extrapolation of pressure trends.

2.3 Hydraulic scenario models input in the Geomechanical subsidence model.

For the wells simulated by the Geomechanical subsidence model, the hydraulic head data sets available between June 1970 and February 2004 were used. Extraction (sinks) from the aquifer consists of offshore oil, gas and water extraction and onshore extraction from rural and industrial users. Sources of water influx into the aquifer are infiltration from precipitation and compaction dewatering processes. Each of these parameters is quantified using available data.

2.3.1 Offshore sinks

Estimates from the producers of the offshore oil, gas and water suggest that oil and water production will cease around 2015. Gas production is already on the decline and is estimated to cease by 2038.
Current data for oil and gas has been extrapolated along their existing production decline curves to reach zero in 2015 for the oil and 2038 for the gas.

2.3.2 Onshore sinks

The main sources of onshore water extraction in the basin are coal mine dewatering in the Latrobe Valley, and irrigation and industrial use in the Yarram area and greater Seaspray Depression. Hatton et al. (2004) has shown that in the short term (since 1969) the Rosedale Fault System effectively isolates the hydrodynamic system in the Latrobe Valley/North Strzelecki Terrace from that in the Seaspray Depression/Central Deep to the south. For this study, it has been assumed that the Rosedale Fault System is a no-flow boundary such that any extraction to the north of the fault system is unlikely to have a significant impact on aquifer recovery south of the Rosedale fault system.

Historical data on water extraction for irrigation and industrial use in the Yarram region from 1969 – 2000 indicated an increasing linear trend for onshore water extraction (Hatton, et al., 2004). To ensure the sustainability of the aquifer, it is assumed that onshore water extraction follows the linear trend until it reaches a maximum of 12,500 ML. At this point, onshore water extraction of 12,500 is held constant into the future.

The estimate of 12,500 ML maximum annual extraction was based on figures from the Gippsland Groundwater Issues Technical Working Group Report to the Steering Committee (Evans, 1999). According to the report, the total extraction licenses held are for 9,000 ML, with average annual usage estimated in 1998 to be only about half of the entitlement, i.e. 5,000 ML. The other extractors from the Latrobe Group aquifer are urban/industrial users who extract about 3,500 ML per year. Therefore, it was assumed that onshore water extraction would continue to increase until agricultural users have maximised their extraction licenses fully (9,000 ML) and all urban/industrial usage is accounted for (3,500 ML). Hence, once the total onshore water extraction reaches a yearly extraction of 12,500 ML, this is assumed to be held constant into the future.

2.3.3 Aquifer recharge estimates

The determinations of aquifer recharge are based on published estimates (Sinclair Knight Merz, 1999), and their results imply that:

1. Recharge is affected only by onshore water extraction, i.e. increased onshore water extraction would increase the infiltration/runoff ratio of total precipitation.
2. Offshore fluid production occurs too far away from the recharge zone to have a significant impact on recharge rates.

Given this, Leong (2006) derived the following equation for the relationship between onshore water extraction and recharge rates, where:

\[
\text{Recharge Rate} = 1.528 \times \text{Onshore Water Extraction} + 9416
\]

This relationship was used to estimate onshore recharge to the Latrobe Aquifer system for the water balance. As onshore water extraction is limited to 12,500 ML/yr, this would result in a maximum recharge rate of 28,516 ML/yr. This may or may not exceed the maximum physical recharge limit (i.e. rainfall). However, it fits within other published estimates and variations in excess of rainfall may be attributed to leakage from overlying aquifers.

2.3.4 Compaction dewatering

Another source of recovery to the aquifer is compaction dewatering into the Latrobe Aquifer system in the offshore. There is a westwards flux of formation water within the aquifer in the offshore regions due to the compaction dewatering of shales and muds. As the shale/mud layers compact, formation water is squeezed out vertically into adjacent aquifers. While at any one location this flux is small, it occurs across the entire geographic area of the compacting shale/mud layer so the cumulative contribution of formation water to the aquifer can be large.
The volume of water contributed to the aquifer is estimated by selecting a line of cross-section through the basin roughly perpendicular to the flow direction. The flux is then calculated across the line of section based on the hydraulic gradient, the cross sectional area of the aquifer and an estimate of the permeability. This forms an estimate of total contribution of shale dewatering to the aquifer, since this flow system is not driven by any other recharge process. The flux is calculated for virgin hydraulic head conditions since this should represent the long term contribution of formation water to the aquifer. The flux into the Upper Latrobe aquifer due to compaction dewatering was estimated to be 3,050 ML/yr. The flux into Lower Latrobe due to compaction dewatering was estimated to be 1,527 ML/yr. Full details of how the flux was calculated can be found in Leong (2006).

2.3.5 Hydraulic head modelling scenarios

The Geomechanical subsidence model requires input of the predicted hydraulic head change in the aquifer. We consider two scenarios in the modelling: In the first scenario we assume continuation of the observed pore pressure decline following the same trend due to the continuation of all the current extraction processes (onshore coal mining dewatering, agricultural and industrial water extraction, offshore oil, gas and water production) leading to a “pessimistic” scenario. Linear regression of available hydraulic head data sets starting at 1970 and ending at 2004 was used to predict future hydraulic head until year 2056.

In the second scenario, we consider pressure recovery due to the expected cessation of oil and gas production by years 2015 and 2038 respectively and include onshore infiltration from precipitation and the offshore compaction recharge into the Latrobe Aquifer. This scenario is a more “realistic” scenario than the first one. Both of these scenarios provide a bracket for the expected pressure drop and the resulting predicted subsidence.

2.3.6 Other possible hydraulic head scenarios

It should be noted that there are other, worth examining, hydraulic head scenarios that are not included in this study. Namely the possibility that the offshore Gippsland Basin may eventually be utilized for deep geological storage of CO₂ which would accelerate the aquifer pressure recovery and reduce the predicted subsidence. In this sense, a third “optimistic” subsidence scenario would be one of zero if not negative eventual net subsidence. Predicting and modelling this scenario was not within the scope of this study.
Figure 1. Gippsland Basin Risk Study: topography and bathymetry
Figure 2. Gippsland Basin Risk Study: mines and oil and gas fields in the study area
Figure 3. Pre-Production hydraulic head distribution for the Upper Latrobe Aquifer System (after Hatton et al., 2004).
Figure 4. Mid 1980s hydraulic head distribution for the Upper Latrobe Aquifer System (after Underschultz et al., 2006).
Figure 5. Mid 1990s hydraulic head distribution for the Upper Latrobe Aquifer System (after Underschultz et al., 2006).
Figure 6. Estimated hydraulic head for the Upper Latrobe aquifer in 2004 (after Underschultz et al., 2006).
3 COASTAL SUBSIDENCE

3.1 Background

Concerns of possible coastal land subsidence due to pressure decline in the Latrobe Aquifer have been discussed by Hatton et al. (2004). Sinclair Knight Merz (2001c) modelled subsidence at the Golden Beach West 1 well of the Gippsland Coast and concluded that depending on the model assumptions there is a 10% chance that subsidence could exceed 4 meters by year 2069. These calculations have been conducted using Terzaghi’s theory of one-dimensional consolidation (e.g. Scott, 1980) within a statistical approach for input parameter selection. Hatton et al. (2004) recommend that a more comprehensive risk assessment study of potential subsidence in the coastal region should include petrophysical measurements and further subsidence modelling. Both Hatton et al. (2004) and Sinclair Knight Merz, (2001a, b &c) identify the lack of measured physical rock parameters for the Latrobe Aquifer as contributing the most uncertainty to numerical simulation results. Furthermore, the subsidence risk is expected to be geographically variable along the Gippsland Coast due to variations in:

1. The degree of water level decline (hydraulic head) in the Latrobe Aquifer System.
2. Coastal topography.
3. The composition of the Latrobe Aquifer lithology (rock type) and its associated rock properties.

First stage simulations of subsidence conducted by CSIRO (Underschultz et al., 2006), with parameters identical to the previous deterministic model by Sinclair Knight Merz (2001a), produced similar but not identical results as the CSIRO model predicted only half of that subsidence. The most likely reason for the discrepancy is ambiguity on the preconsolidation stress. The sensitivity analysis has shown that uncertainty in the preconsolidation stress creates the most variation in predicted total subsidence.

3.2 Objectives

This study aims at assessing and quantifying the geographically variable risk of subsidence along the Gippsland Coast and hence reducing the uncertainty in predicted subsidence described by Sinclair Knight Merz (2001c). The study area extends from South of the Darriman Fault System to the Lake Wellington Fault System as shown in Figures 7 and 8. Pore pressure measurements and available aquifer thickness data were used for ultimate subsidence predictions at various locations of the coast. Observational data from the high resolution GPS monitoring sites operated by Victoria DPI between June 2004 and November 2005 has been examined in this study.

3.3 Model assumptions

Formation pressure and aquifer thickness/lithology data for this investigation were collected from the Victorian DPI Well Completion Reports available in the public domain. The pressure data sets were available for the wells in the blue circles in Figure 7. Aquifer thickness/lithology data was available for the wells in red circles. Those data sets provide mainly the aquifer thickness and the thickness of the overlying layers. For wells with pressure data but no thickness/lithology information, thickness/lithology from the nearest neighbouring well was used. For example, some wells may not penetrate the entire Latrobe Aquifer so aquifer thickness could not be determined.

Subsidence results from increasing the stresses borne by the solids part of the sediments (the effective stress). This can happen when an additional load is applied to the sediments or when the fluid that was bearing part of the original load on the sediments escapes or gets pumped out of the sediments (Underschultz et al., 2006). The components of any subsidence prediction model are as follows:
1. Sediments compressibility
2. Hydraulic conductivity of compressible layers
3. Preconsolidation stress
4. Sediments thickness
5. Hydraulic head decline

Sands have very high permeability and low compressibility (at maximum, 10 times less than that of clays) and they settle immediately in response to the pressure drop and the resultant effective stress increase due to fluid withdrawal. Clays are very compressible and of low permeability which results in a delayed response to the effective stress increase on the sands above and below them. The Latrope Group consists of interbedded sands, clays and coal seams. Owing to the lack of data and lack of geophysical log interpretations which prohibits quantification of the amount of these compressible clays and coal seams we do not consider the details of the compressible but low permeability layers within the aquifer. We hence treat the aquifer thickness as a compressible layer with effective compressibility higher than that of sands and lower than that of clays.

Due to the above lithological simplification and our interest in extreme scenarios we calculate the ultimate subsidence. This implies that the extra time the compressible material takes to settle is neglected. This prohibits accurate consideration to the time needed to achieve the predicted settlements.

The preconsolidation stress is the maximum stress the sediments experienced in the past. Exceeding this stress implies a significant increase in the material compressibility and a transition into a range of high and mainly irrecoverable settlements in response to effective stress increase.

It was established by Sinclair Knight Merz (2001a, b & c) that, due to the past burial history and sea level change, and due to the lack of evident subsidence at the Gippsland Coast, that the aquifer is overconsolidated by up to 4000 KPa in the Latrobe Valley and by analogy also in the Yarram region. This means that the aquifer has experienced in the past a stress (preconsolidation stress $\sigma'_c$) higher than current time stresses. As a result, they estimated the average preconsolidation stress at Yarram to correspond to 100 m pressure head depletion and at Latrobe to 190 m. At Golden Beach West 1, this was estimated to correspond to 200 m. Sinclair Knight Merz (2001c) suggests that defining the strata to be overconsolidated in the central coastal region is more problematic. Evidence for the overconsolidation of the Late Cretaceous to Tertiary sediments of the Latrobe Formation can be found by fault analysis and in the tectonic history of the offshore Gippsland Basin. The majority of faults observed on the seismic lines display normal offsets, but are frequently associated with folds, notably in their hanging walls and above the faults themselves. The geometry of these faults and associated folds is strongly suggestive of compressional reactivation (inversion) of a previously extensional normal fault system (Underschultz et al. 2006). This is supported by minor reverse offsets on some faults. While it is true that observed inversion on the major basin forming fault zones does not necessarily imply similar inversion away form the fault zones (O’Brien, Victoria DPI, personal communication), this chronology conforms to the previous tectonic assessments of the Gippsland Basin. For example, Willcox et. al. (1992) states "Tectonically, the Gippsland Basin has undergone multiple phases of deformation. Two major structural styles have been described for the offshore part of the basin: 1) poorly-defined extensional tilt-blocks with normal rotational, and accommodation faults, active principally during basin formation and basin subsidence (Early Cretaceous to Early Eocene) and, 2) sub-parallel anticlines and shear faults generated by Tertiary compression (Threlfall et. al., 1976) and thought by Etheridge et al. (1985) to be related to a reactivation of Early Cretaceous normal and transfer faults."

Considering that the maximum effective stress changes due to the pressure head depletion within the assumed scenarios within this study are less than these limits (particularly the 200 m estimated at Golden Beach West 1), we therefore accept that the aquifer has been subjected to higher stresses in the past than the current and future predicted stresses. As a result, we use the elastic mechanical parameters throughout the modeling.
3.4 Water level prediction scenarios

In the simulated wells, pore pressure measurements were available between June 1970 and February 2004. We consider two scenarios in the modelling that provide a bracket for the possible pressure drop in the Latrobe Aquifer and the subsequent subsidence.

Scenario 1: In the first scenario we assume continuous decline in the pore pressure due to the continuation of all the current extraction processes (onshore coal mining dewatering, agricultural irrigation activities and commercial water extraction, offshore oil, gas and water production) leading to a “pessimistic” scenario (worst scenario) with high head losses. This is achieved using linear regression and extrapolation of the available pressure data.

Scenario 2: In the second scenario, we consider pressure recovery due to a combination of the expected cessation of oil production by year 2015 and the expected decline of gas extraction processes and the onshore infiltration from precipitation and the offshore compaction recharge into the Latrobe Aquifer. This scenario is considered a more “realistic” scenario than the first one.

There is also the possibility that the offshore Gippsland Basin may be utilized for deep geological storage of CO$_2$ which would accelerate the aquifer pressure recovery. In this sense, a third “optimistic” scenario could be one of negligible or zero net subsidence. Such a scenario is not considered by this study.

The extent of the study areas for the pessimistic or realistic scenarios is indicated in Figure 8. At the time-scale of our modelling, the Rosedale Fault System is considered a no flow boundary (Hatton et al. 2004, Undeschultz et al., 2006) that isolates the hydraulic systems in The North Strzelecki Terrace to the North from the hydraulic systems in the Central Deep/Sea Spray Depression to the south. North of this fault system pressure draw down is impacted mainly by coal mine dewatering. The study conducted by Leong (2006) where the realistic hydraulic scenario was predicted, stopped south of the Rosedale Fault System. In the area north of this fault system coal mining and associated aquifer dewatering is expected to continue in the foreseeable future and hence we predict the continued decline of the hydraulic head in that area as per the pessimistic scenario only.

3.5 Geomechanical modelling approach

We calculate the ultimate subsidence due to an increase in the effective stress of the aquifer. The increase in the effective stress at a specific location in the aquifer from an initial value $\sigma'_0$ to a final value $\sigma'_{fs}$ is generated by pore pressure depletion resulting from fluid extraction. A reduction or increase in the pore pressure ultimately causes an equal increase or reduction in the effective stress (the stress born by the solid grains) as the total stress remains constant. As the formation is overconsolidated, the elastic coefficient specific storage ($S_{ske}$) can be used in the following equation (Underschultz et al., 2006) to calculate the ultimate subsidence value ($\Delta H$)

$$\Delta H = H_0 S_{ske} / \gamma_w \left( \sigma'_{fs} - \sigma'_0 \right), \quad \sigma'_{fs} < \sigma'_0$$

(2)

$$S_{ske} = \frac{\gamma_w}{E_{me}}$$

(3)

where $\gamma_w$ is the unit weight of water, $E_{me}$ is the constrained elastic stiffness modulus (equals inverse of the elastic modulus of volume compressibility), where the term elastic refers to recoverable mechanical behaviour. It is clear from eq (2) that the predicted subsidence is directly related to the
aquifer thickness affected by pressure drop, the effective stress increase (brought in by fluid withdrawal) and the sediments compressibilities. Inherent in this equation is the assumption that the sediments are overconsolidated.

3.5.7 The mechanical parameters

We use eq (2) to calculate the amount of subsidence as fluid extraction or recovery takes place. We start with the Sinclair Knight Merz (2001a) mean value of the mechanical parameter which was implemented in the subsidence calculation at Yarram: Alberton 3 and was taken from a study by Helm (1984) at Latrobe Valley Coal Mines. The value of this parameter is

\[
S_{skm} = 2.0 \times 10^{-5} \text{ m}^{-1}
\]

\[
E_{mc0} = 0.5 \text{ GPa}
\]

As mentioned earlier, the mechanical parameters are usually sensitive to the sediments type (e.g. for intact clays E can be 0.3 GPa, for intact sandstone E can be 20 GPa). In our case, the aquifer is sand interbedded with clay lenses and coal seams. The exact determination of aquifer compressibility requires clear knowledge of the lithology. This information was unavailable during the course of the research so we used a simple lithology.

A map of the aquifer thickness from Mehin (1995) is shown in Figure 9. Note that the thickest Latrobe Strata (>1 km) occurs along the coastline just south of the Rosedale Fault. This is also where the sandy strata of the Golden Beach Group occurs directly underlying the Latrobe Gp which provides additional thickness to the aquifer system (see Figure 10). It should be noted that we considered the “Aquifer” to be defined as being between the base of the Lakes Entrance Fm and the first occurrence of a thick mud or shale layer below the Latrobe Gp strata. In some locations this corresponds to the top of the Strzelecki Gp and in other locations it may include some or all of the sandy Golden Beach Gp (see Figure 10). Sinclair Knight Merz (2001c) describes the Latrobe strata at Golden Beach to be over 1600 m but with a portion of that likely to be sealing. There remains some uncertainty in the effective aquifer thickness for the Latrobe Aquifer strata near Golden Beach. Without a vertical set of formation pressure measurements, the actual effective aquifer thickness remains speculative.

In this section, we calculate the cumulative subsidence for both the pessimistic and the realistic scenarios with the temporary crude assumption that the value of each mechanical parameter represents the aquifer everywhere along the coastline. Our aim is to show the importance of the mechanical parameters estimation. In the case of the realistic scenario, the aquifer experiences incremental swelling due to the predicted pressure recovery as explained in section 2.3. The results of the calculation are shown in Table 1.

As expected, the calculation predicts larger subsidence for the pessimistic extraction scenario compared to the realistic extraction/recovery scenario. In the realistic scenario, subsidence reduces in year 2056 compared to year 2031 as the pressure head recovery progresses, while in the pessimistic scenario subsidence continues to increase with time due to the continuous loss of pressure head. This is a direct response to the pressure profiles adopted within these scenarios. For both scenarios in years 2031 or 2056, the largest subsidence is predicted at Golden Beach West 1 where the aquifer is thickest. In the pessimistic scenario this value is 2514 mm and 3509 mm in years 2031 and 2056 respectively, while these figures are 1492 mm and 1394 mm for the realistic scenario. This is in accordance with equation (1) and is mainly due to using the same compressibility everywhere on the coastline.

3.5.8 Reducing the uncertainty in the mechanical parameter

In addition to the simplified lithology of the Latrobe Aquifer, it is very unlikely for the same type of rock to respond to the same stress increment in a unique manner when it has been in equilibrium at varying depths in the ground. Rocks at higher depths usually have higher elastic moduli. As a result
we scaled down the mechanical stiffness $E_{me}$ used by Sinclair Knight Merz (2001a) at Yarram, where the aquifer is very thin and shallow, following two methods as follows.

**Method 1 (M1a & M1b)**

Acar and El-Tahir (1986) has shown that the mechanical stiffness $E$ of artificially cemented sands has been shown to increase with effective confining pressure $\sigma_c$ according to a power law with exponent $n=0.43$. They gave the following relation.

$$E = E_0 \sigma_c^n$$

$$n = 0.5 - 0.2$$

We tested varying the constrained modulus of elasticity $E_{me}$ used in the subsidence calculation with the effective confining pressure at either the centre (method M1a) or top (method M1b) of aquifer using eq (5) with an average value of $n=0.35$. Table 2 shows the aquifer thickness and the total thickness of the overlying layers. The overlying layers are saturated with water. A density of 2.4 kg/m$^3$ is used to calculate the total vertical stress at the top or centre of aquifer. In calculating the effective confining pressure $\sigma'_c$ in columns 7 and 9 of Table 2, we used a $k_0$ (ratio of effective mean horizontal to vertical stress) value of 0.5 (this is deemed suitable for sandstones with friction angle of 30º) to calculate the horizontal stresses $\sigma'_h$.

$$\sigma'_h = k_0 \sigma'_v$$

$$\sigma'_c = \frac{\sigma'_v + 2\sigma'_h}{3}$$

We have then scaled up the modulus $E_{me}$ and hence scaled down $S_{ske}$ using an average exponent of 0.35 (remember the direct inverse relation between $E_{me}$ and $S_{ske}$ eq (3)). These scaled values for $E_{me}$ and hence $S_{ske}$ using the mean confining pressure at the centre or top of the aquifer are shown in Table 3.

**Method 2 (M2)**

Helm (1976) reports that, using constant skeletal specific storage coefficients ($S_{ske}$) overestimates the ultimate predicted subsidence by 30-50%, Helm accordingly suggests scaling this parameter down as the effective vertical stress increases. Since we have started with one value for $S_{ske}$ that we have used throughout the Gippsland Basin, we thought it would be logical to scale down this mechanical parameter with the vertical effective stress at the centre of the aquifer that differs from well to well depending on the thickness of the aquifer and overlying layers. Accordingly we have reduced $S_{ske}$ (and hence increased $E_{me}$) with the increase of the effective vertical stress $\sigma'_v$ at the centre of the aquifer. The scaled values for $S_{ske}$ and $E_{me}$ are shown in Table 3 under method 2.

$$S_{ske} = CC^*/\sigma'_v$$

$$CC^* = S_{ske}/\sigma_0$$

### 3.5.9 Vic DPI ground elevation measurements

The Vic DPI conducted highly accurate ground elevation measurements in the Gippsland Basin region to identify if ground subsidence is taking place. The location of the monitoring stations is shown in Figure 11 as red dots. The results of the monitoring survey between June 2004 and November 2005 concluded that no significant subsidence has been detected at the monitoring stations. We examined the results of this survey which are listed in Table 4. Since the measuring devices used in this survey have an accuracy (standard deviation $\delta_1 = 6$ ) of 6 mm, if we assume a normal distribution, then the
measured subsidence value $x$, which is the difference between readings of two devices, has accuracy of $\delta = 8.5$ mm where $\delta$ is defined by (e.g. Ross, 2000, Spiegel, 1975)

$$\delta = \sqrt{\delta_1^2 + (-1)^2 \delta_2^2}$$  \hspace{1cm} (8)

If we are to have a mean subsidence measurement of zero mm then we can be 95% confident that any measurement $x$ within the range in eq (9) indicates that the subsidence $x$ is statistically insignificant (negligible).

$$1.96\delta \geq x \geq -1.96\delta$$  \hspace{1cm} (9)

These bracket values are

$$16.6 \text{ mm} \geq x \geq -16.6 \text{ mm}$$  \hspace{1cm} (10)

Hence any subsidence measurement below 16.6 mm can be considered as less than the accuracy limit of the measurement devices and therefore an unreliable value.

### 3.5.10 Comparison of Vic DPI measurements and the model predictions

The Vic DPI measurements and the calculated values of subsidence within the period from June 2004 to November 2005 are shown in Table 4. These results were compared with the realistic predicted subsidence at the nearest well (as not all the data locations agree), Figure 11. In Table 4 we show the predicted realistic subsidence values using the unscaled and the scaled mechanical parameters according to methods 1 and 2 explained above. It is obvious that the scaling of the mechanical parameters according to method 2 predicts the smallest subsidence. These subsidence values are below 16.6 mm for all cases. As a result, in the rest of the calculations we have decided to adopt scaling the mechanical parameter according to method 2.

With this knowledge of the Vic DPI measurements, it was confirmed that the sediments must be overconsolidated. It was not possible to calibrate the mechanical parameters of the study as

1. The realistic model predictions and the DPI measurements were both within the DPI measurement errors.
2. Our predictions are ultimate subsidence rather than the time dependent subsidence due to the lack of stratigraphic data determining the thicknesses of compressible and less compressible layers in the aquifer.

The values for $S_{ske}$ and $E_{me}$ in columns 6 and 7 of Table 3 are adopted in predicting the subsidence for years 2031 and 2056. Both the subsidence measured by Vic DPI and the corresponding predicted realistic subsidence, using the scaled moduli according to method 2, are presented in Figure 12. In this plot, wells are ordered from South to North along the coastline. Examining the predicted subsidence results in Figure 12, one can say that the entire coastline is not at an even risk of subsidence. This is due to varying extraction rate, varying aquifer thickness and mechanical response. The agreement between the Vic DPI measured, although within the error of measurements, and the predicted realistic measurements at Salt Lake 1 and Seacombe East is noted.

The Vic DPI results shown in Figure 12 are of a random nature and do not correlate geographically. Once accurate (statistically significant) subsidence measurements are obtained it will be possible to use those to back calculate the mechanical parameters and calibrate a predictive subsidence model that incorporates the aquifer lithology.
3.6 Subsidence prediction results and conclusions

The subsidence predictions for years 2031 and 2056, according to the realistic and pessimistic hydraulic head scenarios adopted in this study, are presented in Figure 13 and summarised in Table 5. Table 6 lists the total pressure head and the pressure head changes contributing to the predicted subsidence in either scenario for years 2031 and 2056. The largest subsidence is predicted for the Latrobe Aquifer at Golden Beach West 1. In year 2056 we predict this subsidence to be between 480 mm (the realistic scenario) and 1208 mm (the pessimistic scenario).

Figures 14-17 present the contoured subsidence predictions for both scenarios for years 2031 and 2056. According to the realistic scenario in year 2031, subsidence between 0.22 m to 0.51 m is expected in the coastal area between the Rosedale and Darriman Fault Systems. Less subsidence (between 0.1 m and 0.25 m) is predicted south of the Darriman Fault System. The corresponding values predicted in year 2056 are 0.2 m to 0.48 m between the Rosedale and Darriman Fault Systems and 0.1 m to 0.2 m south of the Darriman Fault System.

According to the pessimistic scenario, in year 2031, subsidence between 0.1 m to 0.35 m is predicted in the coastal region between the Lake Wellington and Rosedale Fault Systems; subsidence between 0.3 m to 0.87 m is expected in the coastal area between the Rosedale and Darriman Fault Systems. Less subsidence (between 0.1 m and 0.3 m) is predicted south of the Darriman Fault System. The corresponding values predicted in year 2056 are 0.2 m to 0.4 m in the coastal region between the Lake Wellington and Rosedale Fault Systems; 0.47 m to 1.2 m between the Rosedale and Darriman Fault Systems and 0.15 m to 0.5 m south of the Darriman Fault System. A summary of these results is provided in Table 7.

In both modelled scenarios the region between the Rosedale and Darriman Fault Systems is expected to have the highest subsidence. This is also the area where the Latrobe Aquifer is the thickest despite the fact that the mechanical compressibilities were adjusted to account for the aquifer thickness and burial. Further examination of the stratigraphy in this region is necessary to define the effective aquifer thickness. It may be that intraformational hydraulic barriers prevent the entire Latrobe thickness from depressurizing due to regional fluid extraction (i.e. less total subsidence) or it could be that low permeability compressible layers may contribute to larger but delayed subsidence.

In a study by Sinclair Knight Merz (2001c), the Latrobe aquifer thickness at Golden Beach West 1 was estimated to be 1600 m yet the lower 600 meter layer was considered impermeable. Only one third or two thirds of the remaining thickness was considered to be affected by the aquifer pressure depletion. Within the affected thickness, it is estimated that thin clay/coal lenses allow pressure depletion to propagate across the one third or two third thickness considered. The thickness of these clay/coal layers was estimated to be 220.2 m thick out of the 356 m total thickness for the first case and by 299.5 m thick out of the 570 m total thickness for the second case. In this study we consider the aquifer to be 1102 m thick. The elastic compressibility Sinclair Knight Merz (2001b) used for Golden Beach West-1 was based on scaling up the elastic value calculated by Helm (1984) for the Latrobe Valley of $1.6x10^{-5}$ to $3.5 \times 10^{-5}$ to account for aquifer thickness. The scaled up values used by Sinclair Knight Merz (2001b) were in the range of $5x10^{-6}$ to $8.3x10^{-7}$. In our study the scaled up value adopted is $6.89X10^{-6}$ which is larger than the mean value used by Sinclair Knight Merz (2001b) but falls within the range of values used. The accurate determination of aquifer thickness and stratigraphy goes hand in hand with the determination of the rock mechanical and hydraulic properties in the study area. Appendix A shows 5 hypothetical cases where different aquifer thicknesses, hydraulic conductivities and preconsolidation stresses are used to demonstrate the impact of uncertainty in these parameters on the timing and value of predicted subsidence.

Other processes not considered in this report might result in a lower predicted subsidence. For example, the region might be undergoing geological inversion due to the tectonic stress conditions which cause uplift. This effect was not studied in this project.
Uncertainty in the predicted subsidence can be attributed to one or more of the following reasons

1. The settlement computed is the ultimate settlement. In addition to the rate of pressure depletion dictated by the fluid withdrawal rate, the determination of the exact settlement rate and time requires knowledge of the exact thickness of the compressible layers affected by the stress increase due to the pressure decline, and their exact hydraulic conductivity.

2. Impermeable layers (e.g. clayey limestone) in the Latrobe Aquifer that we may have not captured in our aquifer thickness estimate, if present, could lead to vertical compartmentalization of the pressure drawdown in those areas of the aquifer. In this case the entire thickness of the aquifer, as we defined it, may not be affected by pressure reduction and the predicted ultimate subsidence may be overestimated.

3. The layers on top of the aquifer are not included in the subsidence calculation, these layers are usually more compressible than the aquifer. Their effect was treated as an overburden pressure.

4. The subsidence predictions are based on the assumption that the aquifer at the Gippsland Coast is over consolidated. The deviation from this assumption (if it can be justified) can have significant impact on the subsidence predicted. The preconsolidation stress determines when the transition to the non recoverable large subsidence occurs.

5. The mechanical compressibilities used in the predictions were guided by values adopted at the Latrobe Valley Coal Mines by Helm (1984) and those were deduced by back calculations from subsidence measurements and measurements of the overconsolidation stress.

6. Other processes not considered in this report might be affecting the observed subsidence. For example, the region might be undergoing geological inversion due to the tectonic stress conditions which causes uplift. This effect was not studied nor quantified within this study.

Hence a better estimation of the subsidence requires:

1. A better knowledge of the detailed stratigraphy and lithology of these areas aided by geological and petrophysical log interpretation.

2. Pressure measurements throughout the entire vertical profile of the aquifer.

3. Drilling for cores and performing tests on undisturbed samples to predict the mechanical properties and overconsolidation stress of the sediments in the aquifer along the coastline. Sample quality is particularly important in the case of the sensitive clays.

4. Performing tests to estimate the hydraulic conductivity of the sediments.

5. Longer duration measurements of surface subsidence using high resolution GPS can be very valuable in calibrating (back calculating) the mechanical parameters in the absence of cores.

6. Knowledge of the geodynamics of the region might add insight into the subsidence calculations.

Other potential hydraulic head recovery scenarios particularly the possibility that the offshore Gippsland Basin may be utilized for deep geological storage of CO₂ which would accelerate the aquifer pressure recovery and reduce the predicted subsidence was not considered in this study either.

Due to the regional nature of the predicted land settlement, it is not expected to affect the structural integrity of buildings. To ensure the serviceability of pipelines, particularly in the vicinity of the Rosedale Fault system, special investigation might be needed particularly once a better estimation of the subsidence is complete.
Figure 7. Locations modelled for subsidence. Circles in blue indicate wells where pore pressure measurements were taken. Circles in red indicate wells where aquifer thickness data is available from well completion reports (after Hatton et al., 2004).
Figure 8. Gippsland Basin Risk Study, subsidence data extent for the subsidence model.
<table>
<thead>
<tr>
<th>Well name</th>
<th>Aquifer thickness(m)</th>
<th>Predicted cumulative subsidence (mm)</th>
<th>Predicted cumulative subsidence (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Year 2031</td>
<td>Year 2056</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pessimistic</td>
<td>Realistic</td>
</tr>
<tr>
<td>Seacombe 7- East Seacombe 1</td>
<td>275.0</td>
<td>-341</td>
<td></td>
</tr>
<tr>
<td>Sale 13 and 15001-Wellington Park 1</td>
<td>300.2</td>
<td>-379</td>
<td></td>
</tr>
<tr>
<td>Meerlieu -Wrixondale 1</td>
<td>165.0</td>
<td>-177</td>
<td></td>
</tr>
<tr>
<td>Woodside 12 -Woodside South</td>
<td>362.0</td>
<td>-345</td>
<td>-286</td>
</tr>
<tr>
<td>Wulla Wullock 5-North See Spray 1</td>
<td>518.5</td>
<td>-867</td>
<td>-712</td>
</tr>
<tr>
<td>Wulla Wullock 5-Carrs Creek 1</td>
<td>988.2</td>
<td>-1653</td>
<td>-1356</td>
</tr>
<tr>
<td>Wulla Wullock 5-Lake Reeve 1</td>
<td>695.9</td>
<td>-1174</td>
<td>-969</td>
</tr>
<tr>
<td>Dutson Downs 1</td>
<td>1072.6</td>
<td>-1725</td>
<td>-1172</td>
</tr>
<tr>
<td>Golden Beach West 1</td>
<td>1102.8</td>
<td>-2514</td>
<td>-1492</td>
</tr>
<tr>
<td>Seacombe South 1</td>
<td>600.0</td>
<td>-911</td>
<td>-634</td>
</tr>
<tr>
<td>Salt Lake 1</td>
<td>658.4</td>
<td>-857</td>
<td>-581</td>
</tr>
<tr>
<td>Wonga Binda 1</td>
<td>653.8</td>
<td>-851</td>
<td>-576</td>
</tr>
<tr>
<td>Woodside 4</td>
<td>400.0</td>
<td>-186</td>
<td>-184</td>
</tr>
<tr>
<td>Gippsland 3</td>
<td>436.6</td>
<td>-386</td>
<td>-291</td>
</tr>
<tr>
<td>Merriman 1</td>
<td>727.5</td>
<td>-1059</td>
<td>-673</td>
</tr>
</tbody>
</table>

Table 1. Predicted subsidence for years 2031 and 2056 at various wells with the respective aquifer thickness.
Figure 9. Gippsland Basin Risk Study: A map of the Latrobe Aquifer thickness from Mehin (1995).
Figure 10. Gippsland Basin Risk Study: Cross-sections of the Gippsland Basin from Mehin (1995).
Figure 11. Gippsland Basin Risk Study: Vic DPI high resolution GPS monitoring sites (red dots) and some other reference well locations.
<table>
<thead>
<tr>
<th>Well name</th>
<th>Aquifer Thickness (m)</th>
<th>Aquifer Overburden Stress Calculation</th>
<th>Stresses at Centre of Aquifer (MPa)</th>
<th>Stresses at Top of Aquifer (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thickness of Saturated Sediments (m)</td>
<td>Total Vertical Overburden Stress (MPa)</td>
<td>Total Vertical Stress at Centre of Aquifer (MPa)</td>
<td>Effective Vertical Stress at Centre of Aquifer (MPa)</td>
</tr>
<tr>
<td>Seacombe 7- East Seacombe 1</td>
<td>275</td>
<td>1090.88</td>
<td>26.18</td>
<td>29.48</td>
</tr>
<tr>
<td>Sale 13 and 15001-Wellington Park 1</td>
<td>300.23</td>
<td>721.13</td>
<td>17.31</td>
<td>20.91</td>
</tr>
<tr>
<td>Meerlieu -Wrixondale 1</td>
<td>165</td>
<td>779.5</td>
<td>18.71</td>
<td>20.69</td>
</tr>
<tr>
<td>Woodside 12 -Woodside south</td>
<td>362</td>
<td>585.4</td>
<td>14.05</td>
<td>18.39</td>
</tr>
<tr>
<td>Wulla Wullock 5-North See Spray 1</td>
<td>518.47</td>
<td>559</td>
<td>13.42</td>
<td>19.64</td>
</tr>
<tr>
<td>Wulla Wullock 5-Carrs Creek 1</td>
<td>988.16</td>
<td>663.24</td>
<td>15.92</td>
<td>27.78</td>
</tr>
<tr>
<td>Wulla Wullock 5-Lake Reeve 1</td>
<td>695.86</td>
<td>903.73</td>
<td>21.69</td>
<td>30.04</td>
</tr>
<tr>
<td>Dutson Downs 1</td>
<td>1072.59</td>
<td>705</td>
<td>16.92</td>
<td>29.79</td>
</tr>
<tr>
<td>Golden Beach West 1</td>
<td>1102.77</td>
<td>700.73</td>
<td>16.82</td>
<td>30.05</td>
</tr>
<tr>
<td>Seacombe South 1</td>
<td>600</td>
<td>1078.23</td>
<td>25.88</td>
<td>33.08</td>
</tr>
<tr>
<td>Salt Lake 1</td>
<td>658.36</td>
<td>773.22</td>
<td>18.56</td>
<td>26.46</td>
</tr>
<tr>
<td>Wonga Binda 1</td>
<td>653.8</td>
<td>586.5</td>
<td>14.08</td>
<td>21.92</td>
</tr>
<tr>
<td>Gippsland 3</td>
<td>436.56</td>
<td>347.78</td>
<td>8.35</td>
<td>13.59</td>
</tr>
<tr>
<td>Merriman 1</td>
<td>727.52</td>
<td>694</td>
<td>16.66</td>
<td>25.39</td>
</tr>
</tbody>
</table>

Table 2. Calculation of the confining pressures at centre or top of aquifer.
<table>
<thead>
<tr>
<th>Well name</th>
<th>Method 1: scaling with mean confining pressure (Acar and El-Tahir, 1986)</th>
<th>Method 2; scaling with vertical applied stress (Helm, 1976)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M1a: $S_{\text{sk}}$ scaled using stress at aquifer centre $\times 10^6$ (m$^{-1}$)</td>
<td>M1a: $E$ scaled using stress at aquifer centre (GPa)</td>
</tr>
<tr>
<td>Seacombe 7- East Seacombe 1</td>
<td>8.89</td>
<td>1.12</td>
</tr>
<tr>
<td>Sale 13 and 15001-Wellington Park 1</td>
<td>10.23</td>
<td>0.98</td>
</tr>
<tr>
<td>Meerlieu -Wrixondale 1</td>
<td>10.27</td>
<td>0.97</td>
</tr>
<tr>
<td>Woodside 12-Woodside south</td>
<td>10.80</td>
<td>0.93</td>
</tr>
<tr>
<td>Wulla Wullock 5-North Sea Spray 1</td>
<td>10.50</td>
<td>0.95</td>
</tr>
<tr>
<td>Wulla Wullock 5-Carrs Creek 1</td>
<td>9.11</td>
<td>1.10</td>
</tr>
<tr>
<td>Wulla Wullock 5-Lake Reeve 1</td>
<td>8.83</td>
<td>1.13</td>
</tr>
<tr>
<td>Dutson Downs 1</td>
<td>8.86</td>
<td>1.13</td>
</tr>
<tr>
<td>Golden Beach West 1</td>
<td>8.83</td>
<td>1.13</td>
</tr>
<tr>
<td>Seacombe South 1</td>
<td>8.50</td>
<td>1.18</td>
</tr>
<tr>
<td>Salt Lake 1</td>
<td>9.29</td>
<td>1.08</td>
</tr>
<tr>
<td>Wonga Binda 1</td>
<td>10.03</td>
<td>1.00</td>
</tr>
<tr>
<td>Woodside 4</td>
<td>10.08</td>
<td>0.99</td>
</tr>
<tr>
<td>Gippsland 3</td>
<td>12.37</td>
<td>0.81</td>
</tr>
<tr>
<td>Merriman 1</td>
<td>9.44</td>
<td>1.06</td>
</tr>
</tbody>
</table>

Table 3. Scaled mechanical parameters using two methods.
<table>
<thead>
<tr>
<th>Well</th>
<th>Nearest Measured Subsidence June 2004- November 2005</th>
<th>Predicted Realistic Subsidence June 2004- November 2005</th>
<th>Unscaled (mm)</th>
<th>Scaled realistic subsidence (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nearest station</td>
<td>Measured subsidence (mm)</td>
<td></td>
<td>M1a</td>
</tr>
<tr>
<td>Seacombe 7- East Seacombe 1</td>
<td>ST15</td>
<td>-2.70</td>
<td>-7.80</td>
<td>-3.47</td>
</tr>
<tr>
<td>Sale 13 and 15001-Wellington Park 1</td>
<td>ST11</td>
<td>-1.20</td>
<td>-8.40</td>
<td>-4.29</td>
</tr>
<tr>
<td>Meerlieu -Wrixondale 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Woodside 12 -Woodside south</td>
<td>ST5</td>
<td>-4.10</td>
<td>-14.77</td>
<td>-7.98</td>
</tr>
<tr>
<td>Wulla Wullock 5-Carrs Creek 1</td>
<td>ST9</td>
<td>-13.90</td>
<td>-22.75</td>
<td>-10.36</td>
</tr>
<tr>
<td>Wulla Wullock 5-Lake Reeve 1</td>
<td>ST9</td>
<td>-13.90</td>
<td>-13.30</td>
<td>-5.87</td>
</tr>
<tr>
<td>Dutson Downs 1</td>
<td>ST13</td>
<td>-2.10</td>
<td>-23.16</td>
<td>-10.26</td>
</tr>
<tr>
<td>Golden Beach West 1</td>
<td>ST13</td>
<td>-2.10</td>
<td>-18.16</td>
<td>-8.01</td>
</tr>
<tr>
<td>Seacombe South 1</td>
<td>ST14</td>
<td>-2.60</td>
<td>-13.19</td>
<td>-5.60</td>
</tr>
<tr>
<td>Salt Lake 1</td>
<td>ST7</td>
<td>-3.80</td>
<td>-11.36</td>
<td>-5.27</td>
</tr>
<tr>
<td>Wonga Binda 1</td>
<td>ST7</td>
<td>-3.80</td>
<td>-11.28</td>
<td>-5.65</td>
</tr>
<tr>
<td>Woodside 4</td>
<td>ST3</td>
<td>3.90</td>
<td>-6.14</td>
<td>-3.10</td>
</tr>
<tr>
<td>Gippsland 3</td>
<td>ST3</td>
<td>3.90</td>
<td>-10.72</td>
<td>-6.63</td>
</tr>
<tr>
<td>Merriman 1</td>
<td>ST8</td>
<td>1.70</td>
<td>-15.22</td>
<td>-7.18</td>
</tr>
</tbody>
</table>

Table 4. Calibration of the compressibilities based on comparisons between measured and calculated subsidence using unscaled and scaled mechanical parameters.
Comparison of Subsidence Measured by DPI and Predicted from June 2004 to November 2005

Figure 12. Comparison between measured (by Vic. DPI) and predicted scaled calculated subsidence values (model prediction) for the period between June 2004 and November 2006 plotted from south to north along the Gippsland coastline.
Figure 13a. Predicted subsidence at Seacombe 7 WL & East Seacombe 1G

Figure 13b. Predicted subsidence at Sale 13 and 15001-Wellington Park 1

Figure 13c. Predicted subsidence at Meerlieu - Wrixondale 1

Figure 13d. Predicted subsidence at Wulla Wullock 5-North See Spray 1

Figure 13e. Predicted subsidence at Wulla Wullock 5-Carrs Creek 1

Figure 13f. Predicted subsidence at Wulla Wullock 5-Lake Reeve 1.
Subsidence
Dutson Downs 1

-900  -800  
-700  -600  
-500  -400  
-300  -200  
0

Subsidence (mm)
Pessimistic scenario
Realistic scenario

Figure 13g. Predicted subsidence at Dutson Downs 1.

Subsidence
Golden Beach West 1

-1400  -1200  
-1000  -800  
-600  -400  
-200  0

Subsidence (mm)
Pessimistic scenario
Realistic scenario

Figure 13h. Predicted subsidence at Golden Beach West 1.

Subsidence
Woodside 12 WL & Woodside South

-350  -300  
-250  -200  
-150  -100  
-50  0

Subsidence (mm)
Pessimistic scenario
Realistic scenario

Figure 13i. Predicted subsidence at Woodside 12 –and Woodside South.

Subsidence
Seacombe South 1

-450  -400  
-350  -300  
-250  -200  
-150  -100  
0

Subsidence (mm)
Pessimistic scenario
Realistic scenario

Figure 13j. Predicted subsidence at Seacombe South 1.

Subsidence
Salt Lake 1

-500  -450  
-400  -350  
-300  -250  
-200  -150  
-100  -50  0

Subsidence (mm)
Pessimistic scenario
Realistic scenario

Figure 13k. Predicted subsidence at Salt Lake 1.

Subsidence
Woonga Binda 1

-600  -500  
-400  -300  
-200  -100

Subsidence (mm)
Pessimistic scenario
Realistic scenario

Figure 13l. Predicted subsidence at Wonga Binda 1.
Figure 13m. Predicted subsidence at Gippsland 3.

Figure 13n. Predicted subsidence at Merriman 1.

Figure 13. Predicted subsidence based on the pessimistic and realistic extraction scenarios
<table>
<thead>
<tr>
<th>Well Name</th>
<th>Predicted cumulative subsidence (mm) 2031</th>
<th>Predicted cumulative subsidence (mm) 2056</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pessimistic</td>
<td>Realistic</td>
</tr>
<tr>
<td>Seacombe 7- East Seacombe 1</td>
<td>-119.67</td>
<td>-167.92</td>
</tr>
<tr>
<td>Sale 13 and 15001-Wellington Park 1</td>
<td>-187.77</td>
<td>-261.04</td>
</tr>
<tr>
<td>Meerlieu -Wrixondale 1</td>
<td>-88.65</td>
<td>-125.43</td>
</tr>
<tr>
<td>Woodside 12 -Woodside south</td>
<td>-194.00</td>
<td>-161.01</td>
</tr>
<tr>
<td>Wulla Wullock 5-North See Spray 1</td>
<td>-457.01</td>
<td>-374.92</td>
</tr>
<tr>
<td>Wulla Wullock 5-Carrs Creek 1</td>
<td>-615.83</td>
<td>-505.20</td>
</tr>
<tr>
<td>Wulla Wullock 5-Lake Reeve 1</td>
<td>-404.49</td>
<td>-333.79</td>
</tr>
<tr>
<td>*Dutson Downs 1</td>
<td>-598.98</td>
<td>-407.04</td>
</tr>
<tr>
<td>Golden Beach West 1</td>
<td>-865.75</td>
<td>-513.61</td>
</tr>
<tr>
<td>Seacombe South 1</td>
<td>-284.99</td>
<td>-198.40</td>
</tr>
<tr>
<td>Salt Lake 1</td>
<td>-335.18</td>
<td>-227.03</td>
</tr>
<tr>
<td>Wonga Binda 1</td>
<td>-401.74</td>
<td>-272.11</td>
</tr>
<tr>
<td>Woodside 4</td>
<td>-88.65</td>
<td>-87.86</td>
</tr>
<tr>
<td>Gippsland 3</td>
<td>-294.01</td>
<td>-221.86</td>
</tr>
<tr>
<td>Merriman 1</td>
<td>-431.60</td>
<td>-274.20</td>
</tr>
</tbody>
</table>

Table 5. Final predicted subsidence in years 2031 and 2056 for both the pessimistic and realistic hydraulic head scenarios.
Table 6. Predicted total head and water pressure head change for the pessimistic and realistic scenarios for both years 2031 and 2056

<table>
<thead>
<tr>
<th>Well</th>
<th>Total Head (m) 2031</th>
<th>Total Pressure Head change (m) 2031</th>
<th>Total Head (m) 2056</th>
<th>Total Pressure Head change (m) 2056</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seacombe 7- East</td>
<td>-21.49</td>
<td>-61.99</td>
<td>-46.49</td>
<td>-86.99</td>
</tr>
<tr>
<td>Seacombe 1</td>
<td>-15.01</td>
<td>-64.01</td>
<td>-39.67</td>
<td>-88.67</td>
</tr>
<tr>
<td>Sale 13 and 15001-Wellington Park 1</td>
<td>-12.71</td>
<td>-53.4924</td>
<td>-34.99</td>
<td>-75.99</td>
</tr>
<tr>
<td>Meerlieu-Wrixondale 1</td>
<td>-20.17</td>
<td>-48.17</td>
<td>-42.10</td>
<td>-70.10</td>
</tr>
<tr>
<td>Woodside 12 -Woodside south</td>
<td>-21.64</td>
<td>-83.64</td>
<td>-47.50</td>
<td>-109.50</td>
</tr>
<tr>
<td>Wulla Wullock 5-North See Spray 1</td>
<td>-21.64</td>
<td>-83.64</td>
<td>-47.50</td>
<td>-109.50</td>
</tr>
<tr>
<td>Wulla Wullock 5-Carrs Creek 1</td>
<td>-21.64</td>
<td>-83.64</td>
<td>-47.50</td>
<td>-109.50</td>
</tr>
<tr>
<td>Wulla Wullock 5-Lake Reeve 1</td>
<td>-21.64</td>
<td>-83.64</td>
<td>-47.50</td>
<td>-109.50</td>
</tr>
<tr>
<td>Dutson Downs 1</td>
<td>-35.39043</td>
<td>-80.39</td>
<td>-67.81</td>
<td>-112.81</td>
</tr>
<tr>
<td>Golden Beach West 1</td>
<td>-54.00</td>
<td>-113.99877</td>
<td>-99.11</td>
<td>-159.11</td>
</tr>
<tr>
<td>Seacombe South 1</td>
<td>-35.92</td>
<td>-75.92</td>
<td>-66.97</td>
<td>-106.97</td>
</tr>
<tr>
<td>Salt Lake 1</td>
<td>-27.09</td>
<td>-65.09</td>
<td>-53.30</td>
<td>-91.30</td>
</tr>
<tr>
<td>Wonga Binda 1</td>
<td>-27.09</td>
<td>-65.09</td>
<td>-53.30</td>
<td>-91.30</td>
</tr>
<tr>
<td>Woodside 4</td>
<td>-4.19</td>
<td>-23.19</td>
<td>-14.42</td>
<td>0.14</td>
</tr>
<tr>
<td>Gippsland 3</td>
<td>-19.21</td>
<td>-44.21</td>
<td>-43.87</td>
<td>-68.87</td>
</tr>
<tr>
<td>Merriman 1</td>
<td>-19.24</td>
<td>-80.77</td>
<td>-50.84</td>
<td>-104.37</td>
</tr>
</tbody>
</table>

Table 6. Predicted total head and water pressure head change for the pessimistic and realistic scenarios for both years 2031 and 2056
Figure 14. Gippsland Basin Risk Study 2031 realistic scenario predicted subsidence data and contours. Pessimistic and realistic scenarios coincide between the Lake Wellington and Rosedale Fault System, Figure 15.
Figure 15. Gippsland Basin Risk Study 2031 pessimistic scenario predicted subsidence data and contours.
Figure 16. Gippsland Basin Risk Study: 2056 realistic scenario predicted subsidence data and contours. Pessimistic and realistic scenarios coincide between the Lake Wellington and Rosedale Fault System, see Figure 17.
Figure 17. Gippsland Basin Risk Study: 2056 pessimistic scenario predicted subsidence data and contours.
### Region on the coastline

<table>
<thead>
<tr>
<th>Region on the coastline</th>
<th>In 2031 Realistic scenario</th>
<th>In 2031 pessimistic scenario</th>
<th>In 2056 Realistic scenario</th>
<th>In 2056 pessimistic scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>between the Lake Wellington and Rosedale Fault System</td>
<td>0.10-0.35</td>
<td>0.10-0.35</td>
<td>0.20-0.40</td>
<td>0.20-0.40</td>
</tr>
<tr>
<td>between the Rosedale and Darriman Fault Systems</td>
<td>0.22-0.51</td>
<td>0.30-0.87</td>
<td>0.20-0.48</td>
<td>0.47-1.20</td>
</tr>
<tr>
<td>south of the Darriman Fault System</td>
<td>0.10-0.25</td>
<td>0.10-0.30</td>
<td>0.10-0.20</td>
<td>0.15-0.50</td>
</tr>
</tbody>
</table>

Table 7. Summary of subsidence results at various regions of the coastline. Pessimistic and realistic scenarios coincide between the Lake Wellington and Rosedale Fault System

## 4 EXTREME WAVE CONDITIONS AND SEA LEVEL PREDICTION IN THE NEXT 50 YEARS

### 4.1 Objective

This part of the study aims at estimating the extreme (50-year-return) wave heights, storm surge and high tide across Gippsland Coast under the current, 2031 and 2056 climate change affected sea levels. The study area is bordered by 146.4°E ~ 148.2°E and -37.6°S ~ -39.2°S, as shown in Figure 18.

![Figure 18. Study area map for the extreme wave prediction model](image)
4.2 Extreme sea level projections to 2056 under climate change

The extreme sea level discussed here includes the change of mean sea level (msl), tidal effect, and storm surge as Figure 19 shows, where wave setup is the rise in the mean water level above the still-water elevation of the sea due to wave breaking while the wave runup is the maximum vertical extent of wave uprush on a beach or structure above the still water level. The setup can be estimated to be about one sixth of the breaking wave height. Runup depends on the very detailed beach slope and permeability, within 3 to 5 meters cross the shoreline. The resolution of our wave model is 500 meters, thus is unable to properly represent runup. This extreme wave study is confined to 50-year-return wave height estimation only. Setup and runup are not included in this wave model result.

Figure 19. The contributions to sea level extremes at the coast (after McInnes, et al., 2005).

Mean sea level is affected by long-term climate change. Mean sea level rise occurs as a result of both thermal expansion of the ocean as it warms up and the melting of ice sheets and glaciers. According to the Intergovernmental Panel on Climate Change (IPCC) (2001) the low, mid and high mean sea level rise for next 50 years is 0.05 m, 0.17 m, and 0.33 m (0.8 to 8.0 cm per decade). Storm tide level and climate change in eastern Victoria was studied by McInnes, et al. (2003, 2005a-b, 2006) by using the Victorian tide gauge residual records for the period 1966-2003. It was found that winds are likely to intensify in coastal regions of Victoria, particularly in winter as a result of more intense low pressure systems. Low pressure systems off the east coast of Australia may become more frequent.

Table 8 shows the worst case scenario extreme storm tide level for selected locations around the Gippsland Lakes under current climate, 2031 and 2056 high mean sea level rise scenarios (after McInnes, et al., 2005, 2006). The 2031 values are obtained by interpolating between the current and 2056 climate.

<table>
<thead>
<tr>
<th>Locations</th>
<th>Return Period (yr)</th>
<th>Current Climate(m)</th>
<th>2031 Climate</th>
<th>2056 Climate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>High (m)</td>
<td>High (m)</td>
</tr>
<tr>
<td>Lakes Entrance</td>
<td>50</td>
<td>0.95</td>
<td>1.14</td>
<td>1.34</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.91</td>
<td>1.10</td>
<td>1.28</td>
</tr>
<tr>
<td>Metung (onshore)</td>
<td>50</td>
<td>0.56</td>
<td>0.75</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.52</td>
<td>0.72</td>
<td>0.90</td>
</tr>
<tr>
<td>Tambo Bay</td>
<td>50</td>
<td>0.54</td>
<td>0.55</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.51</td>
<td>0.53</td>
<td>0.81</td>
</tr>
<tr>
<td>Port Albert</td>
<td>50</td>
<td>1.70</td>
<td>1.91</td>
<td>2.12</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>1.65</td>
<td>1.85</td>
<td>2.06</td>
</tr>
</tbody>
</table>

Table 8. Extreme storm tide level for selected locations around the Gippsland Lakes under current climate, 2031 and 2056 high mean sea level rise scenarios.(after McInnes, et al., 2005, 2006)
4.3 Extreme wave analysis for the region

4.3.11 Data selection

To obtain 50-year-return extreme wave parameters (height, period, and direction), long-term wave observation data in the area are essential. The research area is remote and lacks long-term direct wave observation. To date the available long-term wave records are from two sources:

Satellite observation: up to 14 years and multi-satellite observations (Topex-Poseidon from 25 Sep. 1992, ERS-2, from 8 Oct. 2001, Geosat Follow- On, from 18 Oct 2001, Jason, from 15 Jan 2002, ENVISAT, from 8 Oct 2002) of significant wave height (SWH) were provided by the Defence Oceanographic Data Centre (DODC) of Australia. This data set allows a good spatial and temporal sampling. However, the observations for a particular location are not continuous. Topex- Poseidon has a short repeat cycle (the same spot on the ocean is passed over every 10 days), but a low spatial resolution (its ground tracks are 315 km apart at the equator). On the other hand, ERS passes are tighter (90 km apart at the equator) but it has a longer repeat cycle as it only measures the same point on the globe every 35 days. Neither wave period nor wave directions were observed.

CSIRO WAM wave hind-cast results: The wave data estimates from surface wind speed, generated by the Australian Bureau of Meteorology's regional atmospheric model, provided input to the WAM wave model to yield estimates of wave height and period (Hayes et al., 2005). The data are six-hourly predictions of significant wave height, period and mean wave direction, grided at 0.1° degree spatial resolution, for the period of March 1997 to February 2002, inclusive.

4.3.12 Extreme wave analysis

Extrapolating the trends in the relatively short wave record to likely future events is a common practice in civil and offshore engineering fields (Goda, 1988, Allen, 1999). Lemm et al. (1999) estimated the 50 and 100 year-return wave heights along the Perth coast using 2.5 year 20-minutes wave data. The primary data source in the Gippsland region for current extreme wave analysis is the CSIRO 5-year wave hind-cast results. Three representative wave record locations in deep-water were selected (marked by the red-dot in Figure 18). The water depth and coordinates of these points are shown in Table 9. Among these three sampling points Gippsland #2 and #3 are selected, as the prime ones for extreme wave analysis. The Gippsland #1 is a reference point used to double-check the results.

<table>
<thead>
<tr>
<th>Water depth (m)</th>
<th>longitude</th>
<th>Latitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gippsland #1</td>
<td>-46</td>
<td>147.2°E</td>
</tr>
<tr>
<td>Gippsland #2</td>
<td>-65</td>
<td>147.7°E</td>
</tr>
<tr>
<td>Gippsland #3</td>
<td>-63</td>
<td>146.7°E</td>
</tr>
</tbody>
</table>

Table 9. Wave sampling locations

A set of 115 storms, defined as independent events sufficient to generate significant wave heights (Hs) exceeding 3.0 m, were identified over the period between March 1997 and February 2002. The average frequency of occurrence for storms has been estimated as \( \lambda = 23/\text{year} \). The extreme wave height distributions were determined by the method of least squares. The best fits were Weibull distributions with a shape parameter of 2.0, using the method recommended by the Working Group on Extreme Wave Statistics, IAHR (Goda, 1988). Figure 20 and Table 10 show the resulting extreme wave estimates. This analysis is based on the CSIRO wave data from 1997 to 2002. Predictions are subject to some uncertainty as a direct consequence of the short duration of existing wave data series. The large wave height is not necessarily corresponding to long wave period (Table 11). In fact many long period swells correlate to low wave height. To obtain the appropriate wave period for the extreme waves, the top 115 storm wave records are analysed (Figure 21). The relationship of significant storm
wave height, \( H_s \), and their corresponding wave period, \( T \), is analysed using the least-square method. The trend line equation is:

\[
T = 4.82 + 0.755H_s
\] 

\[(10)\]

Figure 20. Extreme wave heights and their return periods by CSIRO wave data.

<table>
<thead>
<tr>
<th>Average return interval (yr)</th>
<th>Significant wave height ( H_s ) (m)</th>
<th>Wave Period ( T ) (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>7.72</td>
<td>10.65</td>
</tr>
<tr>
<td>25</td>
<td>8.20</td>
<td>11.02</td>
</tr>
<tr>
<td>30</td>
<td>8.30</td>
<td>11.09</td>
</tr>
<tr>
<td>40</td>
<td>8.44</td>
<td>11.20</td>
</tr>
<tr>
<td>50</td>
<td>8.55</td>
<td>11.28</td>
</tr>
<tr>
<td>60</td>
<td>8.64</td>
<td>11.34</td>
</tr>
<tr>
<td>70</td>
<td>8.71</td>
<td>11.40</td>
</tr>
<tr>
<td>80</td>
<td>8.78</td>
<td>11.45</td>
</tr>
<tr>
<td>90</td>
<td>8.83</td>
<td>11.49</td>
</tr>
<tr>
<td>100</td>
<td>8.88</td>
<td>11.52</td>
</tr>
<tr>
<td>200</td>
<td>9.19</td>
<td>11.76</td>
</tr>
</tbody>
</table>

Table 10. Extreme wave climate estimates for deep water boundary.

<table>
<thead>
<tr>
<th>Storm Ranking</th>
<th>( H_s ) (m)</th>
<th>( T ) (s)</th>
<th>Storm Ranking</th>
<th>( H_s ) (m)</th>
<th>( T ) (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.4</td>
<td>9.9</td>
<td>26</td>
<td>4.8</td>
<td>8.5</td>
</tr>
<tr>
<td>2</td>
<td>6.6</td>
<td>9.7</td>
<td>27</td>
<td>4.8</td>
<td>8.6</td>
</tr>
<tr>
<td>3</td>
<td>6.4</td>
<td>9.5</td>
<td>28</td>
<td>4.8</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>6.4</td>
<td>11</td>
<td>29</td>
<td>4.7</td>
<td>8.7</td>
</tr>
<tr>
<td>5</td>
<td>6.4</td>
<td>8.5</td>
<td>30</td>
<td>4.7</td>
<td>8.3</td>
</tr>
<tr>
<td>6</td>
<td>6.2</td>
<td>9.9</td>
<td>31</td>
<td>4.7</td>
<td>8</td>
</tr>
<tr>
<td>7</td>
<td>6.2</td>
<td>9.5</td>
<td>32</td>
<td>4.7</td>
<td>8.7</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>9.8</td>
<td>33</td>
<td>4.6</td>
<td>8.3</td>
</tr>
<tr>
<td>9</td>
<td>6</td>
<td>9.1</td>
<td>34</td>
<td>4.6</td>
<td>7.8</td>
</tr>
<tr>
<td>10</td>
<td>5.9</td>
<td>9.2</td>
<td>35</td>
<td>4.5</td>
<td>7.9</td>
</tr>
<tr>
<td>11</td>
<td>5.9</td>
<td>7.9</td>
<td>36</td>
<td>4.5</td>
<td>8.2</td>
</tr>
<tr>
<td>12</td>
<td>5.8</td>
<td>9.6</td>
<td>37</td>
<td>4.5</td>
<td>7.4</td>
</tr>
<tr>
<td>13</td>
<td>5.7</td>
<td>9.1</td>
<td>38</td>
<td>4.4</td>
<td>7.9</td>
</tr>
<tr>
<td>14</td>
<td>5.7</td>
<td>8.8</td>
<td>39</td>
<td>4.3</td>
<td>8.4</td>
</tr>
</tbody>
</table>
Table 11. Wave parameters of the top 50 storms in 5 years (1997-2002) for the deep water-Gippsland region.

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>5.6</td>
<td>8.8</td>
<td>40</td>
<td>4.3</td>
<td>7.9</td>
</tr>
<tr>
<td>16</td>
<td>5.5</td>
<td>9</td>
<td>41</td>
<td>4.3</td>
<td>7.7</td>
</tr>
<tr>
<td>17</td>
<td>5.5</td>
<td>10.1</td>
<td>42</td>
<td>4.3</td>
<td>7.4</td>
</tr>
<tr>
<td>18</td>
<td>5.5</td>
<td>9</td>
<td>43</td>
<td>4.2</td>
<td>8.1</td>
</tr>
<tr>
<td>19</td>
<td>5.3</td>
<td>8.3</td>
<td>44</td>
<td>4.2</td>
<td>8</td>
</tr>
<tr>
<td>20</td>
<td>5.2</td>
<td>8.6</td>
<td>45</td>
<td>4.2</td>
<td>7.5</td>
</tr>
<tr>
<td>21</td>
<td>5</td>
<td>8.8</td>
<td>46</td>
<td>4.2</td>
<td>7.6</td>
</tr>
<tr>
<td>22</td>
<td>5</td>
<td>8.9</td>
<td>47</td>
<td>4.2</td>
<td>7.9</td>
</tr>
<tr>
<td>23</td>
<td>5</td>
<td>7.8</td>
<td>48</td>
<td>4.2</td>
<td>7.2</td>
</tr>
<tr>
<td>24</td>
<td>4.9</td>
<td>8.5</td>
<td>49</td>
<td>4.1</td>
<td>7.3</td>
</tr>
<tr>
<td>25</td>
<td>4.8</td>
<td>8.9</td>
<td>50</td>
<td>4.1</td>
<td>7.3</td>
</tr>
</tbody>
</table>

4.3.13 Wave direction

The direction of the largest wave is significantly different from the southwesterly storm wind direction. The wave direction data indicate the fact that the Gippsland region is within the eastern segment of Bass Strait which is protected to the west and south, and so the largest waves are mainly from the south-east, between 110° and 130° (Hayes, et al., 2005).

4.3.14 Wave transformation over shallow waters

The original wave model has a spatial step of 0.1° which is about 10 km. To predict 50-year-return storm wave propagation from deep water to shore, a fine resolution model is necessary. This model
must be capable of incorporating wave refraction, reflection, shoaling (shoaling is the deformation of wave height and wave length as it approaching the shore line.), and breaking.

The propagation of small amplitude surface gravity waves over a seabed of mild slope can be described by the mild slope equations (Berkhoff, 1972)

\[
\frac{\partial}{\partial x} \left[ c_g \frac{\partial \phi}{\partial x} \right] + \frac{\partial}{\partial y} \left[ c_g \frac{\partial \phi}{\partial y} \right] + \omega^2 \frac{e}{c} \frac{\partial \phi}{\partial x} = 0
\]

(11)

where \(x\) is the principal direction of propagation, \(y\) is the transverse direction, \(\phi\) is velocity potential function, \(\omega\) is the radian frequency of waves, \(c\) is the celerity or phase velocity (i.e. the speed at which the wave crest travels), \(c_g\) is wave group velocity (the wave energy transporting speed).

This equation takes account of the combined effects of refraction, shoaling and diffraction. To solve this elliptic type equation a fine grid (in the order of a fraction of wave length) is needed and the computational cost is very high. To promote computational efficiency a parabolic version of the mild slope equation is derived (Radder, 1979)

\[
\frac{\partial \phi}{\partial x} = ik - \frac{1}{2}k \left[ \frac{\partial (k c_g)}{\partial x} \right] \phi + i \frac{1}{2}k \left[ \frac{\partial c_g}{\partial y} \right] \left[ \frac{\partial \phi}{\partial y} \right]
\]

(12)

Where \(i = \sqrt{-1}\), \(x\) is the main direction of propagation, \(y\) is the transverse direction, \(k\) is the wave number, \(k = \frac{2\pi}{L}\), and \(L\) is wave length.

Equation (3) is solved numerically by software called the Regional Coastal Processes (RCP) wave transformation model. The RCP model was originally developed by US Army Corps of Engineers (Larson and Kraus, 1989). A comprehensive model redevelopment has subsequently been carried out in CSIRO Petroleum (Li, 2003, 2005, 2006). The problematic restriction that one grid coordinate \(x\) has to be approximately parallel to the predominant wave direction has been removed. The model is robust and able to deal with the complicated geometry of the coastline.

For wave breaking and transformation inside surf zone (the surf zone is the area between the landward limit of the waves and where the farthest seaward wave breaks.), the RCP model uses the following general criterion (CERC, 1984).

\[
\frac{H_b}{h_b} = b(m) - a(m) \frac{H_b}{T^2}
\]

(13)

Where \(H_b\) is the breaking wave height, \(h_b\) is the water depth at which breaking is initiated, \(m\) is beach slope, \(a(m) = 4.40(1 - e^{-0.8m})\), \(b(m) = \frac{1.56}{1 + e^{-0.85m}}\), and \(T\) is the wave period.

Inside the surf zone the broken wave height is calculated by using the energy equation within the surf zone.

\[
\nabla \cdot \left( a^2 c_g \nabla s \right) = -\frac{\kappa}{h} \left\{ a^2 c_g \left| \nabla s \right| - \left[ \frac{g}{2 \omega} \right]^2 h^2 c_g \left| \nabla s \right| \right\}
\]

(14)

where \(\kappa\) is the rate of energy dissipation coefficient, \(\kappa = 0.2\), \(h\) is the average water depth, \(\gamma\) is the ratio between the broken wave height and the water depth, \(g\) is gravity acceleration, \(a\) is wave amplitude function, \(s\) is wave phase function.

The simulation model grid covers 168 x 110 km², with 500m resolution. The Bathymetry used here is Geoscience Australia 0.0025º (250 m) resolution digital elevation model. Within the study region, offshore bathymetry drops dramatically from 0 to -20 m, then deepens gradually from the -20m contour to -80 m (Figure 22).
4.4 50-year-return wave heights across Gippsland Coast

The 50-year-return wave heights across the Gippsland coast for the current time, 2031 and 2056 extreme sea level conditions are calculated. The extreme sea levels used here are the 50-year-return storm tide levels for 2006, 2031 and 2056 provided by Dr Kathleen McInnes, CSIRO marine and Atmospheric Research. The wave height transformation from deep water to shore is simulated by the numerical model described in section 1.3.4. The details of the wave model input conditions are listed below:

4.4.15 Current Climate

Sea level: 50-year-return storm tide level under current climate (provided by Kathy McInnes, CMAR). Deep water wave parameters: 50-year-return wave height $H_s=8.55$ m, wave period $T=11.28$ s, wave direction=120°. Figure 23 shows the model result of the 50-year-return wave height distribution under current climate with the wave from the southeast (dir=120°).

4.4.16 2031 Climate with high sea level rise

Sea level: 50-year-return storm tide level, interpolate from 2006 and 2056 data provided by Kathy McInnes, CMAR. Deep water wave height: $H_s=8.55$ m, $T=11.28$ s, Dir=120°. Figure 24 shows the model result of the 50-year-return wave height distribution under the 2031 high sea level rise scenario with the wave from the southeast (dir=120°).

4.4.17 2056 Climate with high sea level rise

Sea level: 50-year-return storm sea level at 2056 (provided by Kathy McInnes, CMAR). Deep water wave height: $H_s=8.55$ m, $T=11.28$ s, Dir=120°. Figure 25 shows the model result of the 50-year-return wave height distribution under the 2056 high sea level rise scenario with the wave from the southeast (dir=120°).
Figure 23. 50-year-return wave height distribution under the current climate; highest wave path is from the southeast direction=120° (shown in the white arrows).

Figure 24. 50-year-return wave height distribution under the 2031 high sea level rise scenario; highest wave path is from the southeast direction=120° (shown in the white arrows).
4.5 Conclusions of extreme wave height calculations

From the analysis of extreme wave and sea level model predictions we conclude that:

According to the storm surge simulations, the typical wind direction associated with the largest storm surges in the area is usually southwesterly (around 225°). However, the strong refraction for waves from such a direction curves the wave propagation lines more perpendicular to the shoreline. For both the Lakes Entrance and the Port Albert areas the most dangerous storm waves are those from the southeast (e.g. Dir=110°~130°).

In the shallow water surf zone (water depth $\leq 7.5$ m), sea level rise in 2056 will increase the 50-year-return wave height and wave power by up to 3% and 6% respectively. However, in deep water (water depth $> 7.5$ m) the impact of rising sea level on the 50-year-return wave height is negligible.

According to the storm tide and wave height predictions and within the current mean sea level scenario it is expected that the northern part of the coastline north of the Lake Wellington Fault System will experience between 7 and 9 m wave heights while the region between the Lake Wellington and Rosedale Fault Systems will experience around 7 m wave heights. The region between the Rosedale and Darriman Fault Systems will experience wave heights between 1 and 7 m while south of the Darriman Fault System these wave heights are about 1 m. Within the 2031 mean sea level scenario these values are 7-9 m, 7-8.5 m, 3-7 m, and 1 m respectively. In year 2056 these values are expected to be 8.5-9 m, 7-9 m, 3-7 m, and 1 m respectively. Table 12 summarizes these results. The wave height predictions present high values with a high underlying uncertainty stemming from the limited duration of the current CSIRO data set used in the prediction. Certainty can be improved by using a data set that extends over a period longer than the 5 years specific to the study area.
<table>
<thead>
<tr>
<th>Region</th>
<th>Current mean sea level (m)</th>
<th>2031 mean sea level (m)</th>
<th>2056 mean sea level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North of Lake Wellington Fault System</td>
<td>7-9</td>
<td>7.9</td>
<td>8.5-9</td>
</tr>
<tr>
<td>Between Lake Wellington and Rosedale Fault Systems</td>
<td>7</td>
<td>7-8.5</td>
<td>7.9</td>
</tr>
<tr>
<td>Between the Rosedale and Darriman Fault Systems</td>
<td>1-7</td>
<td>3-7</td>
<td>3-7</td>
</tr>
<tr>
<td>South of the Darriman Fault System</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 12. Summary of storm tide and wave heights within three examined mean sea level scenarios.
Figure 26. Gippsland Basin Risk Study, present day combined extreme sea level/storm tide/wave height contours (m).
Figure 27. Gippsland Basin Risk Study; 2031 combined extreme sea level/storm tide/wave height contours (m).
Figure 28. Gippsland Basin Risk Study; 2056 combined extreme sea level/storm tide/wave height contours (m).
5 INUNDATION RISK MAPS

The research aim has been to explore inundation risk due to the individual and combined effects of land subsidence (resulting from aquifer pore pressure depletion) and extreme mean sea level and extreme storm wave calculations. The study area is shown in Figure 29. The project also explores the worst case scenario when both factors are combined. For this purpose we have used a Digital Elevation Model (DEM) of the land surface. The DEM data is the 3 ARC Second (90 m) data set that was averaged from the original 1 ARC second (30 m) data set prepared by Shuttle Radar Topography Mission (SRTM) in the year 2000 and obtained through the United States Geological Survey (2000). Figures 30-33 present the region covered by this DEM. The vertical resolution of the original DEM model has a positive bias with a mean difference of 1.75 m and a standard deviation of 4.96 m. This makes the accuracy < 11 m (at 95% confidence level). Moreover if we examine these Figures, we note gaps in the elevation data in various places but mainly around the lakes. This is due to the loss of accuracy of the radar interferometry technology used to obtain these elevations when water surfaces or waves are encountered. The vertical resolution and to a less extent these voids in the DEM data will impact the accuracy of the inundation risk predictions. The fact that we are predicting the ultimate settlement will bias our results to overestimate inundation. The fact that we are using elevation measurements conducted 30 years after fluid extraction commencement will bias our results to overestimate inundation. The error resulting from the DEM overestimating the ground elevation will bias our results to underestimate inundation.

5.1 Inundation risk due to land subsidence

Coastal inundation risk maps due to land subsidence are presented in Figures 34-40. The map in Figure 34 shows that the risked regions are not observable at the scale of the map. Maps in Figures 35-40 provide magnified sections of the coastline where in both years 2031 and 2056 small areas of inundation risk due to subsidence can be seen at the margins of Lake Reeve near the coastline and some of the margins of Lake Coleman.

5.2 Inundation risk due to storm tide and extreme wave

Coastal inundation risk maps due to the predicted 50-year-return storm tide and wave height (i.e. if the highest tide and worst storm occur simultaneously) clearly show that parts of the Gippsland Coastline could be at risk of inundation (Figures 41-44). It should be noted that the joint probability of the 50-year-return wave and the 50-year-return storm tide is ranging from 2/50 to 1/2500 yr⁻¹. To combine the two and assign probabilities requires knowledge of the level of dependence of the two. This inundation is a risk that increases from the present time to year 2056 due to climate change induced sea level rise. The predicted inundation is mainly at the borders of the existing lakes in the zone between the lakes and the coastline. The width of the inundated regions, in many areas, exceeds one km even within the current mean sea level scenario. Inundated regions > 2 km width are predicted within the 2056 mean sea level scenario particularly in the area north of the Lake Wellington Fault System (Figure 44). It should be noted that significant uncertainty underlies these predictions, which could be improved with accessing and analysing a wave record of duration longer than the 5 years record which was used in the study. Moreover, a more accurate digital elevation map would increase the accuracy of the predicted inundation maps.
5.3 Inundation risk due to the combined effect.

The simulations conducted predict that subsidence due to fluid extraction, although small in comparison, will exacerbate the risk of inundation of the coastline due to extreme storm tide and wave conditions with larger parts of the Gippsland Coastline being affected. The area north of the Lake Wellington Fault System was not included in the subsidence study so predicted inundated areas there are only due to storm tide and extreme wave height calculations.

Despite all the uncertainties involved in the calculations, we have tried to quantify the land subsidence contribution to the combined risk of inundation at the coastline. We see in Table 13 that the predicted subsidence contribution to the combined inundation risk ranges between 1% and 20%. The larger subsidence contributions are associated with areas of very low combined risk of inundation on the coastline south of the Darriman Fault System (Table 14 and Figures 45-52, also see Tables 8 and 13). The error in the vertical resolution of the SRTM DEM data may result in an underestimation of the extent of inundation.

<table>
<thead>
<tr>
<th>Region</th>
<th>Subsidence contribution to the total inundation in 2031 (%)</th>
<th>Subsidence contribution to the total inundation in 2056 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Realistic</td>
<td>Pessimistic</td>
</tr>
<tr>
<td>Between Lake Wellington and Rosedale Fault Systems</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Between the Rosedale and Darriman Fault Systems</td>
<td>2.5</td>
<td>3</td>
</tr>
<tr>
<td>South of the Darriman Fault System</td>
<td>10</td>
<td>12.2</td>
</tr>
</tbody>
</table>

**Table 13. Summary of subsidence contribution to the total inundation risk predicted at the coastline. Pessimistic and realistic scenarios coincide between the Lake Wellington and Rosedale Fault System.**

<table>
<thead>
<tr>
<th>Region</th>
<th>Extreme wave height based on 2031 mean sea level (m)</th>
<th>Subsidence in 2031 (m)</th>
<th>Extreme wave height based on 2056 mean sea level (m)</th>
<th>Subsidence in 2056 (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Lake Wellington and Rosedale Fault Systems</td>
<td>7-8.5</td>
<td>0.10-0.35</td>
<td>7-9</td>
<td>0.20-0.40</td>
</tr>
<tr>
<td>Between the Rosedale and Darriman Fault Systems</td>
<td>3-7</td>
<td>0.22-0.87</td>
<td>3-7</td>
<td>0.20-1.20</td>
</tr>
<tr>
<td>South of the Darriman Fault System</td>
<td>1</td>
<td>0.1-0.3</td>
<td>1</td>
<td>0.1-0.5</td>
</tr>
</tbody>
</table>

**Table 14. Comparison of predicted subsidence limits to predicted extreme wave height levels for the years 2031 and 2056.**
Figure 29. Gippsland Basin Risk Study: extents of data input to the subsidence model.
Figure 30. A 3 arc second (90 m) DEM is used on shore. White colour indicates gaps in the elevation data.
Figure 31. Area covered by the 0.1 arc second (90 m) DEM zoomed to the southern part of the coast line. White colour indicates gaps in the elevation data.
Figure 32. Area covered by the 3 arc second (90 m) DEM zoomed to the central part of the cost line. White colour indicates gaps in the elevation data.
Figure 33. Area covered by the 3 arc second (90 m) DEM zoomed to the northern part of the cost line. White colour indicates gaps in the elevation data.
Figure 34. Gippsland Basin risk study. Inundation risk due to predicted subsidence due to both scenarios for various times.
Figure 35. Gippsland Basin risk study. Inundation risk due to predicted subsidence under both hydraulic head scenarios for year 2031 zoomed to the southern part of the study area.
Figure 36. Gippsland Basin risk study. Inundation risk due to predicted subsidence under both hydraulic head scenarios for year 2031 zoomed to the central part of the study area.
Figure 37. Gippsland Basin risk study. Inundation risk due to predicted subsidence under both hydraulic head scenarios for year 2031 zoomed to the northern part of the study area.
Figure 38. Gippsland Basin risk study. Inundation risk due to predicted subsidence under both hydraulic head scenarios for year 2056 zoomed to the southern part of the study area.
Figure 39. Gippsland Basin risk study. Inundation risk due to predicted subsidence under both hydraulic head scenarios for year 2056 zoomed to the central part of the study area.
Figure 40. Gippsland Basin risk study. Inundation risk due to predicted subsidence under both hydraulic head scenarios for year 2056 zoomed to the northern part of the study area.
Gippsland Basin Risk Study Area
- Sea/Storm Tide/Wave inundations

Legend:
- Oil Field
- Gas Field
- Lakes
- Coast
- Faults

Current Inundation
plus 2031 Inundation
plus 2056 Inundation

Figure 41 Gippsland Basin Risk Study sea level/storm tide/wave inundation risk predicted for various times.
Gippsland Basin Risk Study Area
- Sea/Storm Tide/Wave inundations

Legend
- Oil Field
- Gas Field
- Lakes
- Coast
- Faults

Current Inundation
plus 2031 Inundation
plus 2056 Inundation

Figure 42. Gippsland Basin Risk Study sea level/storm tide/wave inundation risk predicted for various times and zoomed to the southern coast part of the study area.
Figure 43. Gippsland Basin Risk Study sea level/storm tide/wave inundation risk predicted for various times and zoomed to the central coast part of the study area.
Figure 44. Gippsland Basin Risk Study sea level/storm tide/wave inundation risk predicted for various times and zoomed to the northern coast part of the study area.
Figure 45. Gippsland Basin Risk Study 2031 sea level/storm tide/wave plus subsidence inundation risk. Pessimistic and realistic scenarios coincide between the Wellington and Rosedale Fault System.
Figure 46. Gippsland Basin Risk Study: 2031 sea level/storm tide/wave plus subsidence inundation risk zoomed to the southern coast part of the study area.
Figure 47. Gippsland Basin Risk Study: 2031 sea level/storm tide/wave plus subsidence inundation risk zoomed to the central coast part of the study area.
Figure 48. Gippsland Basin Risk Study: 2031 sea level/storm tide/wave plus subsidence inundation risk zoomed to the northern coast part of the study area. Pessimistic and realistic scenarios coincide between the Wellington and Rosedale Fault System.
Figure 49. Gippsland Basin Risk Study: 2056 sea level/storm tide/wave plus subsidence inundation risk. Pessimistic and realistic scenarios coincide between the Wellington and Rosedale Fault System.
Figure 50. Gippsland Basin Risk Study 2056 sea level/storm tide/wave plus subsidence inundation risk zoomed to the southern coast part of the study area.
Figure 51. Gippsland Basin Risk Study 2056 sea level/storm tide/wave plus subsidence inundation risk zoomed to the central coast part of the study area.
Figure 52. Gippsland Basin risk study. 2056 sea level/storm tide/wave plus subsidence inundation risk zoomed to the northern coast part of the study area. Pessimistic and realistic scenarios coincide between the Wellington and Rosedale Fault System.
6 FINAL CONCLUSIONS AND RECOMMENDATIONS

In an effort to reduce uncertainty in previous predictions of coastal subsidence, the CSIRO Wealth From Oceans flagship program conducted this modelling study using data and results of the Hatton Report in parallel with a Victoria Department of Primary Industries (Vic DPI) high resolution GPS ground level elevation monitoring program. In order to put coastal inundation risk due to subsidence in perspective with other coastal risks, this report also examined the risk of coastal inundation due to the 50-year-return storm tide and extreme wave height in the context of climate change and rising sea level.

The findings of the study, suggest that the risk of coastal inundation due to subsidence is small compared to that of storm tide and extreme wave. Whilst it would be possible to further reduce the uncertainty in the expected subsidence with rock property measurements and a better stratigraphic model, it is expected that these would only lead to marginal gains in the prediction of the inundation risk. For this purpose, it is expected that the cost of additional work on subsidence would not be warranted in light of the large uncertainty in the coastal digital elevation model.

The product of this study is a series of coastal subsidence and inundation risk maps for the Gippsland Basin. To arrive at these maps two types of calculations have been conducted: prediction of subsidence at discrete points along the coastline and simulations of the expected extreme (50-year-return) wave heights, storm tides and sea level heights across Gippsland Coast.

Subsidence calculations have been expanded from previous work to incorporate pore pressure and thickness/lithology data from well data along the coastal region of the Gippsland Basin. Two hydraulic head profiles bracketing the possible scenarios of future aquifer depletion, a realistic and a pessimistic scenario, have been input to the subsidence prediction calculations. The hydraulic head profiles used for modelling subsidence in the region north of the Rosedale Fault System are based only on the pessimistic scenario because the aquifer here is mainly impacted by coal mine dewatering (Hatton et al. 2004). Estimates of aquifer recovery described by Leong (2006) which are used to predict the realistic scenario only apply for the region south of the Rosedale Fault System.

Rock compressibility proposed by Sinclair Knight Merz (2001a) to calculate the subsidence at Alberton 3 has been used after being scaled down to account for varying aquifer thickness and confinement. Land subsidence measurements produced by the Victorian DPI high resolution GPS study between June 2004 and November 2005 have been examined. Both the predicted realistic subsidence values and the Vic DPI measurements were within the error of the measuring gauges. This fact, added to the nature of the predicted subsidence (i.e. ultimate subsidence) prohibited the use of these measurements to back estimate and further refine the mechanical parameters at various locations. These measurements are nevertheless valuable in confirming that the aquifer is overconsolidated. Measurements for longer periods would be useful for the purpose of back calculating mechanical parameters if the measurements eventually recorded statistically significant subsidence.

Within the assumptions of the model, the maximum subsidence predicted under the pessimistic hydraulic head scenario (extreme depletion scenario) was at the well where the aquifer is thickest and most depleted, Golden Beach West 1 (1208 mm in year 2056). The subsidence predicted at the same location and time within a more realistic depletion scenario was 480 mm. These figures for year 2031 were 866 mm and 514 mm respectively. At the locations where the aquifer is thick, the model may be over-predicting subsidence because there is a larger uncertainty about the detailed lithology and a possibility of intraformational barriers that could lead to pressure compartmentalization.

Subsidence results have been linked in a Geographic Information System and overlain with a digital elevation model (DEM) of the land surface. The DEM data is the 3 ARC Second (90 m) data set prepared by Shuttle Radar Topography Mission (SRTM) in the year 2000 and obtained through the
United States Geological Survey (2000). Inundation risk resulting from subsidence alone was not visible in the maps except when zoomed to more detail. Areas affected by subsidence risk alone are restricted to small margins of Lake Reeve and Lake Coleman. The presence of gaps in the DEM model for these areas adds uncertainty to the inundation risk here. Due to the regional nature of the predicted land settlement, it is not expected that subsidence will affect the structural integrity of buildings. Special investigation might be needed particularly in the vicinity of the Rosedale Fault to ensure the serviceability of pipelines on the coastline.

Simulations have been conducted to estimate the extreme (50-year-return) storm tide and wave heights across the Gippsland Coast under the current climate and in the context of sea level rise due to global warming for 2031 and 2056. Simulation results were linked to the same above DEM data and inundation risk maps were produced for the situation where the highest tide and worst storm occur simultaneously. This inundation risk increases from the present time to year 2056 due to predicted climate induced sea level rise. The predicted inundation risk is mainly at the borders of the existing lakes in the zone between the lakes and the coastline. The width of the inundated regions, in many areas, exceeds one km even within the current mean sea level scenario. Risk of inundated regions exceeding 2 km width is predicted within the 2056 mean sea level scenario particularly in the area north of the Lake Wellington Fault System, Figure 33.

Coastal inundation risk maps that account for the joint effect of subsidence and the extreme (50-year-return) storm tide and extreme wave heights have also been constructed. The simulations conducted predict that subsidence due to fluid extraction, although small in comparison, will exacerbate the risk of inundation of the coastline due to extreme storm tide and wave conditions with larger parts of the Gippsland Coastline potentially being affected.

The predicted subsidence contribution to the total inundation risk ranges between 1% and 20%. It is important to note that the larger subsidence contributions are associated with areas of very low total risk of inundation along the coastline south of the Darriman Fault System.

It is important to emphasize that the uncertainty in the predicted subsidence risk can be attributed to one or more of the following reasons:

1. The settlement computed is the ultimate settlement. In addition to the rate of pressure depletion dictated by the fluid withdrawal, the determination of the exact settlement rate and time requires knowledge of the exact thickness of the compressible layers affected by the stress increase due to the pressure decline and their exact hydraulic conductivity.
2. Impermeable layers (e.g. clayey limestone) in the Latrobe Aquifer that we may have not captured in our aquifer thickness estimate, if present, could lead to vertical compartmentalization of the pressure drawdown in those areas of the aquifer. In this case the entire thickness of the aquifer, as we defined it, may not be affected by pressure reduction and the predicted ultimate subsidence may be overestimated.
3. The layers on top of the aquifer are not included in the subsidence calculation; these layers are usually more compressible than the aquifer. Their effect was treated as an overburden pressure.
4. The subsidence predictions are based on the assumption that the aquifer at the Gippsland Coast is over consolidated. Deviation from this assumption would have significant impact on the subsidence predicted. The preconsolidation stress determines when the transition to non recoverable large subsidence occurs.
5. The mechanical compressibilities used in the predictions were guided by values adopted at the Latrobe Valley Coal Mines by Helm (1984) and those were deduced by back calculations from subsidence measurements and measurements of the overconsolidation stress.
6. Other processes not considered in this report might be affecting the observed subsidence. For example, the region might be undergoing geological inversion due to the tectonic stress conditions which causes uplift. This effect was not studied nor quantified within this study.
Hence a better estimation of the subsidence and reduced uncertainty would require:

1. A better knowledge of the detailed stratigraphy and lithology of the Latrobe and adjacent strata aided by geological and petrophysical log interpretation.
2. Pressure measurements throughout the vertical extent of the aquifer at various locations.
3. Drilling for cores and performing tests on undisturbed samples to predict the mechanical properties and overconsolidation stress of the sediments in the aquifer along the coastline. Sample quality is particularly important in the case of the sensitive clays.
4. Performing tests to estimate the hydraulic conductivity of the sediments.
5. Longer duration measurements of surface subsidence using high resolution GPS can be very valuable in calibrating (back calculating) the mechanical parameters in the absence of cores.
6. Knowledge of the geodynamics of the region might add insight into the subsidence calculations.

The uncertainty in the storm wave calculations can be attributed to the following reasons:

1. It should be noted that the joint probability of the 50-year-return wave and the 50-year-return storm tide is between 2/50 and 1/2500 yr\(^{-1}\). To combine the two and assign probabilities requires knowledge of the level of dependence between the two.
2. The wave record duration is only 5 years.
3. The GA bathymetry was based on a 250 m resolution DEM with 20 m water depth accuracy.

Hence estimation of the storm tide and extreme wave prediction can be improved if:

1. A wave record longer than 5 years can be used
2. A more accurate digital elevation map for the coastal region and offshore bathymetry were available to increase the accuracy of the predicted inundation maps.

In addition to all the above uncertainties, special attention needs to be paid to the vertical resolution of the SRTM DEM. The accuracy of this data can have the following impact:

1. The positive bias of the error in the vertical resolution leads to overestimating the elevation and hence underestimating the resulting inundation by both contributing processes (subsidence and the 50-year-return storm tide and extreme wave heights).
2. The risk maps showing inundation caused by subsidence include the land settlement during the first 30 years of fluid withdrawal. The DEM data is measured in year 2000, which should include subsidence to 2000 already. This results in overestimation of the contribution of land subsidence to inundation. Please note that this amount was negligible, as per section 5.2.

If further work were to be done, we recommend that continued measurements of the Vic DPI high resolution GPS system and improvements to the accuracy of the DEM model for the Gippsland coast would lead to the most significant further reduction in uncertainty of coastal inundation risk for the least cost.

Moreover, the coastal subsidence risk map produced in this study could be used to guide sampling and data collection (mechanical rock properties from core and vertical pressure profiles of the entire Latrobe Aquifer thickness) in areas of highest subsidence risk. The actual 3-D pressure depletion profile characterized in the first phase of this research could be input to a 3-D numerical subsidence simulation model (instead of the series of 1D models presented here). Similarly, a better constrained stratigraphic and structural geology model along the coastal zone could be built into the model with the compressibility of interbedded soft layers included. The subsidence numerical simulation might include the region north of the Lake Wellington Fault System which in this evaluation was only risked for inundation due to the 50-year-return storm tide and wave height. This would require a hydrodynamic evaluation of the region to predict aquifer recovery/depletion. The upgraded subsidence model could also include the possible transient impact of proposed offshore CO\(_2\) sequestration that might allow a faster recovery of aquifer pressure. When the 3-D numerical model is complete, it could be calibrated against continued observations from the Victorian DPI high resolution GPS monitoring program were it to continue.
7 ACKNOWLEDGMENTS

We thank the Department of Primary Industries and Geoscience Australia for providing us with data and reports. We also appreciate valuable comments and feedback on our preliminary findings and recommendations from Drs Kathy Hill, Geoff O’Brien and Terry McKinley at DPI, Simon Baker, Jennifer Fraser at DSE and Mr Tom Snow and his staff at Esso Australia Pty Ltd. This work was supported by CSIRO Wealth from Oceans Flagship program.

8 REFERENCES

Allen M.S. and Callaghan J. (1999), "Extreme Wave Conditions in the South Queensland Coastal Region", Environmental Protection Agency.
Helm, D. 1976. One-dimensional simulation of aquifer system compaction near Pixley, California. 2 Stress dependent parameters. Water Resources Research V. 12, No. 3 pp 375-391


McInnes, K.L., Macadam, I., Hubbert, G.D., 2006: Climate Change in Eastern Victoria Stage 3 Report: The effect of climate change on extreme sea levels in Corner Inlet and the Gippsland Lakes A Project Undertaken for the Gippsland Coastal Board, the Antarctic Climate and Ecosystem CRC and the Australian Climate Change Research Program


After the completion of this report a new set of ground surface elevation measurements were made available to us by the Victorian DPI high resolution GPS program –Epoch 3 (2007). The survey showed that there is no statistically significant subsidence measured. The measurements obtained until year 2005 (from the previous survey Epoch 2) were larger than those recorded in May 2007 at many stations, Figure 53. The new measurements follow those obtained in Epoch 2 in that no geographical pattern could be deduced from these measurements.

As per the realistic hydraulic head scenario, subsidence predicted between June 2004 and May 2007 will be smaller than double that predicted from June 2004 to November 2005 due to the expected recovery of aquifer pore pressure. The largest subsidence in the period from June 2004 to November 2005 is 8.47 mm and is predicted for Wulla Wullock 5 and Carrs Creek 1 where the aquifer thickness is assumed to be 988m (Table 4). If we double this value we get a subsidence of 16.94 mm which is close to the accuracy limit of the measurement gauges (16.6). This may suggest a possibility of a slight reduction (2%) in the compressibility of the sediments we have used in the modelling at this location. This option is discouraged by the fact that the difference is minimal, and more importantly, by the fact that what we predict is the total ultimate subsidence, which we assume to be immediate, while it will in fact be delayed (see Appendix A). As a result, it is thought that even if the compressibilities we used were representative of the mechanical properties of the compressing sediments, the lack of detailed lithology at the locations studied, which led to the use of the ultimate settlement approach, prohibits direct comparison with DPI measurements and their use to calibrate the mechanical parameters used in the modelling (considering the realistic scenario). The high resolution GPS measurements program needs to continue for a further couple of years until measurements within the accuracy range of the gauges are obtained. These accurate measurements combined with detailed knowledge of the stratigraphy along the coastline could generate more accurate predictions to the subsidence.
Figure 53. DPI high resolution GPS subsidence measurement results.
10 APPENDIX A: VARIOUS FACTORS AFFECTING SETTLEMENT PREDICTIONS

Subsidence results from increasing the stresses born by the solids part of the sediments—the effective stresses. This can happen when an additional load is applied to the sediments or when the fluid that was bearing part of the original load on the sediments gradually escapes or gets pumped out of the sediments (Underschultz et al., 2006). The components of any subsidence prediction model are as follows:

1. Sediments compressibility
2. Hydraulic conductivity of compressible layers
3. Preconsolidation stress
4. Sediments thickness
5. Hydraulic head decline

In this Appendix we show the impact of various sediment properties on the predicted settlements. The figures show the settlement with time due to fluid withdrawal at the rate of 1.86 m/yr for 86 years. We vary the hydraulic conductivity and compressible aquifer thickness and preconsolidation stress. The details of every case are in the figure caption. Cases in Figure 54-58 assume $S_{skc} = 7 \times 10^{-6}$ and $S_{skv} = 7 \times 10^{-5}$ for the compressible layers and $1/10^6$ of that for the sands. The preconsolidation stress in Figure 58 is reduced from 200 m fluid withdrawal to 100 m fluid withdrawal. The settlement predicted in our model corresponds to the case in Figure 55 where all the aquifer thickness used in the subsidence predictions is assumed to respond immediately to the pressure drop in an elastic manner.

Figure 54. Assume $K=1.12 \times 10^{-4}$ m/yr, aquifer thickness=1102 m, all compressible-overconsolidated sediments.
Figure 55. Ultimate settlement achieved by using a high permeability. K=1 m/yr, aquifer thickness=1102 m, consists of compressible and overconsolidated sediments.

Figure 56. K=1 m/yr, aquifer thickness=570 m and compressible clay lenses thickness 299.5 m- overconsolidated sediments. Sands are given one tenth of clay compressibility.
Figure 57. $K=1.12 \times 10^{-4}$ m/yr, aquifer thickness=570 m and clay lenses thickness 299.5 m-overconsolidated sediments. Sands are given one tenth of clay compressibility.

Figure 58. $K=1.12 \times 10^{-4}$ m/yr, aquifer thickness=570 m and clay lenses thickness 299.5 m. The pre-consolidation stress =100 m. Sands are given one tenth of clay compressibility.