Assessment of salinity risks to the groundwater resources of the Northern Adelaide Plains and Central Adelaide PWAs

Steve Barnett
Department for Environment and Water

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81-95 Waymouth St, ADELAIDE SA 5000

Telephone +61 (8) 8463 6946

Facsimile +61 (8) 8463 6999

ABN 36702093234

www.environment.sa.gov.au

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Report prepared by:

Steve Barnett

Water Science Unit

Strategy Science and Corporate Services Division
Department for Environment and Water

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Foreword

The Department for Environment and Water (DEW) is responsible for the management of the State's natural resources, ranging from policy leadership to on-ground delivery in consultation with government, industry and communities.

High-quality science and effective monitoring provides the foundation for the successful management of our environment and natural resources. This is achieved through undertaking appropriate research, investigations, assessments, monitoring and evaluation.

DEW's strong partnerships with educational and research institutions, industries, government agencies, Natural Resources Management Boards and the community ensures that there is continual capacity building across the sector, and that the best skills and expertise are used to inform decision making.

John Schutz
CHIEF EXECUTIVE
DEPARTMENT FOR ENVIRONMENT AND WATER

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Summary

Groundwater in the Tertiary aquifers of the St Vincent Basin is a vital resource which has been widely developed for irrigation and industrial purposes. One of the risks to sustainable development of groundwater resources in the area are increases in groundwater salinity which may occur through several processes, such as sea water intrusion, leaky wells and inter-aquifer leakage. A better definition of the hydrostratigraphy of the basin and a comprehensive evaluation of long term salinity monitoring results in the Northern Adelaide Plains (NAP) and Central Adelaide (CA) Prescribed Wells Areas (PWA) have increased the understanding of the processes that may cause salinity increases in the T1 and T2 aquifers and enabled an assessment of the likelihood of them occurring.

Comprehensive monitoring of irrigation wells in the NAP PWA has indicated the movement of plumes of more saline groundwater originating from leaky wells presents the highest risk of salinity increases, even in pressure cemented PVC cased wells. Although 651 wells display a rising trend in salinity, many of these may experience a declining trend in the future as the higher salinity plumes move downgradient away from these wells. Similarly in the CA PWA, leaky wells and associated higher salinity plumes present the highest risk of salinity increases, but this risk is restricted to the western suburb golf courses which have a long and on-going history of groundwater use.

The widespread occurrence of long term stable trends (in all types of well construction) in areas of heaviest extraction from both aquifers indicates that the likelihood of salinity increases occurring from regional processes such as vertical inter-aquifer leakage is low in both the NAP and CA PWAs. The hydrogeological setting also contributes to this low likelihood through the presence of very thick confining layers and the historical upward leakage of low salinity groundwater before irrigation development occurred. The distribution of salinity trends also indicates that the lateral flow of more saline groundwater has not been the obvious cause of any observed salinity increases.

The risk of sea water intrusion is difficult to assess in both the NAP and CA PWAs because the location of the salt water interface in both confined aquifers is unknown. However, the likelihood is considered low because of the thick protective cover of the Hindmarsh Clay overlying the aquifers. In addition, there is a highly probability of fresh groundwater flow westwards under the ocean when the sea level was historically about 120 m lower than it is today would suggest that fresh groundwater in both T1 and T2 confined aquifers extends a considerable distance offshore. In recent years, the potential risk of sea water intrusion would also have diminished significantly because of the cessation of pumping due to the closure of some industries which has resulted in a strong recovery of the cone of depression in both T1 and T2 aquifers between Outer Harbour and West Lakes.

1 Introduction

The Tertiary aquifers of the St Vincent Basin underlie the Adelaide metropolitan area and the horticultural areas to the north of the city. Groundwater is a vital resource which has been developed for irrigation and industrial purposes as well as providing a storage medium for many MAR schemes. For management purposes, the area has been subdivided into the Northern Adelaide Plains and Central Adelaide Prescribed Wells Areas (NAP PWA and CA PWA), each with very different development scenarios. The NAP PWA is arguably the most intensively developed groundwater resource in Australia for the irrigation of horticulture with extractions of ~12 000 ML/yr, which has caused significant impacts on pressure levels since extractions began in the 1960s. In contrast, development in the CA PWA is much less intensive with extractions estimated at ~4500 ML/yr occurring for limited irrigation and industrial purposes.

One of the risks to sustainable development of groundwater resources in the area are increases in groundwater salinity which may occur by four main processes;

1. Addition of salt into wells from overlying brackish/saline aquifers through corroded casing (leaky wells)
2. Addition of salt by vertical leakage from formations above or below
3. Lateral movement of more saline groundwater within the aquifers
4. Sea water intrusion

The aim of this investigation was to assess the likelihood of these four processes occurring through a more detailed assessment of the hydrostratigraphy, the analysis of well construction methods and an assessment of observed salinity trends and the spatial distribution of these last two factors. Possible causes of the observed trends and implications for management of the resource are also examined.

This investigation of salinity risk has been greatly assisted by other work recently carried out which has also greatly improved the quality of data in the SA_Geodata database:

- The construction details of 2144 wells completed in the T1 and T2 aquifers were verified with corrections made to SA_Geodata where necessary, in particular to the casing type and cementing details.
- The locations of 1591 licenced wells completed in Quaternary and Tertiary aquifers were verified with available GPS readings from the Meter Data Management System and imagery, with most locations requiring corrections in the SA_Geodata database, some by up to several hundred metres.
- The addition of 917 hydrostratigraphic logs to the SA_Geodata database for wells within the St Vincent Basin has allowed the construction of 3D surfaces of the tops of the various aquifers. This enables the "Aquifer monitored" attribute for a well to be determined if the depth is known, even if there is no geological or drillers' logs available. This has allowed the "Aquifer monitored" attribute to be assigned to 3400 new wells, making a total of 21 200 wells (80%) that now have this attribute within the two PWAs.

2 Hydrogeology

The hydrostratigraphy within the St Vincent Basin has been well-defined by numerous investigations. The sedimentary sequence includes Quaternary and Tertiary sediments that extend to a depth of about 600 m below ground surface. These sediments can be broadly divided into five regional hydrostratigraphic units as shown in the geological cross section in Figure 1.

1. Hindmarsh Clay - has a thickness of up to 90 m and consists primarily of mottled clay and silt with interbedded sand and gravel layers which form up to three aquifers up to several metres thick (Q1–Q3 aquifers). These sand aquifers can provide stock, domestic and minor irrigation supplies where salinities are suitable in the NAP PWA. On the plains section of the CA PWA, over 6000 shallow 'backyard bores' have been drilled for domestic purposes.
2. Carisbrooke Sand (Q4) aquifer - comprises very fine grained, poorly consolidated sands about 10 m in thickness which in some areas, may have direct hydraulic connection with the overlying Q3 Aquifer or the underlying T1 Aquifer.
3. T1 Aquifer – comprises calcareous sands and a fossiliferous sandy limestone (Upper Port Willunga Formation) reaching a maximum of about 130 m in thickness. The T1 aquifer is mostly used in the southwest of the NAP PWA and the CA PWA (Fig. 1).
4. Munno Para Clay confining layer - consists of a thin layer of blue-grey shelly clay about 5 m thick.
5. T2 aquifer - consists of limestones and sands of the Lower Port Willunga Formation up to about 90 m in thickness and is mostly developed for irrigation in the northern half of the NAP PWA.

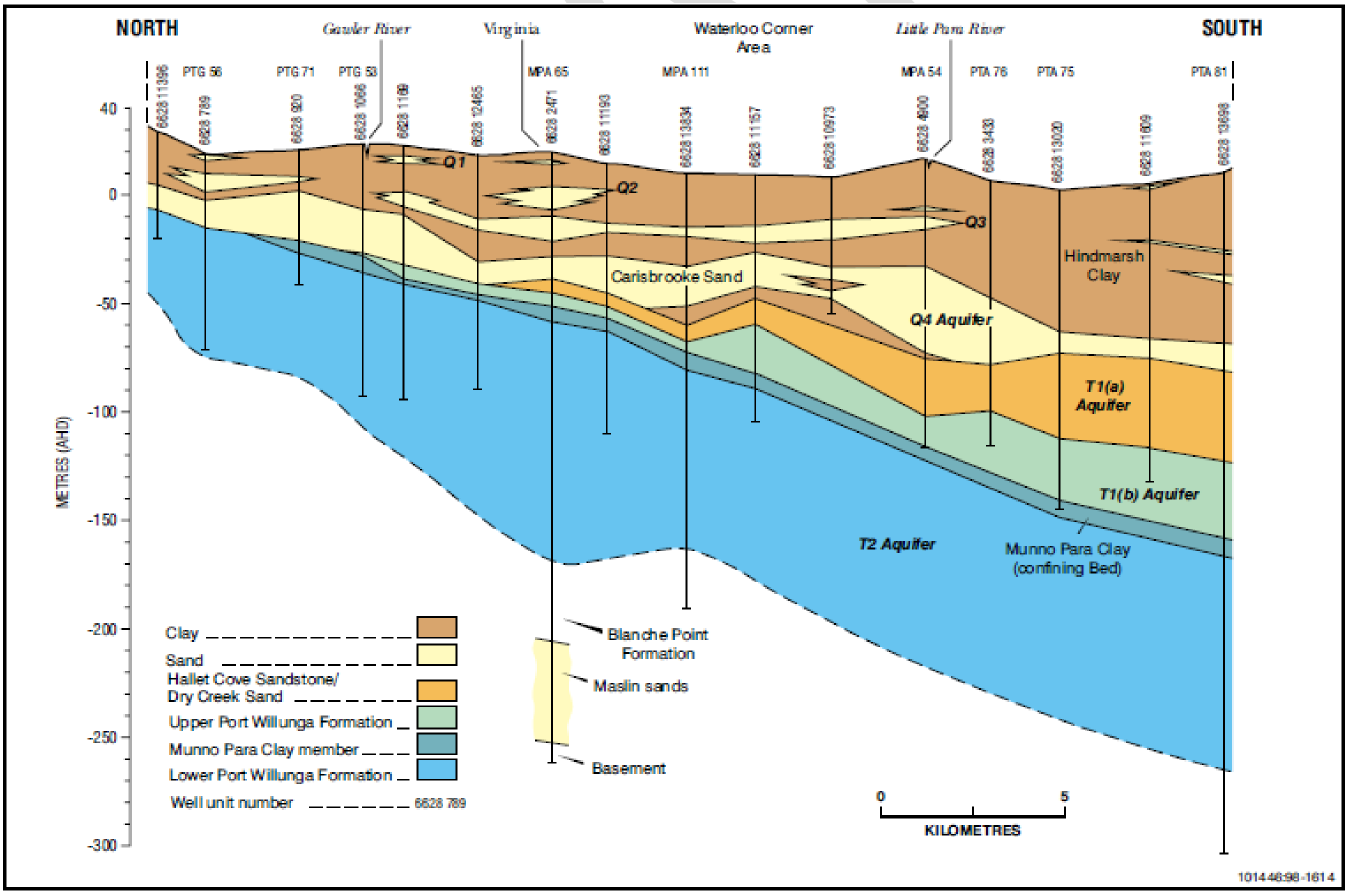


Figure 1. Simplified north-south geological cross section through the St Vincent Basin

3 Sources of salinity risk

There are four main processes that may cause increases in salinity in aquifers.

3.1 Leaky wells

Leaky wells are created by a process depicted in Figure 2, namely the corrosion of un-cemented steel casing by saline groundwater in the upper Quaternary aquifers. The type of well construction is an obvious indicator of the risk of such corrosion occurring, with un-cemented steel casing having the highest risk, pressure cemented steel casing having a medium risk and pressure cemented inert casing (PVC or FRP) having a negligible risk. When the saline water enters the aquifer, it may move downgradient away from the well as a plume of more saline groundwater. Appendix A explains how these plumes may affect the salinity response in nearby wells.

Changes to salinities due to leaky wells is a local scale process that affects individual wells to varying degrees.

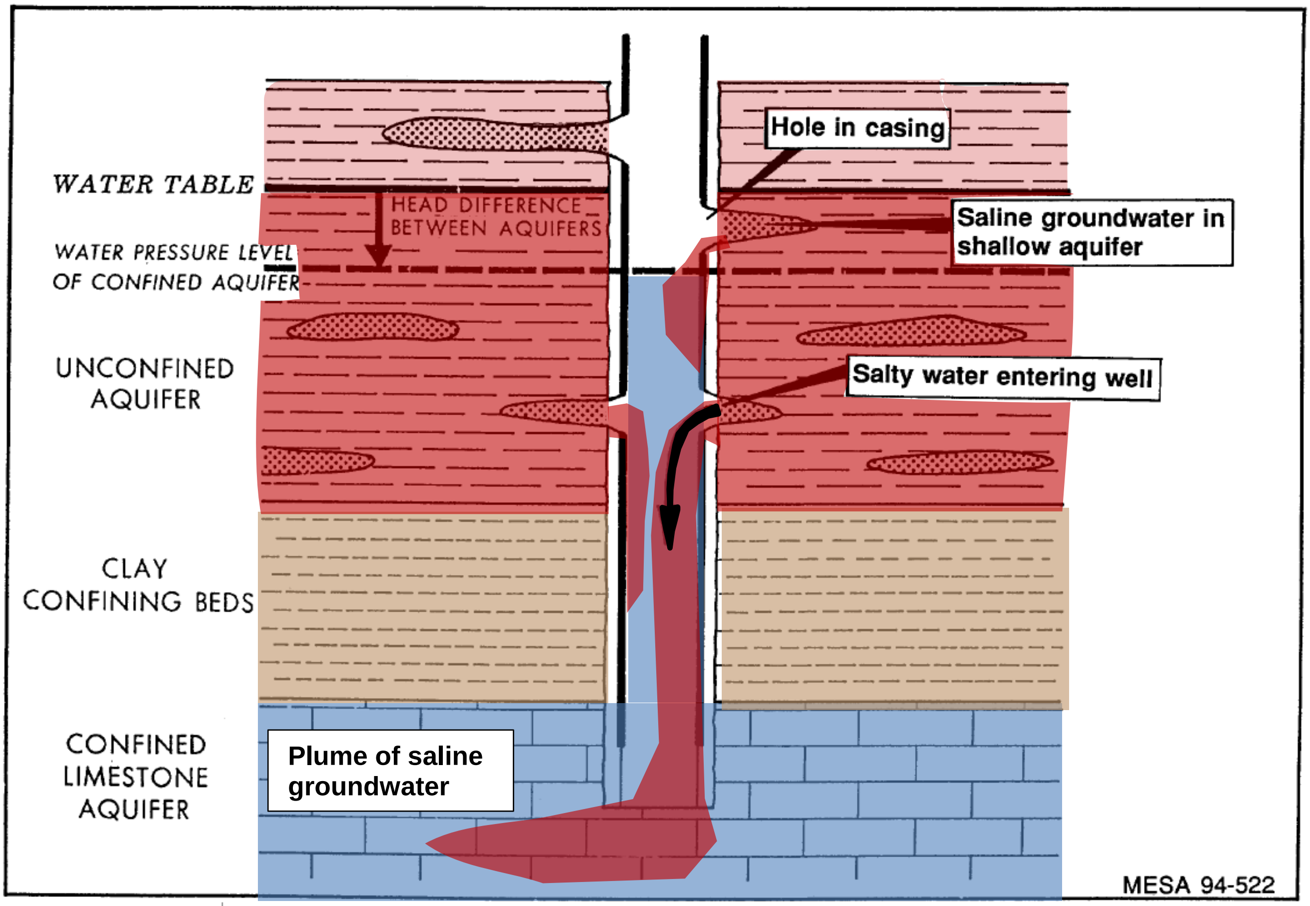


Figure 2. Leaky well process

3.2 Vertical leakage

Salt may be added to an aquifer by vertical leakage from formations above or below (Fig. 3). This process is controlled by the thickness and permeability of any confining layers and the difference in head between the formations that drives vertical movement. In the St Vincent Basin, this is expected to be a sub-regional diffuse process that occurs slowly and would be expected to affect most wells in a high risk area in a uniform way.

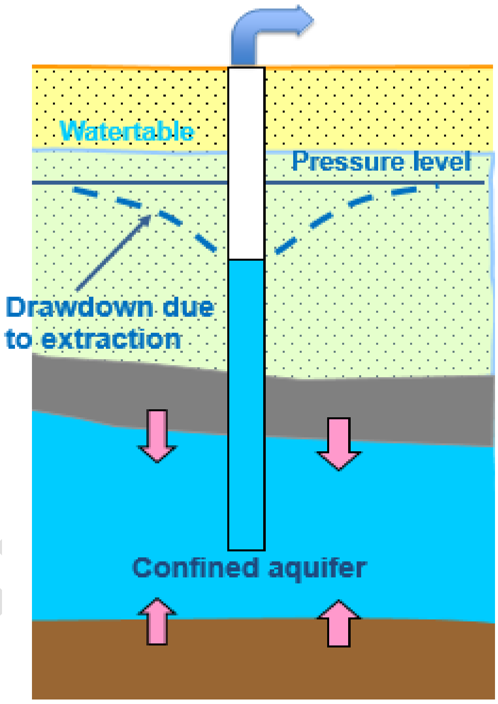


Figure 3. Vertical leakage process

3.3 Lateral movement

Lateral movement of more saline groundwater within the aquifers can occur when drawdowns due to the extraction of good quality groundwater can alter groundwater flow paths and induce movement of more saline groundwater into areas where extraction is occurring as shown in Figure 4. This is a sub-regional diffuse process that occurs slowly and would be expected to affect most wells in a high risk area in a uniform way.

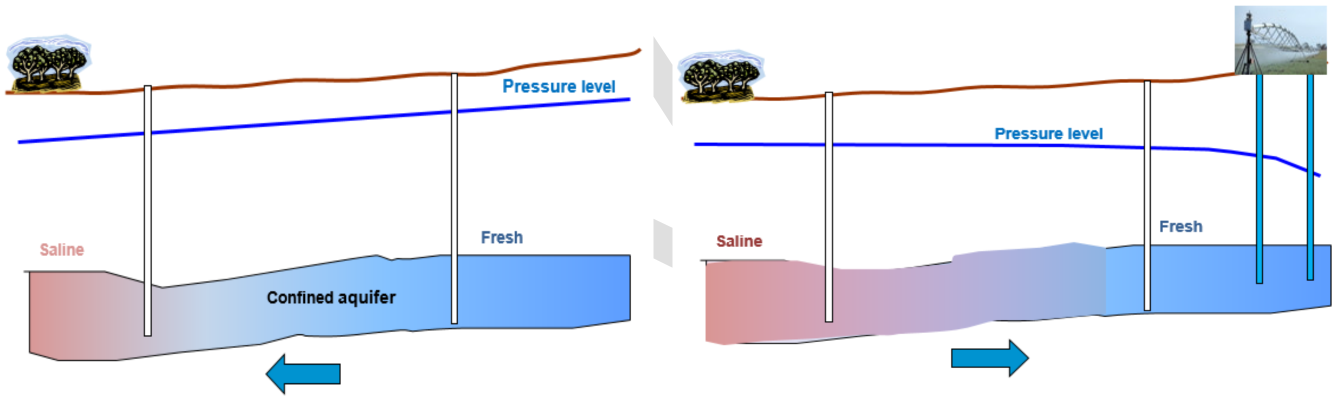


Figure 4. Lateral movement process

3.4 Sea water intrusion

Sea water intrusion is a well-documented process that occurs in aquifers hydraulically connected to the sea. When extraction lowers water levels close to sea, flow reversal may occur as depicted in Figure 4 which could result in sea water entering the aquifer. This is a sub-regional process that occurs slowly and would be expected to affect most wells in the high risk area close to the sea in a uniform way.

4 Well construction

Given that the risk of salinity increase can be highly dependent on the type of well completion, an analysis of the well construction history for the T1 and T2 aquifers in both the NAP and CA PWAs was carried out. Figures 2 and 4 show the number of wells drilled each year and their construction type up until the end of 2016. The un-cemented steel casing completions, which have the highest risk of corrosion, were phased out in the mid-1970s. A number of wells have been backfilled according to specifications or rehabilitated by relining and cementing smaller diameter PVC casing inside the steel casing. However, many of the wells that have not been backfilled or rehabilitated could potentially contribute to contamination of the Tertiary aquifers. Some of these older wells may have collapsed and have blockages and may not present a contamination risk, but a significant number are likely to be at risk of causing salinity contamination between aquifers.

4.1 Northern Adelaide Plains

Figure 5 and Table 1 show that 1081 un-cemented, steel-cased wells have been drilled, mostly during the 1960s, with the main driver for drilling activity being the expansion of irrigated horticulture. 403 wells were completed with pressure-cemented steel casing between 1967 and 1992. Since 1992, 687 wells have been drilled with pressure-cemented PVC casing. Many of these wells would have been drilled to replace older, corroded steel-cased wells.

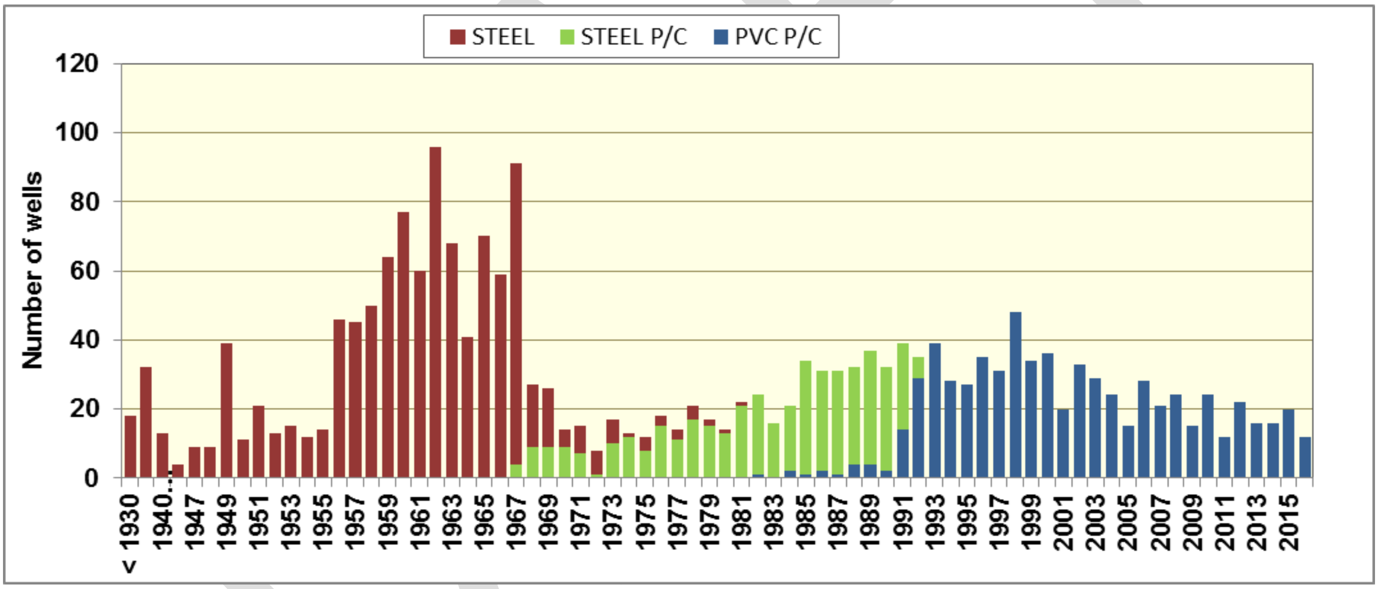


Figure 5. History of well construction in the NAP PWA

Table 1. NAP well completion summary

Well completion	No. of wells	Backfilled	Rehabilitated
Un-cemented steel	1084	440 (40%)	24 (2%)
Pressure cemented steel	405	74 (18%)	14 (3%)
Pressure cemented PVC	695	18 (3%)	2
Total	**2184**	**532 (24%)**	**40 (0.02%)**

Figure 6a shows the spatial distribution of these 2171 wells and their construction. There are no particular patterns of distribution, with the three types of construction widely spread through the PWA. Figure 6b shows the location of the 620 wells with un-cemented steel casing that have not been backfilled, together with the salinity of the shallow Quaternary aquifers. A higher risk of corrosion would occur where salinities are higher.

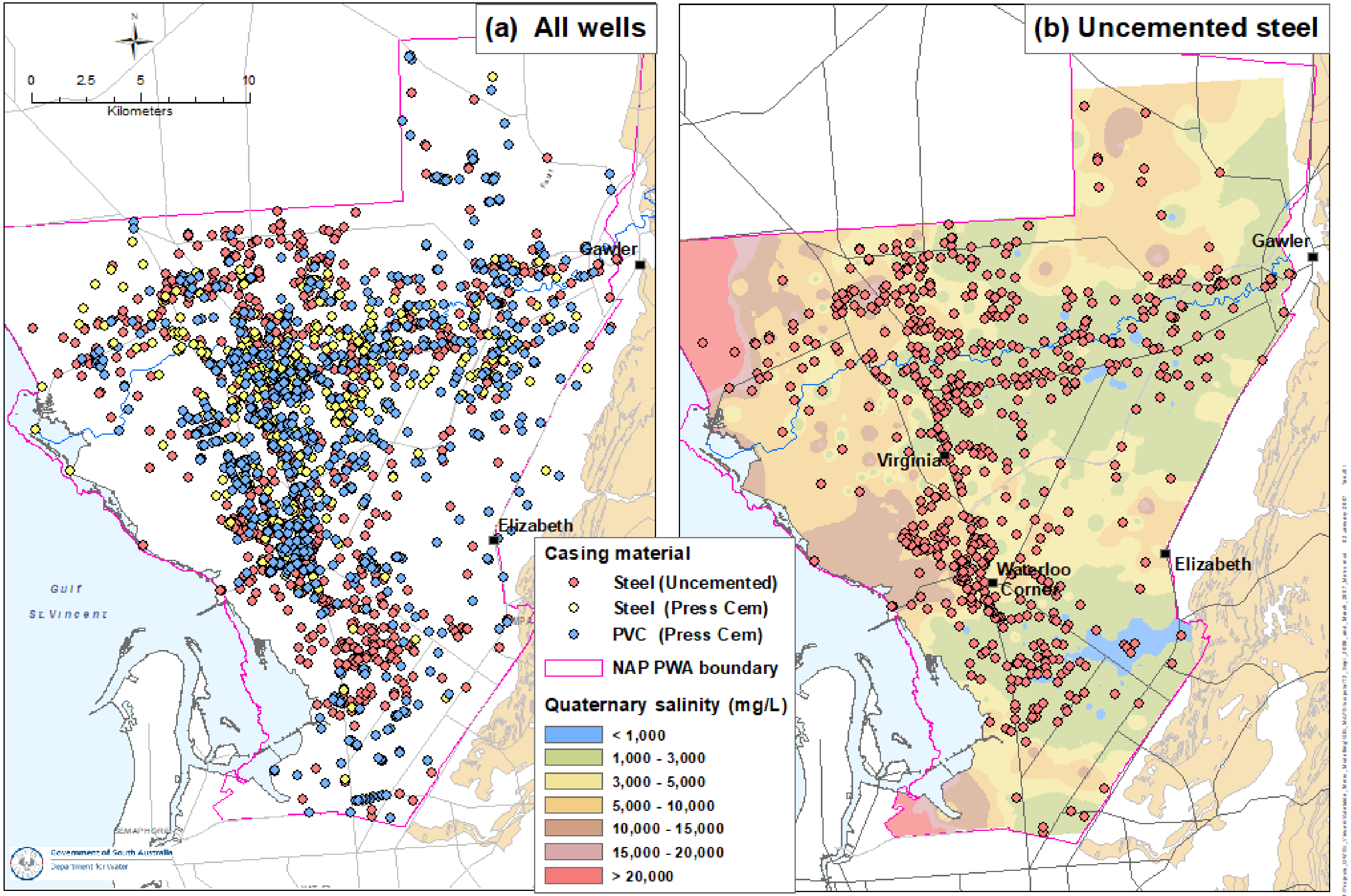


Figure 6. Well construction in the NAP PWA

4.2 Central Adelaide

There was no requirement for reporting drilling activity before 1976 as this area was not prescribed under any legislation. As a result, the SA_Geodata database does not include all the wells that were drilled. However, useful trends can be observed in the wells that are included in the database. The drilling history in the CA PWA is quite different to that in the NAP PWA. Not only were significantly fewer wells drilled, but the main driver for drilling activity appears to be periods of drought when surface water supplies were limited and access to them could be severely restricted (Figure 4). Examples of the need for these wells include industrial supplies and golf course irrigation (1915), public water supply and vegetable irrigation (1935), public water supply (1945), golf course irrigation (1950-51) and irrigation of school ovals (1967-68). More recently, the Millennium Drought resulted in increased drilling activity for the establishment of MAR schemes.

At least 352 un-cemented steel cased wells had been drilled up until 1976 (Figure 7 and Table 2). 65 wells were completed with pressure-cemented steel casing between 1949 and 1970. Since 1970, 247 wells have been drilled with pressure-cemented PVC casing, some of which would have been drilled to replace older steel-cased wells that were corroded.

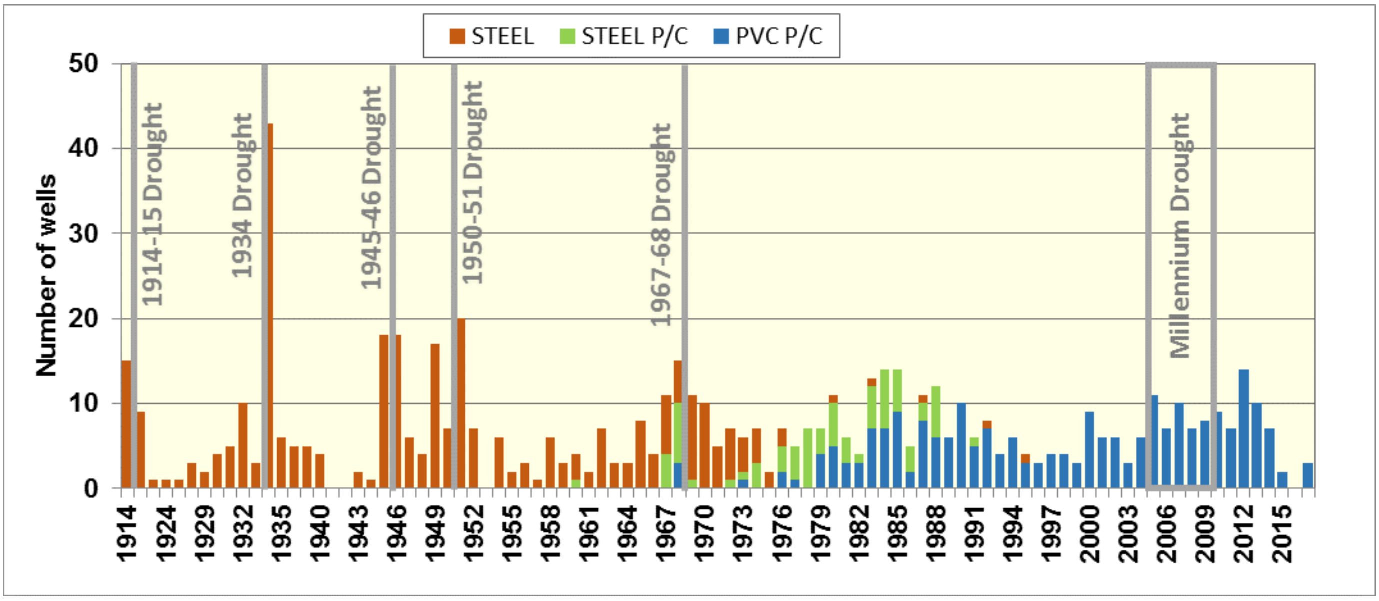


Figure 7. History of well construction in the CA PWA

Table 2. CAP well completion summary

Well completion	No. of wells	Backfilled	Rehabilitated
Un-cemented steel	352	115 (33%)	29 (0.08%)
Pressure cemented steel	65	27 (41%)	6 (0.09%)
Pressure cemented PVC	247	16 (0.06%)	13 (0.05%)
Total	**664**	**158 (24%)**	**48 (0.07%)**

Figure 5a shows the spatial distribution of these 664 wells and their construction. There are no particular patterns of distribution, with the three types of construction widely spread through the western part of the PWA. Figure 5b shows the location of the 208 wells with un-cemented steel casing that have not been backfilled, together with the salinity of the shallow Quaternary aquifers. A higher risk of corrosion would occur where salinities are higher.

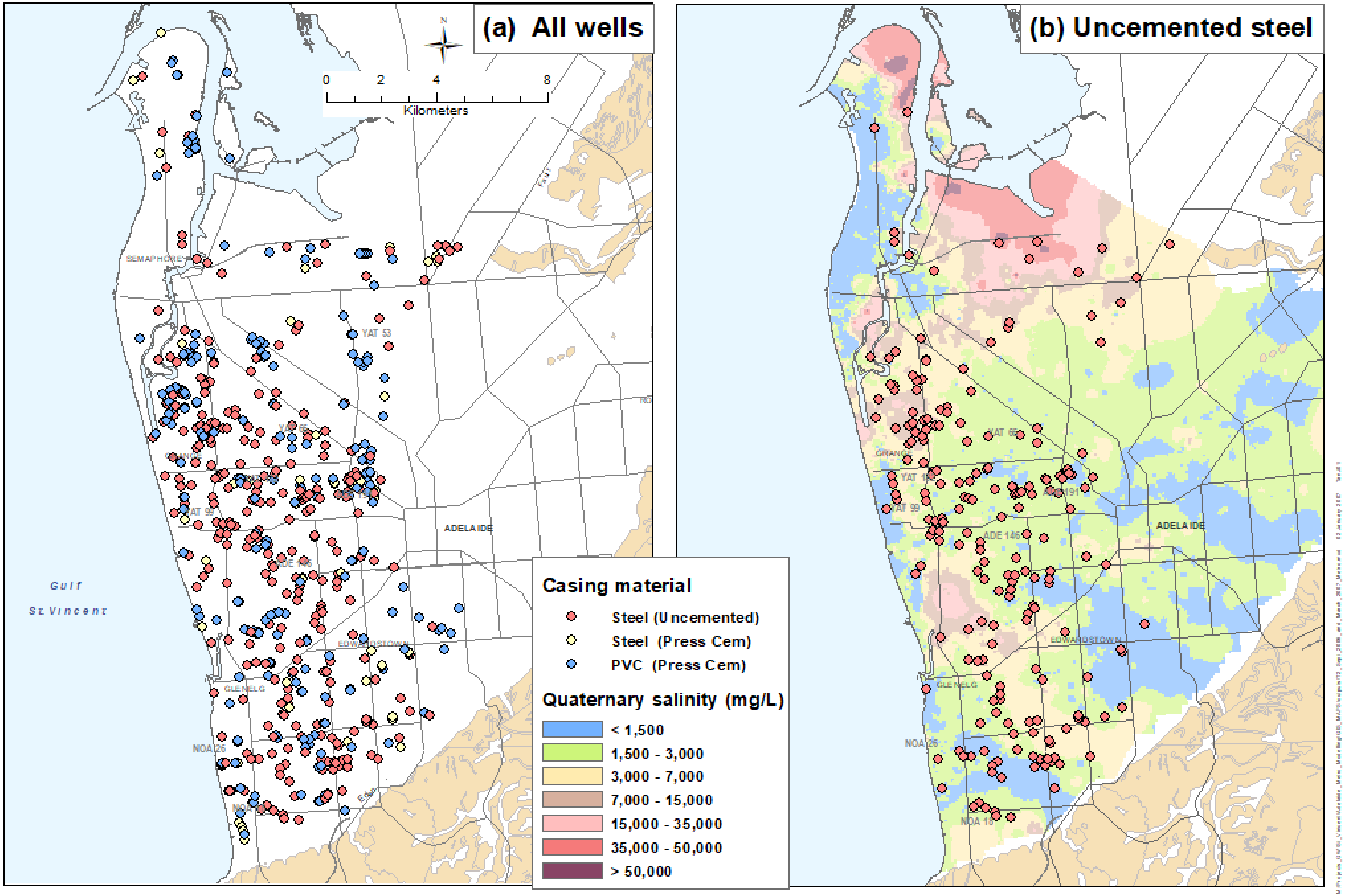


Figure 8. Well construction in the CA PWA

5 Salinity trends

5.1 NAP PWA salinity trends

Since the inception of the NAP Leaky Wells Project in 1998, the number of wells sampled for salinity increased dramatically. Figure 9 shows the gradual rise in the number of Tertiary wells sampled (in blue) until 2007. During this period, almost every licensed Tertiary well visited by a Departmental meter reader would have a sample collected for testing. The total number of licensed wells represents only about half of the total number of wells that had been drilled in the Tertiary aquifers at that time. The remainder would be mostly older abandoned or disused wells that have not been correctly backfilled. Since 2007, the number of wells sampled has gradually decreased to less than 50% of the licensed total. This is probably the result of less samples being submitted by irrigators for testing because they were no longer being notified of the salinity results due to resourcing restraints.

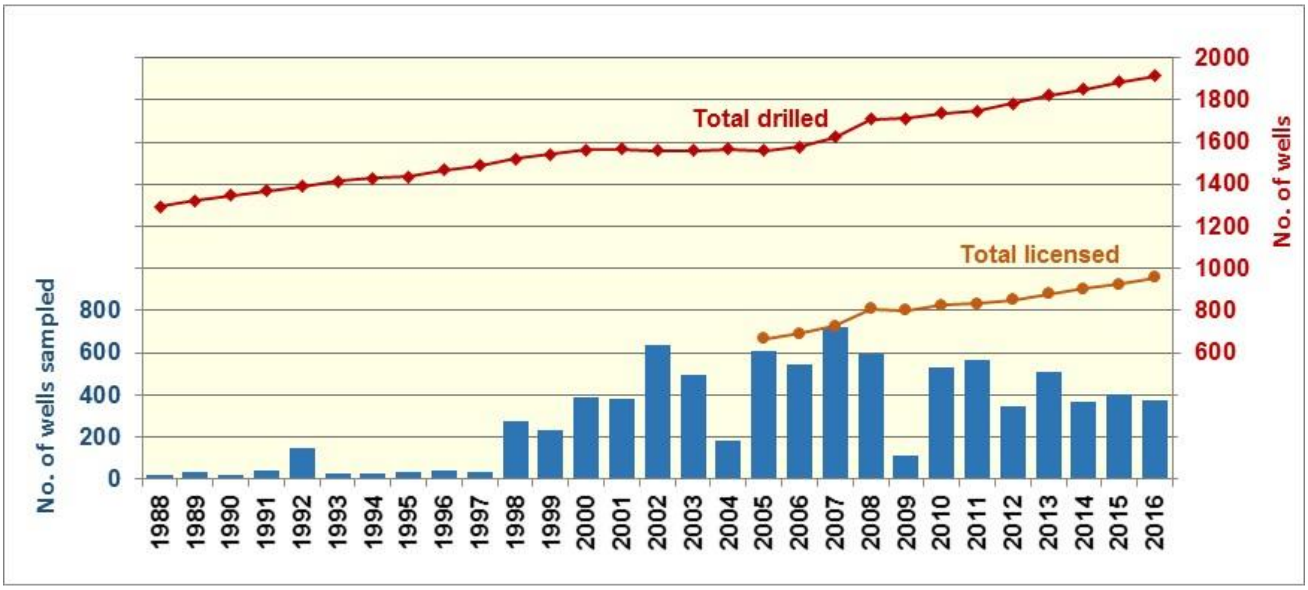


Figure 9. Sampling history in the NAP PWA

A total of 1031 wells had sufficient data (more than three readings over a period of three years or greater) to allow an interpretation of salinity trends, with over 13 000 salinity records being used in the study. Generally, three trends were identified which are listed in Table 3, with the stable classification being applied if the trend was less than +/- 3 mg/L/yr. Each of these trend categories will be discussed in turn to assess how they can inform the assessment of the risks and drivers of salinity change in the NAP PWA.

Table 3. Summary of salinity trends

Trend	No. of wells
Stable	331 (32%)
Rising	651 (61%)
Falling	49 (11.5%)

5.1.1 Stable trends

Stable trends can give a conclusive indication of an absence of local influences on groundwater salinity, such as corroded casing or nearby leaking wells or can indicate a conclusive absence of regional drivers of salinity change, especially when the spatial distribution of the stable trends can be examined. Table 4 gives the well casing type and number of wells with stable trends. About 30% of all licenced wells are showing a stable trend and there is not a great difference between the different types of casing. It would be reasonable to expect that the PVC cased wells would have a higher percentage of wells with stable trends than those with un-cemented steel casing because they have a negligible risk of casing corrosion which could lead to salinity rises within the well. The stable trends in un-cemented steel wells have been observed for 40-50 years.

Table 4. Wells with stable trends

Casing type	No. with stable trends	% of all wells sampled
Steel (Un-cemented)	112	11
Steel (Press Cement)	103	10
PVC (Press Cement)	116	11

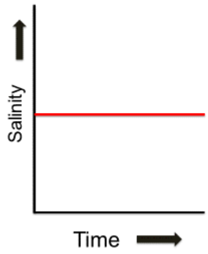


Figure 10 presents the spatial distribution of wells with stable trends for both the T1 and T2 aquifers. The wells are categorised by their casing type. Also shown are the salinity distributions for both aquifers and the potentiometric surface contours to give an indication of maximum recorded drawdowns and the resultant potential for vertical inter-aquifer leakage (T1 aquifer–March 2003 and T2 aquifer–March 2015).

T1 aquifer

The stable trends extend across the region across most salinity classes and all casing types. Where extractions are concentrated in the Waterloo Corner area and a cone of depression existed in the potentiometric surface for some time, quite a few wells have stable trends which suggests that downward leakage of more saline groundwater from the overlying Quaternary sediments is not significant. The stable trends also persist to the northwest of Waterloo Corner near lenses of higher salinity groundwater in the T1 aquifer (especially in the older un-cemented steel cased wells), which suggests that lateral movement of higher salinity groundwater is not significant.

T2 aquifer

The distribution of the T2 aquifer stable trends show similar characteristics to those of the T1 aquifer. They extend across most salinity classes and all casing types and similarly, stable wells occur in the centre of the cone of depression (for this aquifer, near Virginia) and near the boundaries of the higher salinity groundwater. Again, this suggests that lateral flow and upward leakage from the underlying saline T3-4 aquifer are not significant.

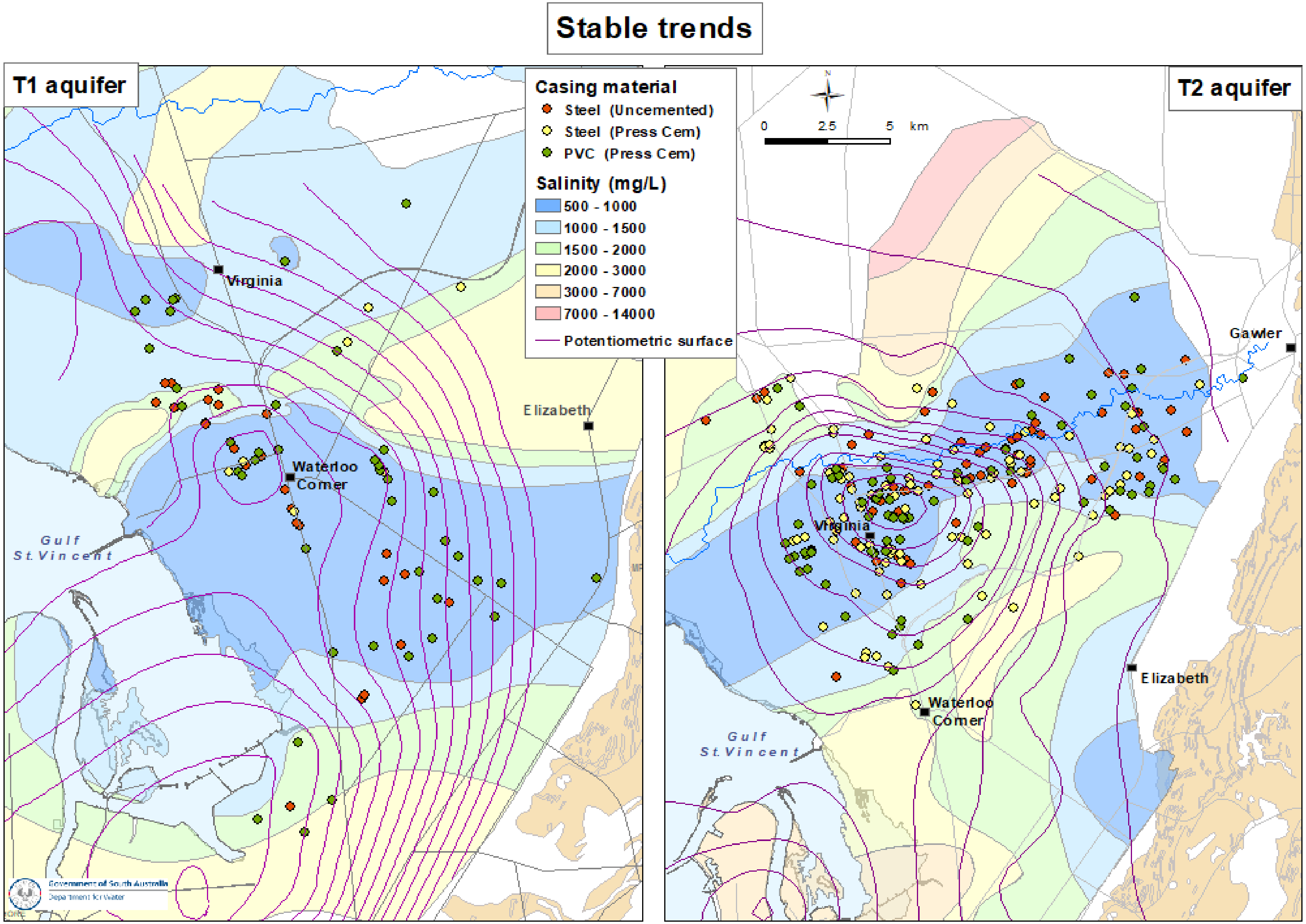


Figure 10. Spatial distribution of wells showing stable salinity trends

Figure 11 below shows salinity graphs from selected T1 aquifer wells which have the highest risk of salinity increases. They are all completed with un-cemented steel casing. Irrigation wells 6628-3900 and 3962 are located in the Waterloo Corner area where intensive pumping caused a cone of depression in the T1 pressure surface shown in Figure 10 which maximizes the potential for downward leakage from the Quaternary sediments. Meanwhile, wells 6628-3975 and 3992 are located to the northwest of Waterloo Corner where the risk of lateral movement of more saline groundwater into lower salinity areas is higher.

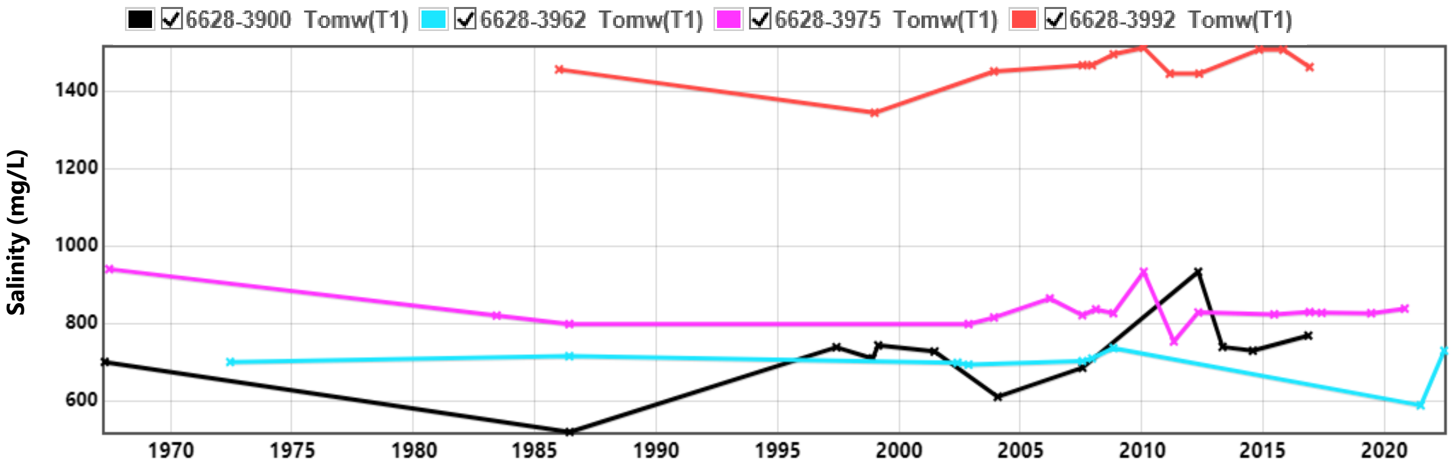


Figure 11. Examples of T1 aquifer wells showing stable salinity trends

Salinity graphs of T2 aquifer irrigation wells are presented in Figure 12. Again, these wells have the highest risk of salinity increases and are all completed with un-cemented steel casing. Irrigation wells 6628-2409 and 2420 are located in the Virginia area where intensive pumping caused a cone of depression in the T2 pressure surface shown in Figure 10 which maximizes the potential for upward leakage from the saline T3-4 aquifer. Wells 6628-922 and 932 are located to the north of Virginia where the risk of lateral movement of more saline groundwater into lower salinity areas is higher.

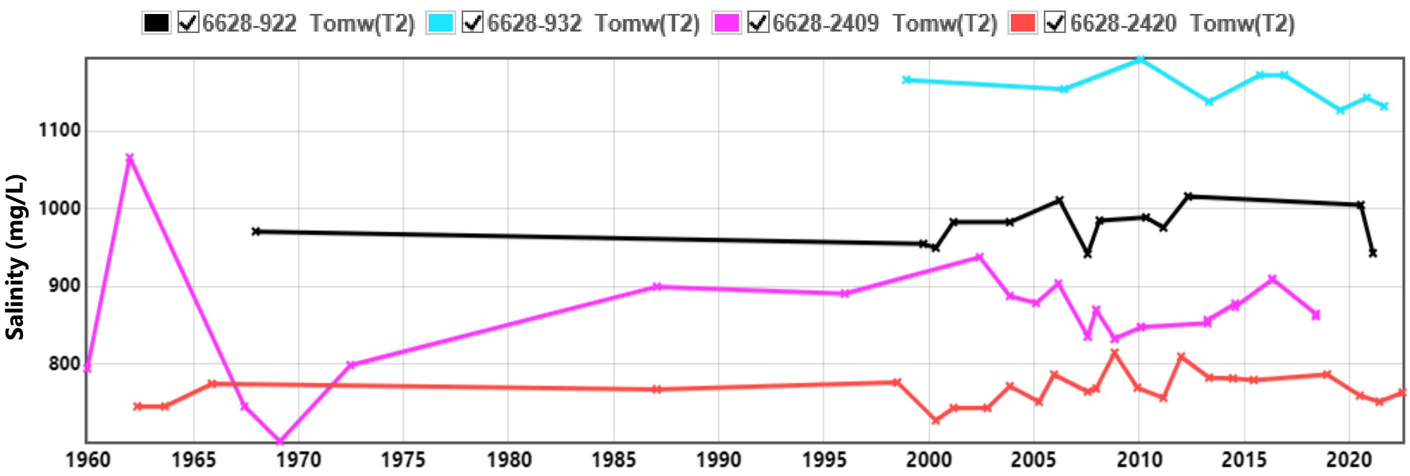


Figure 12. Examples of T2 aquifer wells showing stable salinity trends

5.1.2 Rising trends

The majority of sampled wells in the NAP PWA have experienced or are continuing to record rising salinities, with an equal percentage across the three casing types as shown in Table 5. The rate of the observed rises is mostly fairly gradual which would not normally be expected from the leakage of saline groundwater through corroded casing. The high number of cemented PVC wells experiencing salinity rises also suggests that casing corrosion is not the main cause of rising salinity trends.

Table 5. Wells with rising trends

Casing type	No. with rising trends	% of all wells sampled	Rate of rise (mg/L/y)
Steel (Un-cemented)	255	24	45
Steel (Press Cement)	183	17	48
PVC (Press Cement)	213	20	32

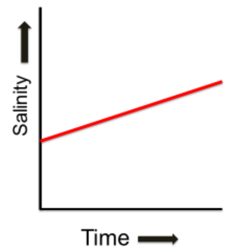


Figure 13 shows the frequency distribution of the rate of salinity rise. For all casing types, the majority of observed increases are below 25 mg/L/y. The un-cemented steel wells show a marginally higher number of wells in the higher rates of rise, but this difference is not great enough to conclude that corroded casing is the main cause of the salinity increases.

The spatial distribution of the wells showing rising trends (Fig. 14) shows no particular pattern and is similar to the distribution of wells showing stable trends. In particular, rising trends are observed within large areas of low salinity groundwater. There is however a large variation in the rates of rise of salinity observed in the wells, ranging from less than 10 to over 1000 mg/L/y. Table 5 shows that the rate of rise is the same order of magnitude across all casing types but is higher for wells with steel casing with the higher risk of corrosion.

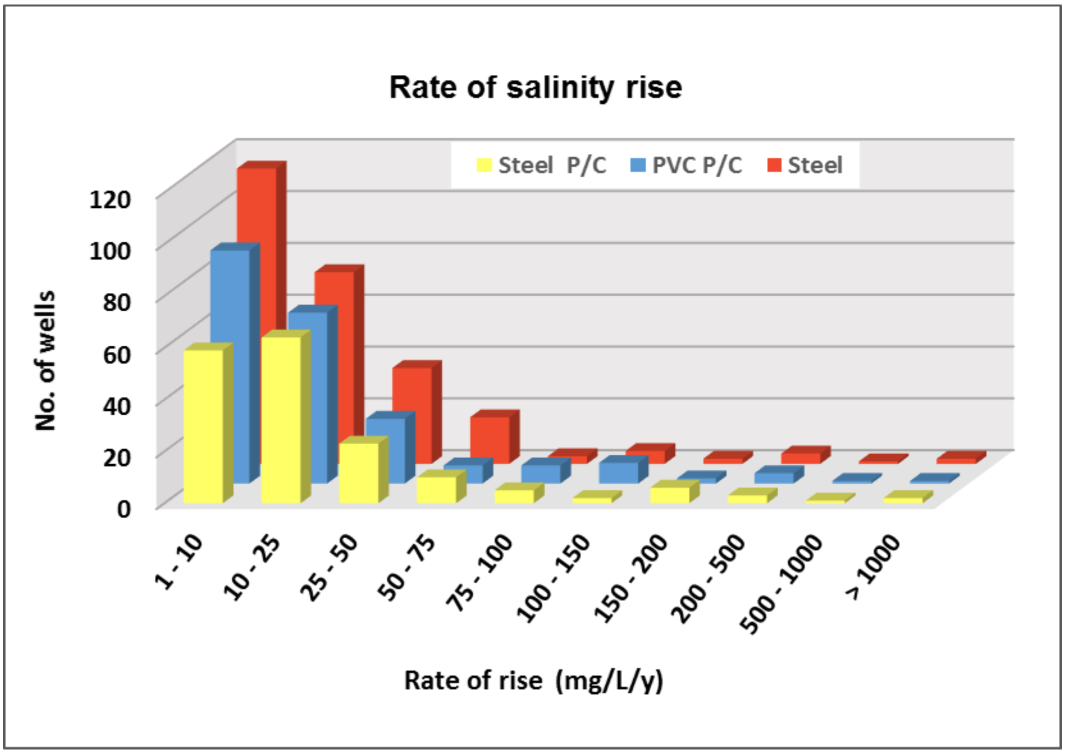


Figure 13. Frequency distribution of the salinity rate of rise

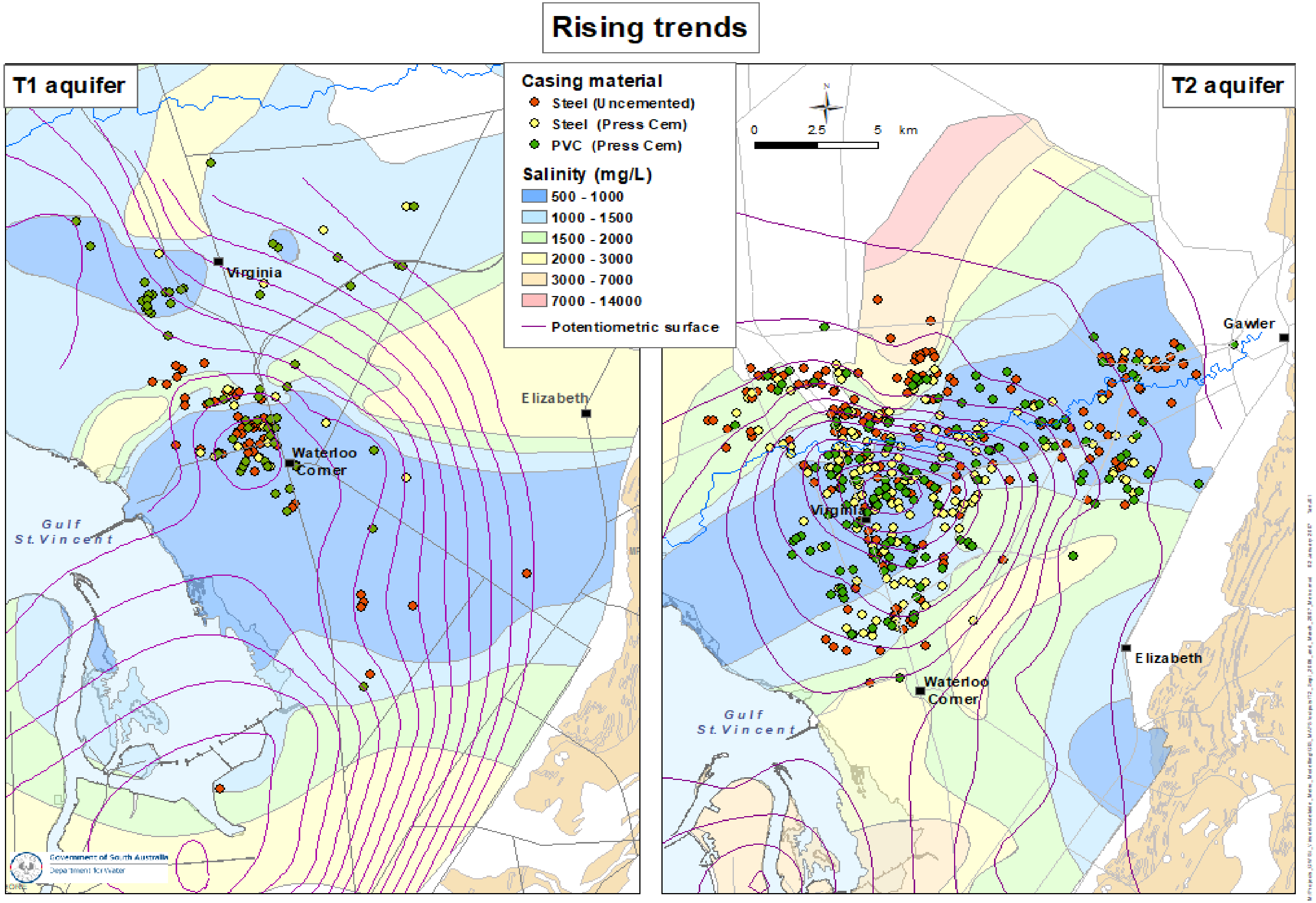


Figure 14. Spatial distribution of wells showing rising salinity trends

Figure 15 below shows salinity graphs from selected T1 aquifer wells which have the lowest risk of salinity increases because they are all completed with cemented PVC casing and are located within large areas of low salinity groundwater and some distance from the cone of depression in the T1 pressure surface shown in Figure 14. The salinity graphs also exhibit a wide range in the rate of salinity increase.

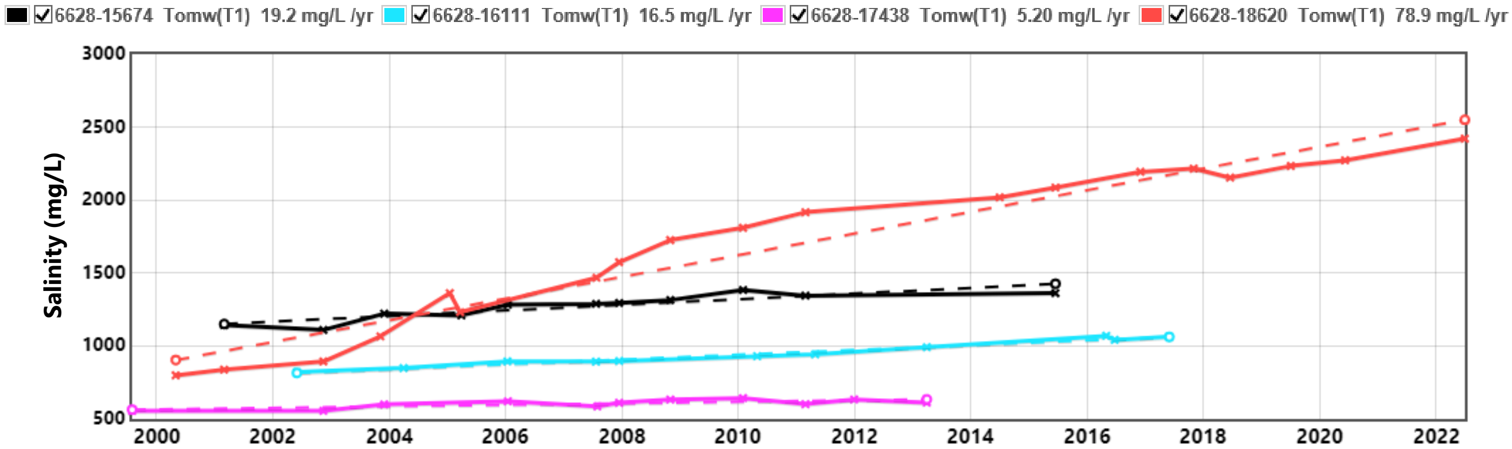


Figure 15. Examples of T1 aquifer wells showing rising salinity trends

Figure 16 similarly shows rising trends for irrigation wells in the T2 aquifer located in low risk areas away from the Virginia cone of depression and within the large area of low salinity groundwater.

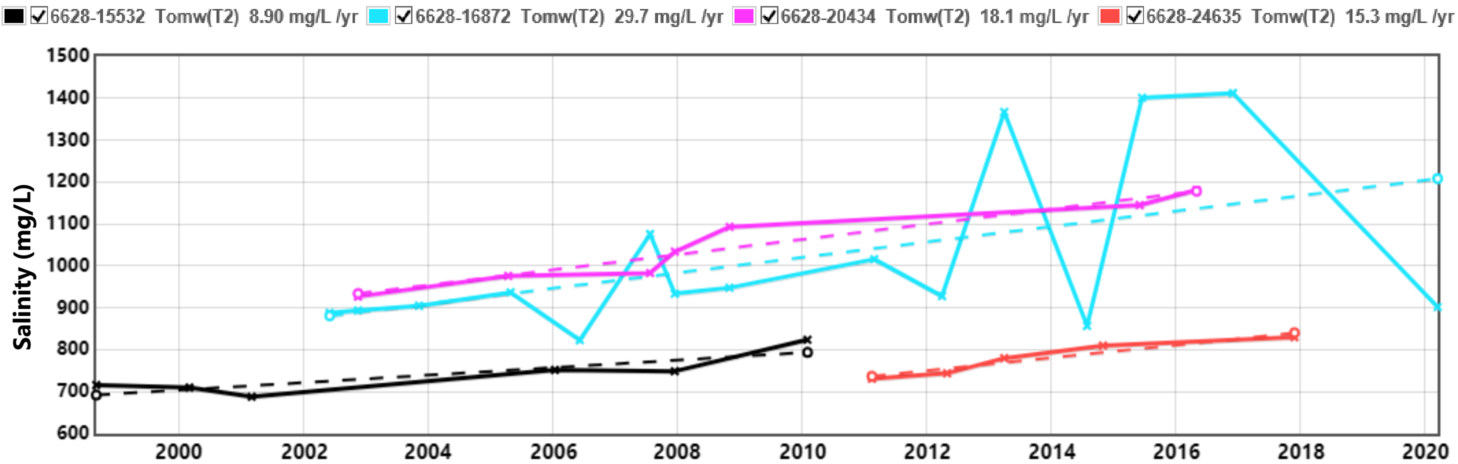


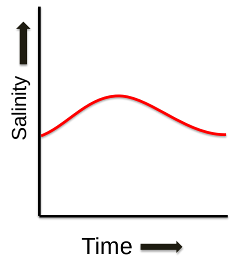
Figure 16. Examples of T2 aquifer wells showing rising salinity trends

5.1.3 Falling trend

About 49 wells are displaying falling trends in salinity during the sample period. Another 67 wells which had been previously classified as having a rising trend in this report, also began displaying a falling trend toward the end of the monitoring record.

Table 6. Wells with falling trends

Casing type	No. with falling trends	% of all wells sampled
Steel (Un-cemented)	21	2
Steel (Press Cement)	36	3.5
PVC (Press Cement)	59	6



Figures 17 and 18 show the falling trends for the T1 and T2 aquifers. Some of these wells show an increasing trend in salinity in the first part of their record, but in more recent years a decline in salinity has been observed. This salinity response is not the sharp increase that would be expected from the ingress of saline water through corroded casing but is more indicative of movement of a more saline plume of groundwater within the aquifer (see Appendix A). The different salinity responses are due to variations in groundwater flow velocity and varying distances from possible sources of the saline plume.

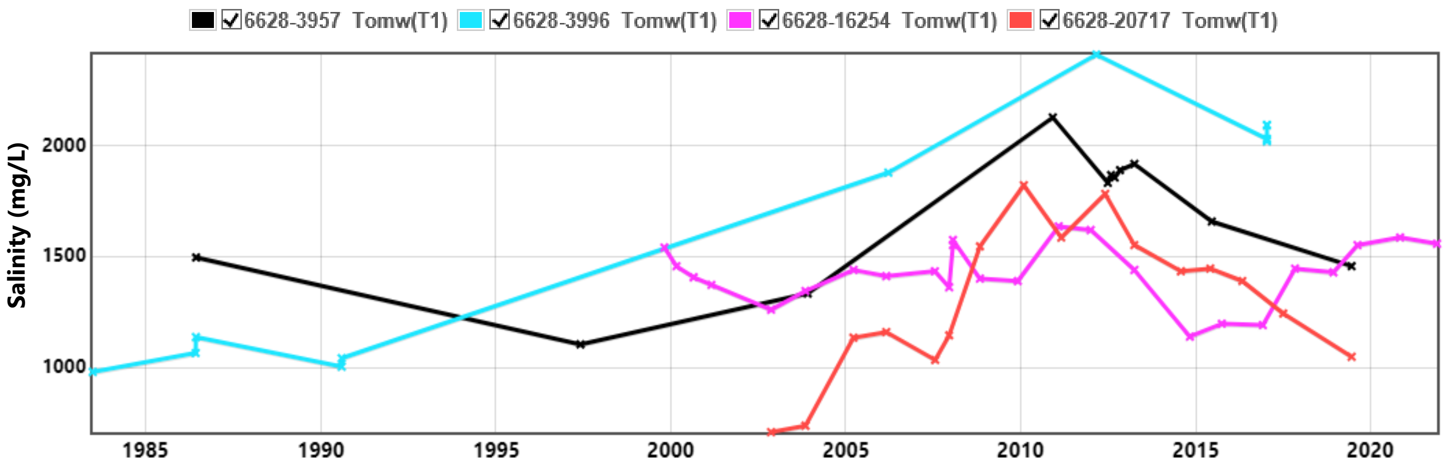


Figure 17. Examples of T1 aquifer wells showing falling salinity trends

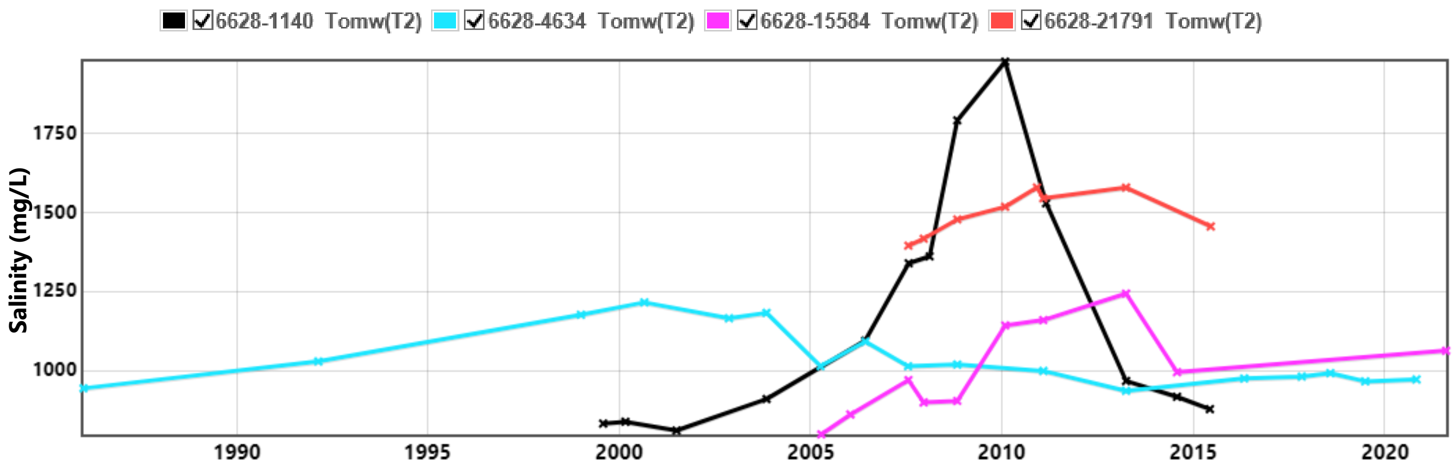


Figure 18. Examples of T2 aquifer wells showing falling salinity trends

Figure 19 shows the position of all these wells which are widely distributed and located well away from any recharge activities and therefore the falling trend cannot be attributed to the addition of lower salinity groundwater to the aquifer. Consequently a falling trend in any well can be assumed to have followed a previous rise in salinity in that well that was not detected by monitoring.

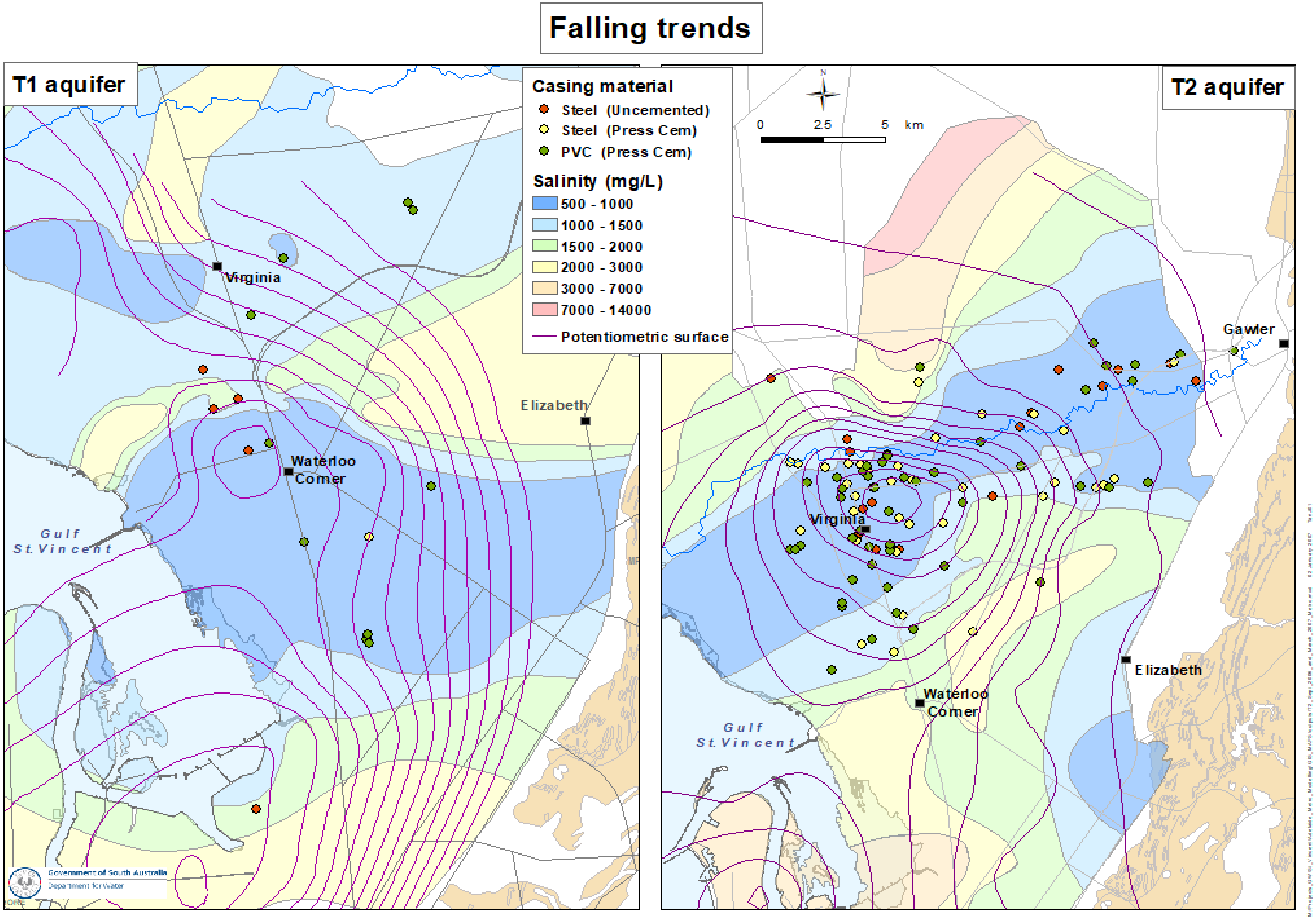


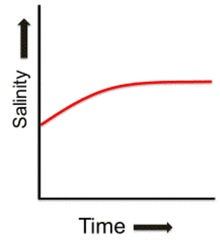
Figure 19. Spatial distribution of wells showing falling salinity trends

5.1.4 Rise then stable trend

About 31 wells which had been previously classified as having a rising trend in this report, began displaying a stable trend toward the end of the monitoring record. These trends are again not typical of what would be expected from a leaky well which would normally exhibit a sudden rise in salinity. The stabilisation of a rising trend again suggests movement of more saline plume within the aquifer which is still being sustained by an actively leaking well located upgradient of the sampled well (see Appendix A).

Table 7. Wells with rising then stable trends

Casing type	No. with rise then stable trends	% of all wells sampled
Steel (Un-cemented)	13	1
Steel (Press Cement)	10	1
PVC (Press Cement)	9	1



Figures 20 and 21 show the rising then stable trends for the T1 and T2 aquifers respectively. The different salinity response are due to variations in groundwater flow velocity and varying distances from the source of the saline groundwater.

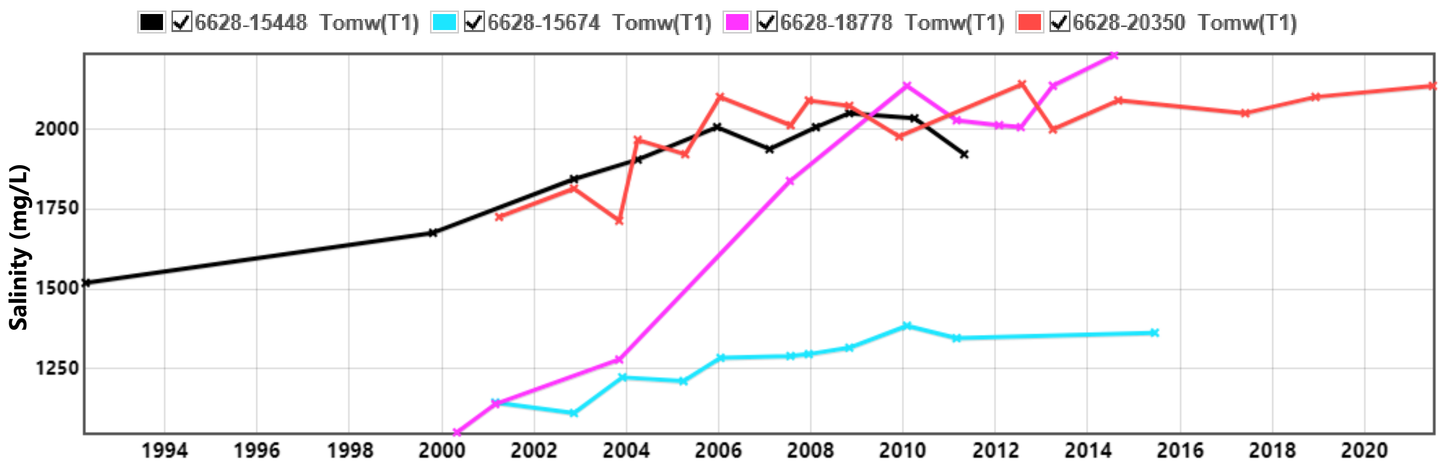


Figure 20. Examples of T1 aquifer wells showing rising then stable salinity trends

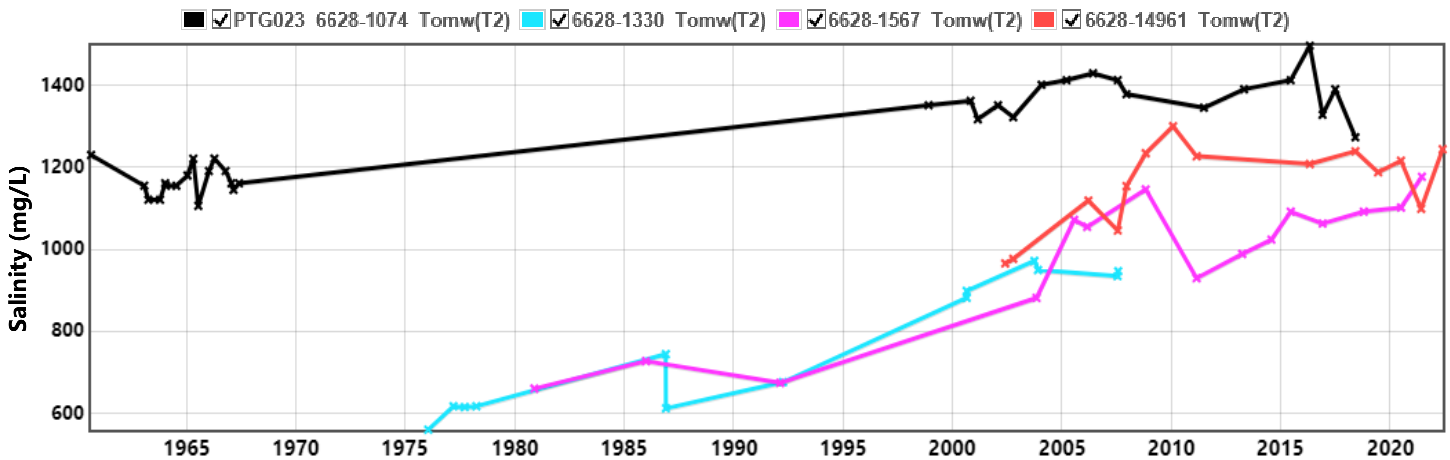


Figure 21. Examples of T2 aquifer wells showing rising then stable salinity trends

5.2 CA PWA salinity trends

In comparison with the NAP PWA, salinity monitoring in the CA PWA has been very limited due to a number of reasons. Most importantly, the intensity of extraction is much lower and there has been no licencing regime in place. In addition, the incidence of leaky wells (which was one of the drivers for monitoring in the NAP PWA), is much lower in the Central Adelaide Plains.

Much of the historical sampling was associated with the use of groundwater from 44 wells in the T1 aquifer for Adelaide's public water supply during drought in the early 1950s. This monitoring record also includes 466 full chemical analyses and 1154 salinity readings taken during the drilling of these supply wells and their subsequent use. These wells were also sampled during the mid-1970s but they were unequipped at the time which resulted in the use of a bailer to collect the samples rather than a pump. This is not considered to be a reliable method and hence most of these results have not been used in this study.

The earliest and most long-standing users of groundwater in the CA PWA have been the golf courses located in the north-western suburbs, with the first irrigation wells being drilled into the T1 aquifer in the 1920s. As all of the early wells were constructed with un-cemented steel casing, there were several instances of significant salinity increases being recorded due to casing corrosion caused by very high salinities in the overlying Hindmarsh Clay (in some areas over 50 000 mg/L). Figure 22 shows long term salinity trends from various golf courses which indicate that aquifer salinities have been relatively stable since irrigation began, although the sharp rises in salinity due to corroded casing and saline plumes can clearly be seen.

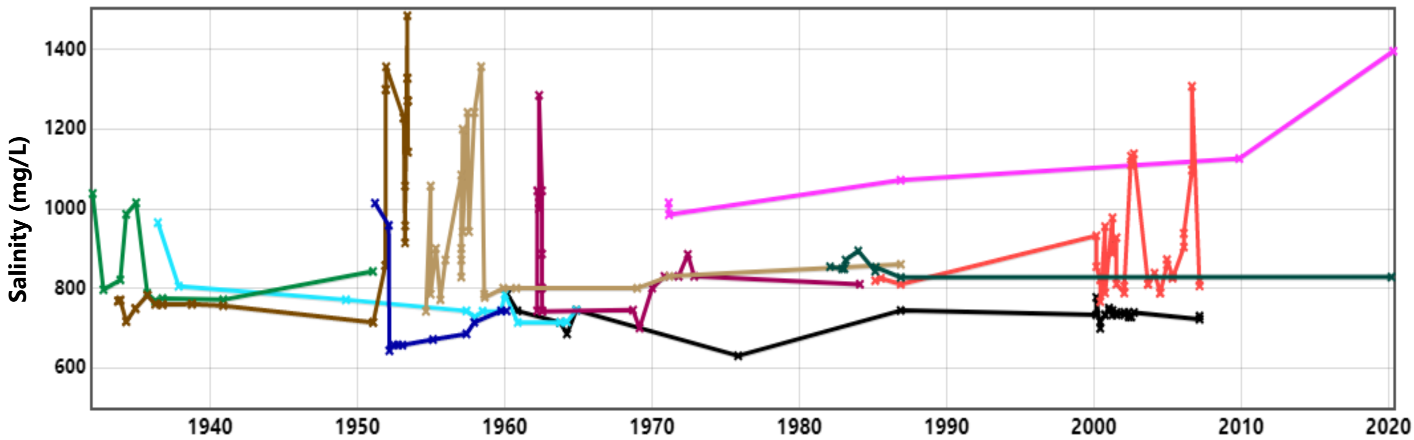


Figure 22. Salinity trends from golf courses in the north-western suburbs

Figure 23 presents trends from selected wells completed in the T1 aquifer in the southwestern suburbs that were used by the then Engineering & Water Supply (EWS) Department to supply Adelaide during previous droughts. The long term trends are stable except for the mid 1970s when bailed samples were used for testing.

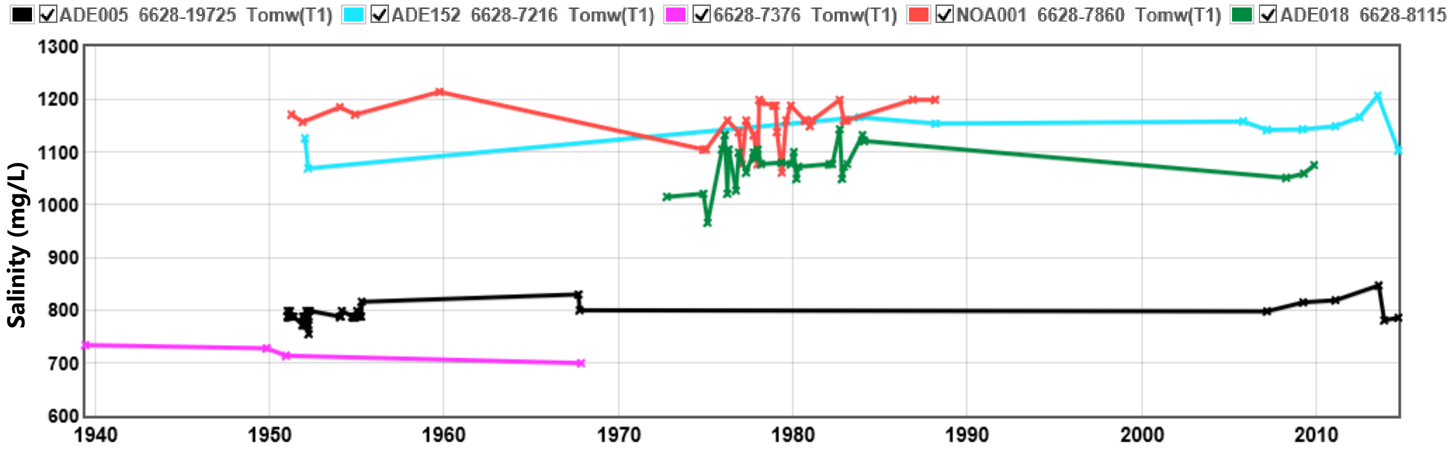


Figure 23. Salinity trends from previous EWS Department supply wells in the southwestern suburbs

Because of its depth and generally higher salinity, very few wells are completed in the T2 aquifer in the CA PWA and extraction volumes are quite low. Figure 24 shows results from several observation wells which again show long term stable trends, bearing in mind that samples from pumped observation wells will not be as reliable as those from regularly pumped production wells.

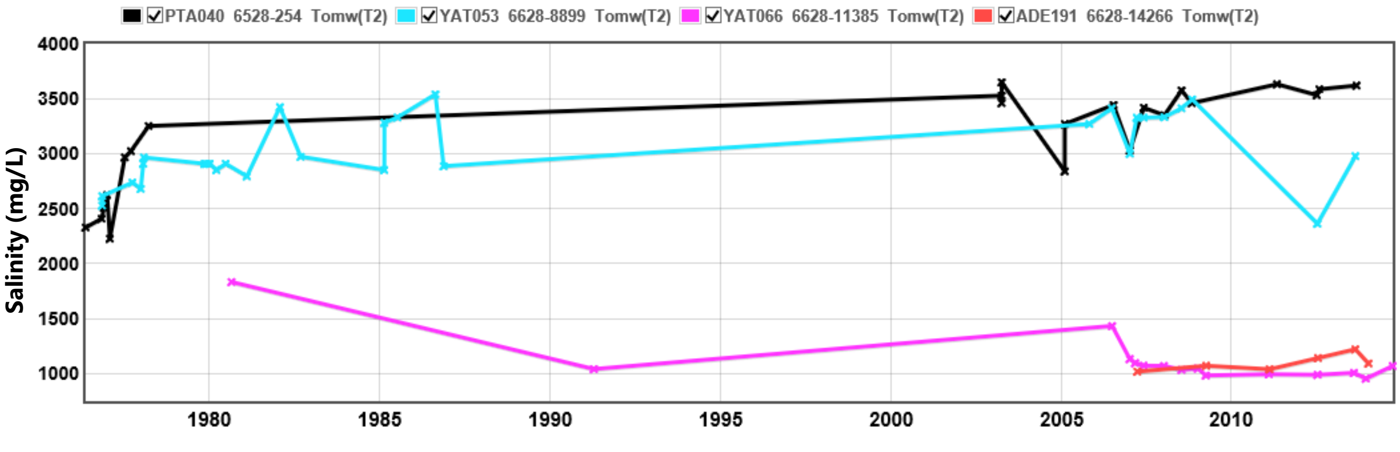


Figure 24. T2 aquifer salinity trends

6 Sources of salinity

Analysis of salinity trends in a number of previous studies and programs has greatly increased the understanding of the various causes of salinity risks for the Tertiary aquifers. A reappraisal of the potential various sources of salinity follows.

6.1 Leaky wells

As stated earlier, the type of well construction is an obvious indicator of the risk of such corrosion occurring, with un-cemented steel casing having the highest risk, pressure cemented steel casing having a medium risk and pressure cemented inert casing (PVC or FRP) having a negligible risk.

6.1.1 Previous work

Because of the much larger number of un-cemented steel cased wells occurring in the NAP, all of the investigations into leaky wells have been carried out in this area. In 1998, the NAP Leaky Wells Project was initiated by the Department of Water, Land and Biodiversity Conservation in response to irrigators throughout the NAP expressing concern over rising groundwater salinities. An initial investigation was carried out in 1999 when salinity results from annual sampling from 1987 to 1998 were analysed from a representative group of 200 wells from the T1 and T2 aquifers from various parts of the NAP PWA (Schuster and Gerges, 1999). Salinity trends were examined and comparisons were made with historical salinity values from the 1960s. Of this initial group, 33 wells (16 %) showed abnormal salinity increases. By extrapolation, it was estimated that about 180 – 240 wells out of the remaining 1200 operational wells would also be showing abnormal salinity increases and further analysis of these operational wells was recommended.

Schuster (2000) reported on a field assessment of the 33 wells showing abnormal salinity increases identified by the above investigation, plus an additional seven un-cemented steel cased wells identified during site surveys. Geophysical well logging (including a downhole camera) was carried out on 15 of these wells. Only eight of the 40 wells were found to have corroded and leaking casing and three had corroded casing that is probably leaking. Thirteen wells were considered to have been affected by saline plumes.

By 2002, a total of 972 licensed operational wells which had sufficient samples to allow salinity trends to be updated were examined, with 80 wells exhibiting abnormally high salinity levels which were subsequently investigated (Wilson, 2002). It was not possible to produce reliable salinity trends for 310 of these wells as water samples were not returned to DWLBC by the licensees.

In an investigation separate to the NAP Leaky Wells Project, the causes for abnormally high salinities in two recently drilled production wells in the Waterloo Corner Area were examined (Osei-Bonsu, Gerges and Zulfic, 2000). This study concluded that the two wells where correctly constructed and the high salinity observed was most likely due to contamination from overlying saline aquifers via an unidentified nearby corroded well.

In 2012, Sinclair Knight Merz Pty Ltd (SKM) were engaged by the Adelaide and Mount Lofty Ranges (AMLR) NRM Board to undertake an assessment of the attributes of identified leaky wells in the NAP PWA (and other prescribed areas) and the subsequent risk to the groundwater resources. A strong correlation was found between the incidence of leaky wells and the age of the well and the type of casing used (SKM, 2012).

Whilst there is no doubt that leaking wells are a major original source of increased salinity in the Tertiary aquifers through the mechanism displayed earlier in Figure 2, it is strongly apparent from the earlier analysis of salinity trends in this report that the observation of rising salinity in any particular well does not mean that the well is leaking. Determination of whether a well may be leaking can be obtained by geophysical logging of the casing condition, or the observation of a sudden and significant rise in salinity or significant fluctuations in salinity. Most operating irrigation wells that have displayed these symptoms would have been backfilled as they are generally the only source of water available for the irrigator.

6.2 Plumes of saline groundwater

The analysis of salinity trends suggests that moving plumes of saline groundwater are a major source of salinity increases in the 651 wells that have been monitored (Appendix A). Evidence supporting this conclusion includes;

- a surprisingly equal percentage across the three casing types (ranging from 60–65 %) that have experienced or are continuing to record rising salinities
- the rate of the observed rises is usually fairly gradual (mostly below 25 mg/L/yr) which would not normally be expected from the leakage of saline groundwater through corroded casing
- the observation of falling, or rising then falling trends.

A spatial analysis of wells completed with pressure cemented PVC casing that exhibit rising trends is presented in Table 8. This group of wells have a very low risk of showing salinity increases due to corroded casing. Table 8 shows the cumulative percentage of PVC wells that are located within a certain distance of uncased steel wells that have a very high risk of leaking and creating plumes of saline groundwater.

Table 8. Proximity of PVC wells with rising trends to un-cemented steel cased wells

Aquifer	Within 50m	Within 100m	Within 200m	Within 400m
T1	25 %	38 %	57 %	73 %
T2	32 %	46 %	67 %	87 %

This analysis shows that the vast majority of PVC wells with rising salinities are within 400 m of an un-cemented steel cased well. Considering that groundwater flow rates are of the order of at least 10 m/yr, and that most un-cemented wells were drilled prior to 1970, it is very likely that plumes generated by un-cemented steel cased wells are responsible for nearly all rising trends in PVC wells.

This raises the question as to whether the salinities in the 651 wells showing a rising trend will continue to rise, or will they stabilize or begin to fall as a plume (produced by a now backfilled leaky well) passes by the well. Only on-going monitoring will resolve that question.

6.3 Downward leakage from the Quaternary aquifers

The potential for salinity increases to occur in the T1 aquifer as a result of downward leakage from the Quaternary aquifers is controlled by two main factors – the head difference between the two aquifers and the salinity in the Quaternary aquifers immediately overlying the T1 aquifer.

Before European settlement, the T1 aquifer was artesian in the western parts of both the NAP PWA and CA PWA. Subsequent extraction from the T1 aquifer has lowered the potentiometric surface below the watertable, creating potential for the downward leakage of groundwater from the Quaternary aquifers. Whether or not this leakage presents a sustainability risk to the T1 aquifer depends on the salinity of the Quaternary groundwater. Each of these factors will be discussed for each PWA.

A consequence of the historical artesian conditions would have been upward hydraulic gradients and a resultant historic upward leakage from deeper aquifers into the overlying shallow Quaternary aquifers (Gerges, 2001) which would have occurred for millennia.

6.3.1 Head difference in the NAP PWA

To ascertain the risk for downward leakage in the NAP, the head difference between the watertable and the T1 potentiometric surface was examined. Whilst the T1 surface is prepared annually from a wide coverage of monitoring wells, the watertable elevation map was prepared from a less widespread number of observation wells plus values from other wells drilled since 2000. The T1 surface for 2003 was chosen as a 'worst case' scenario because it depicts a cone of depression in the Waterloo Corner area which currently no longer exists.

Figure 25 presents the 'worst case' head difference in 2003 which shows the potential for downward leakage extends across the whole area where the T1 aquifer is developed. The magnitude of the head difference generally increases toward the southwest, driven by the previous extractions at Dry Creek for salt harvesting which have now ceased.

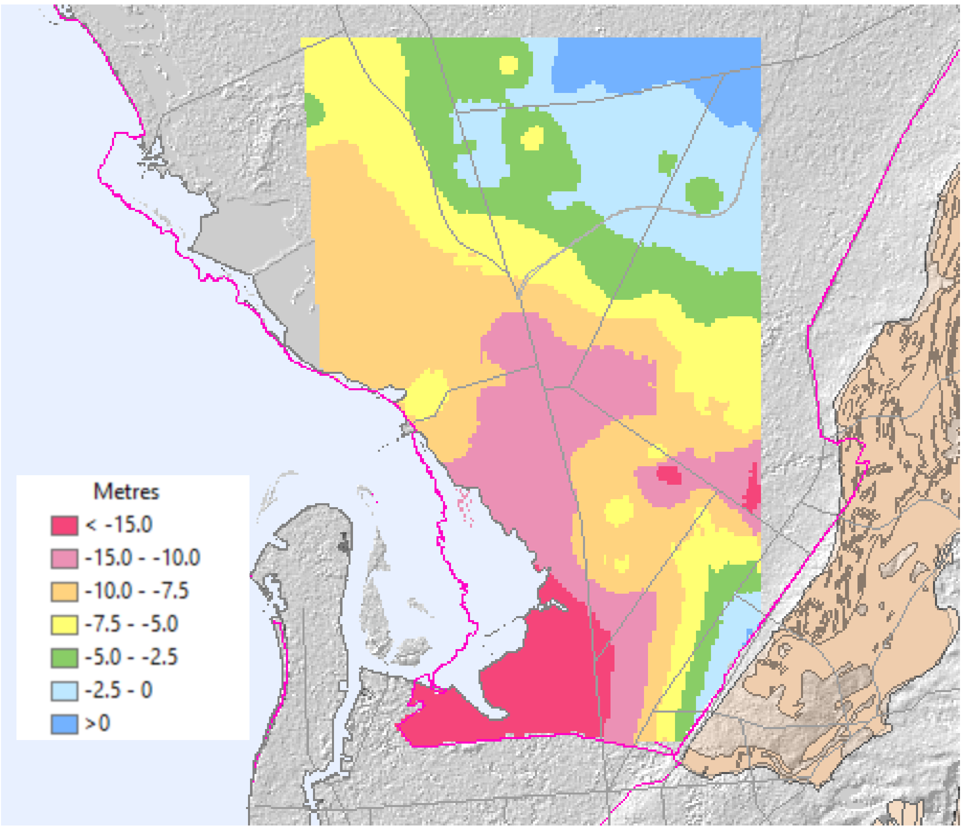


Figure 25. Worst case head difference between Quaternary and T1 aquifers in the NAP PWA

6.3.2 Head difference in the CA PWA

A similar methodology was carried out for the CAP PWA. Figure 26 presents the 'worst case' head difference in 2007 which shows the potential for downward leakage extends across the whole area where the T1 aquifer is developed. The magnitude of the head difference generally increases toward the northwest, driven by the irrigation of golf courses and previous extractions at Dry Creek for salt harvesting and Penrice which have now ceased.

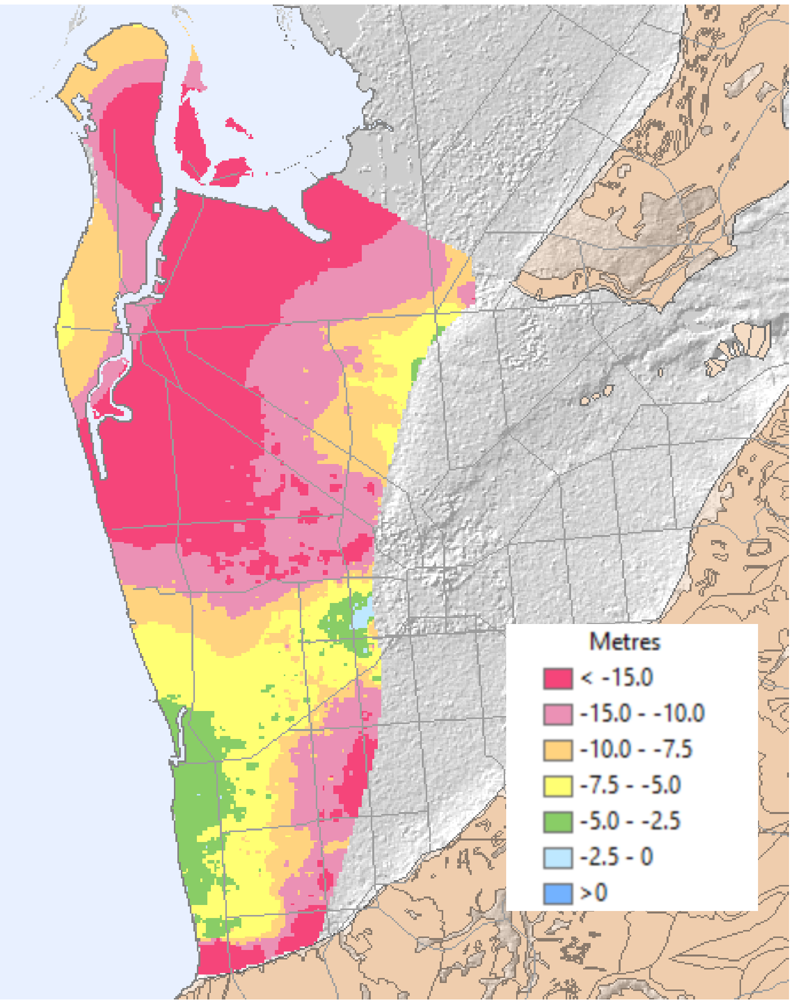


Figure 26. Worst case head difference between Quaternary and T1 aquifers in the CA PWA

6.3.3 Salinity of Quaternary aquifers in the NAP PWA

Salinity distribution maps were prepared for the upper 20 m of the Quaternary aquifers in the NAP and also the bottom 20 m of the Quaternary aquifers. These are compared with the T1 aquifer salinity in Figure 27. It can be seen that the salinities in the deeper parts of the Quaternary aquifers are considerably lower than the upper 20 m of the aquifers which more than likely reflects the historic upward leakage from the previously artesian T1 aquifer.

6.3.4 Salinity of Quaternary aquifers in the CA PWA

Salinity distribution maps were also prepared for the Quaternary aquifers at various depths in the CA PWA. These are compared with the T1 aquifer salinity in Figure 28. It can be seen that the salinities in the deeper Quaternary aquifers are considerably lower than the upper part of the aquifer which more than likely reflects the historic upward leakage from the previously artesian T1 aquifer. The higher shallow aquifer salinities probably reflect the effects of evaporative concentration.

6.3.5 Summary

Although the potential exists for downward leakage, the likelihood of significant salinity increases occurring in the T1 aquifer are low because of the relatively low salinities in the lower Quaternary aquifers. The widespread occurrence of stable T1 salinity trends described previously supports this conclusion.

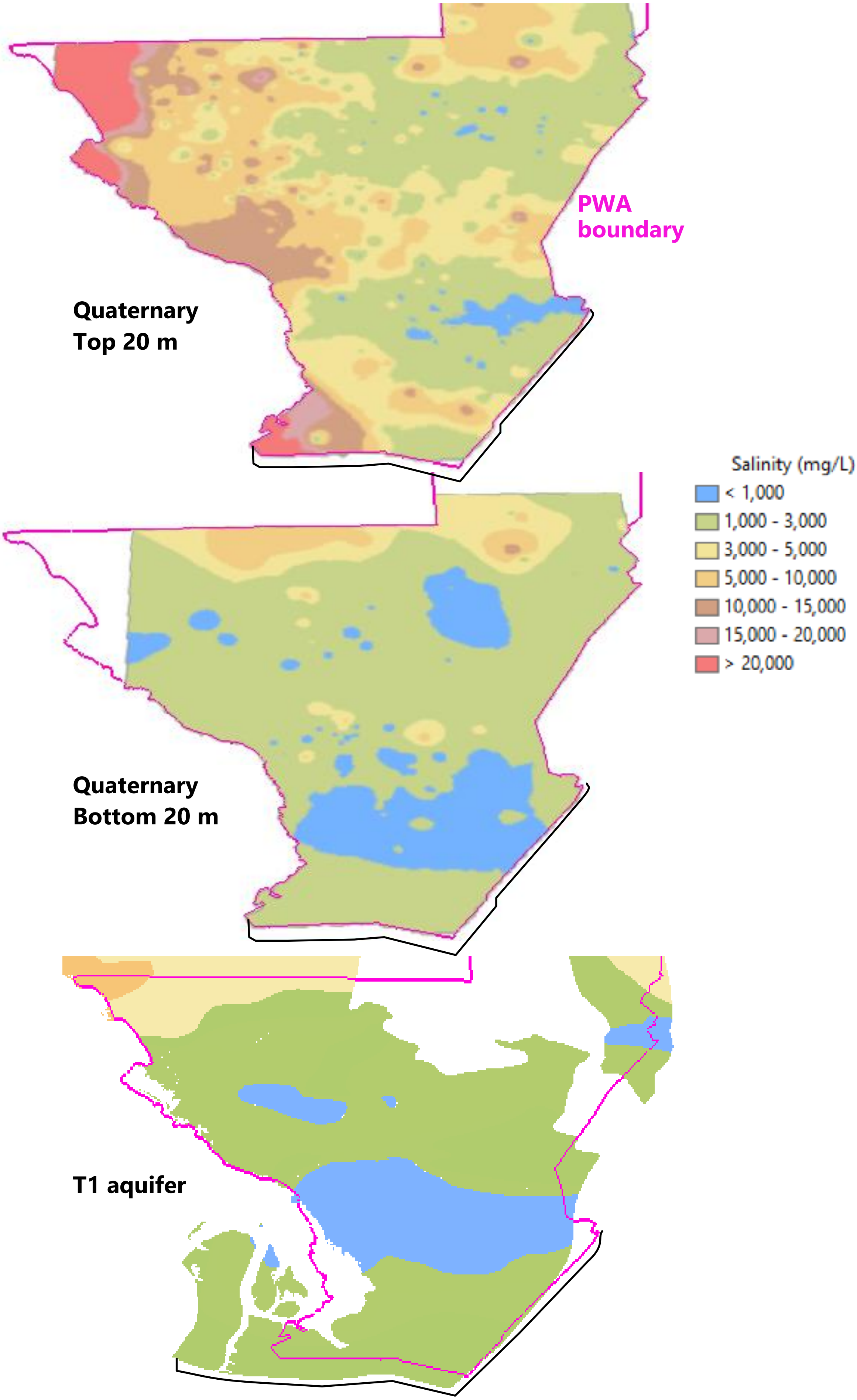


Figure 27. Comparison between Quaternary and T1 aquifer salinities in the NAP PWA

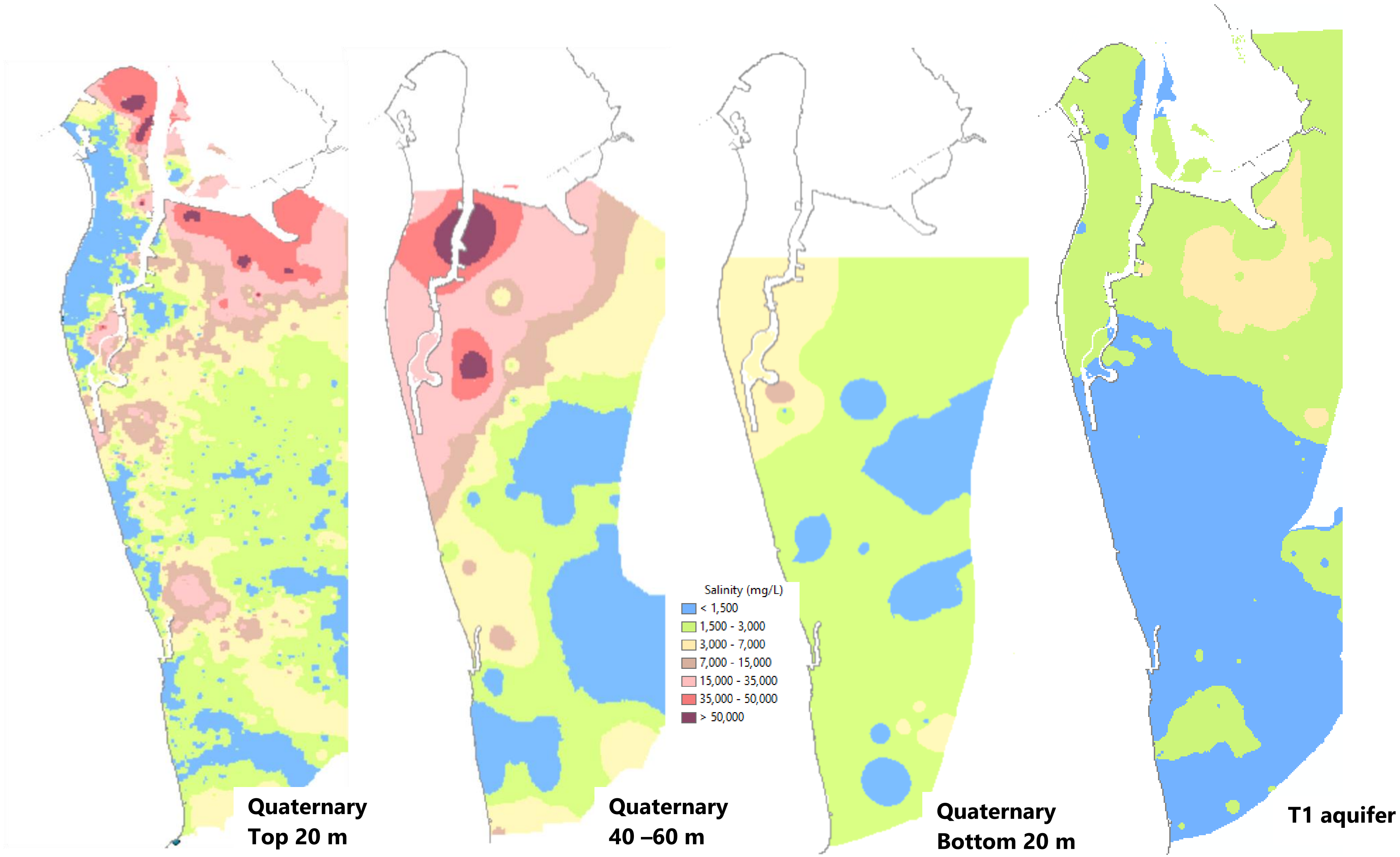


Figure 28. Comparison between Quaternary and T1 aquifer salinities in the western CA PWA

6.4 Upward leakage from the T3-4 aquifers

Given that the deep T3 and T4 aquifers contain highly saline groundwater, any risk of upward leakage into the overlying T2 aquifer should be assessed. Although a potentiometric surface map for the T3 and T4 aquifers does not exist to allow comparison with the T2 surface, it can be safely assumed that potential for upward leakage does exist in the large cone of depression in the T2 surface centered on Virginia in the NAP PWA. In the vicinity of this cone of depression, the intervening low permeability Blanche Point Marl confining layer is about 75 m thick. Most of the T2 production wells are completed about 50-60 m above the base of the aquifer and Figure 10 shows that a considerable number of these wells in the centre of the cone have stable salinity trends.

Elsewhere in the CA PWA, limited information also suggests potential exists for upward leakage into the T2 aquifer, however extraction from the T2 aquifer is quite low and the thickness of intervening low permeability Blanche Point Marl confining layer is generally over 100 m.

Although there are no representative samples from the base of the T2 aquifer, the risk of salinity increases in this aquifer due to upward leakage from the T3 and T4 aquifers is considered negligible due to the thickness of the intervening Blanche Point Marl confining layer.

6.5 Sea water intrusion

Up until recently, it has generally been assumed that the salt water interface in most aquifers lies at the coast. This is a reasonable assumption for unconfined aquifers that are hydraulically connected to the ocean, unless over-extraction has led to movement of the interface inland into aquifers away from the coast.

However, recent work by Post et al. (2013) has discovered significant reserves of fresh groundwater in sediments underlying the continental shelf in many parts of the world. This is because about 20 000 years ago, the sea level was 120 m lower than the current level and this groundwater was most likely recharged when the continental shelf was exposed. Figure 29 shows the position of the coastline at this time, together with the channel of the ancestral River Murray where it flowed across the continental shelf.

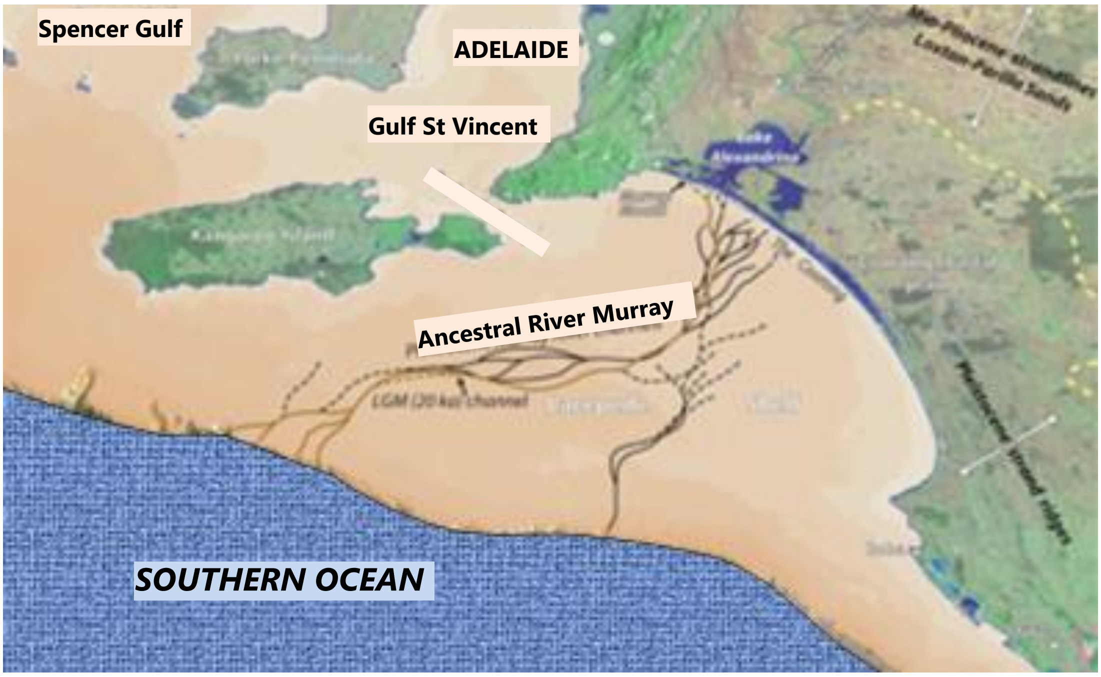


Figure 29. Location of coastline 20 000 years ago

This scenario may have resulted in fresh water entering the offshore T1 and T2 confined aquifers by two mechanisms:

- vertical recharge – given the long time frame and past wetter climates, this is feasible although the large thickness of the overlying Hindmarsh Clay (~ 70 m) may have restricted this process, or
- lateral flows – the lowering of the sea level would have extended the current westerly flow paths of low saline groundwater out under the Gulf, albeit to an uncertain extent.

Whatever the mechanism, there is strong evidence from salinity monitoring to suggest that fresh groundwater in both T1 and T2 confined aquifers extends a considerable distance offshore. Unfortunately, verification of the exact extent would be difficult and expensive to obtain.

There have been long standing cones of depression that extend below sea level in both aquifers. In the T1 aquifer, extraction for industry and irrigation had created a cone of depression down to -3m AHD in the Fulham - Seaton Gardens area by 1947 which subsequently deepened to -20m AHD and expanded to the north to Penrice by 2010. In the T2 aquifer, the cone of depression at Virginia was formed in the 1960s and has currently stabilized at -45m AHD during the irrigation season. Despite the resultant pressure gradients promoting inland groundwater flow from the coast in both aquifers, there have been no salinity increases detected in any observation wells located near the coastline.

Simple calculations of inland groundwater flow velocities driven by the cones of depression at their maximum depth are detailed in Appendix B. Ranges of 30 - 50 m/yr for the T1 aquifer and 5 - 15 m/yr for the T2 aquifer were calculated. In worst case scenarios, groundwater would have moved about 4.5 km inland in the T1 aquifer (assuming development began in the 1930s), and about 1 km inland in the T2 aquifer (assuming development began in the 1960s).

Figure 30 presents a schematic cross section of the worst case T1 aquifer scenario with the cone of depression centered 2.5 km inland with a summer drawdown down to -20m AHD. The estimated groundwater travel distance is also shown.

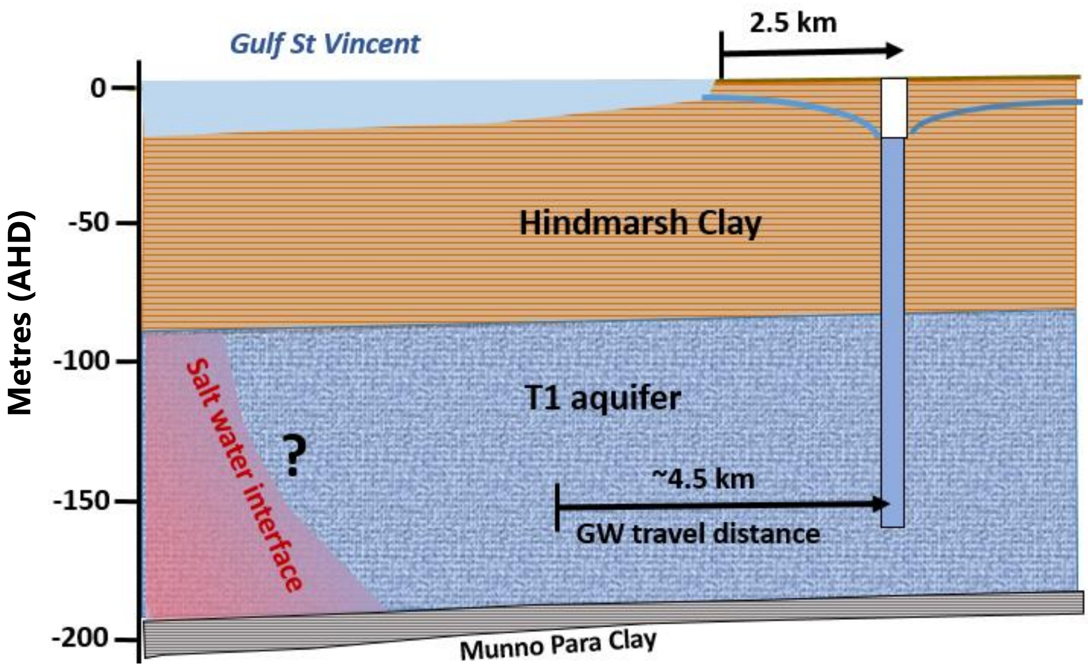


Figure 30. Schematic coastal cross section for the T1 aquifer

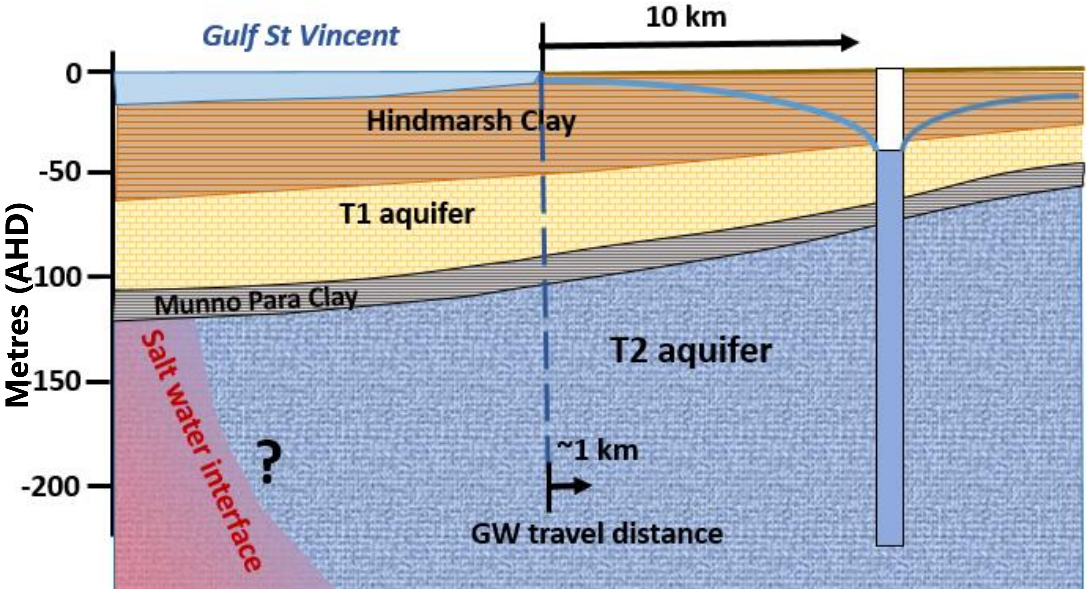


Figure 31. Schematic coastal cross section for the T2 aquifer

The schematic cross section of the worst case T2 aquifer scenario is presented in Figure 31. The cone of depression centered 10 km inland near Virginia has a summer drawdown down to -45m AHD. Because the landward gradient at the coast is low, the estimated groundwater travel distance is only about one kilometer since development began and is also shown in Figure 32.

In recent years, the risk of sea water intrusion has diminished significantly because of the closure of some industries and the resultant cessation of pumping which has resulted in a strong recovery of the cone of depression in both T1 and T2 aquifers between Outer Harbour and West Lakes.

6.6 Lateral movement of more saline groundwater within the aquifers

The creation of cones of depression due to concentrated extraction from both the T1 and T2 aquifers has changed groundwater flow directions and increased the potential for salinity increases arising from the lateral movement of more saline groundwater within the aquifers. The areas at highest risk of this process occur on the margins of zones of low salinity groundwater which are immediately adjacent to higher salinity groundwater. This lateral movement is a regional scale process and if it occurred, would result in widespread and consistent but very gradual salinity increases. Determination of this risk is more difficult because of the presence of other sources of salinity risk i.e. leaky wells.

For the T1 aquifer, this situation occurs to the north of Waterloo Corner. Figure 32 presents the location of irrigation wells with stable trends as well as rising trends. The potentiometric contours and groundwater flow direction are also shown. It can be seen that the distribution of those wells with stable trends are located in and near the higher salinity groundwater. Similarly, wells with rising trends are distributed fairly evenly across the area with no apparent concentration near the boundary between low and high salinity groundwater.

The high risk areas for the T2 aquifer occur on the northern and southeastern parts of the drawdown cone surrounding Virginia where it intersects zones of higher salinity groundwater. Figure 33 shows the location of wells with various trends and displays similar patterns to the T1 aquifer. Wells with stable trends are located in and near the higher salinity groundwater and wells with rising trends are distributed fairly evenly across the area with no apparent concentration near the boundary between low and high salinity groundwater.

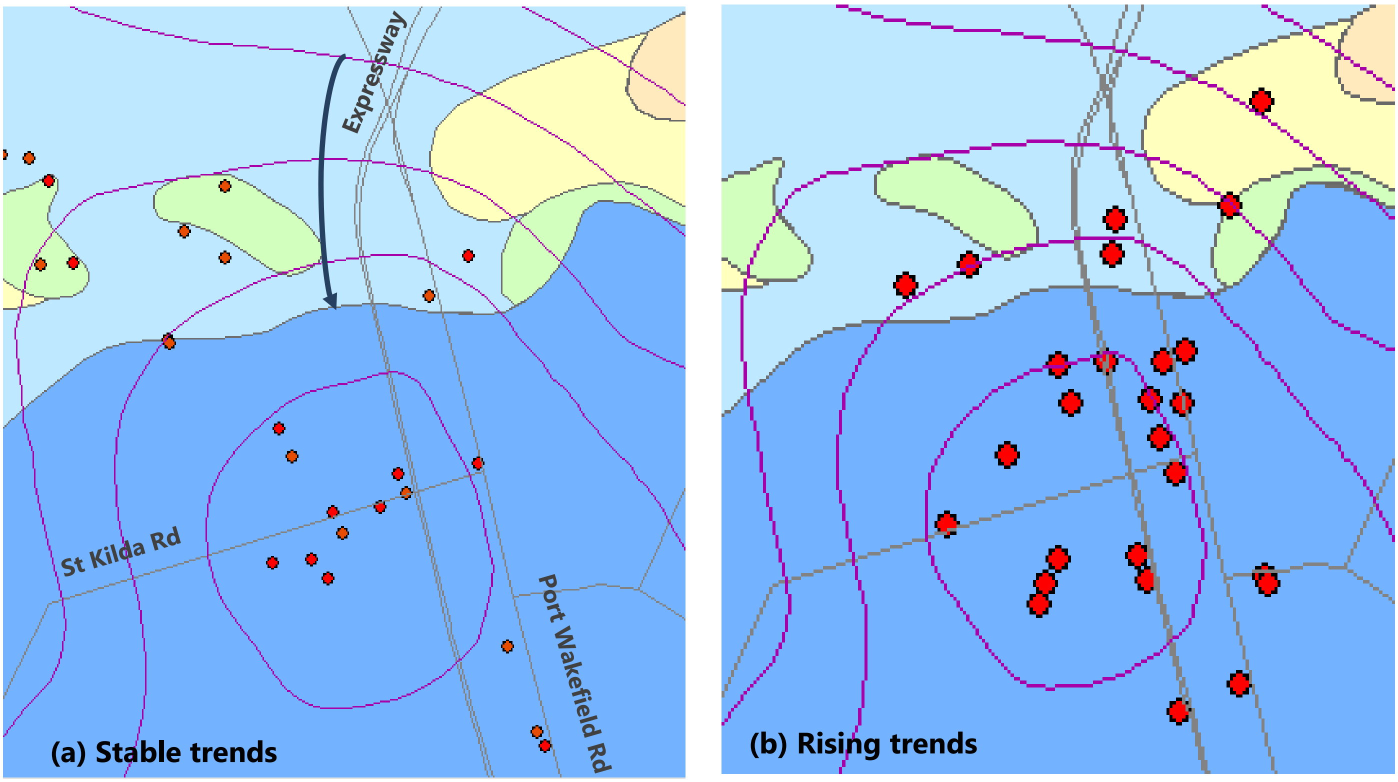


Figure 32. Salinity trends for the T1 aquifer near Waterloo Corner

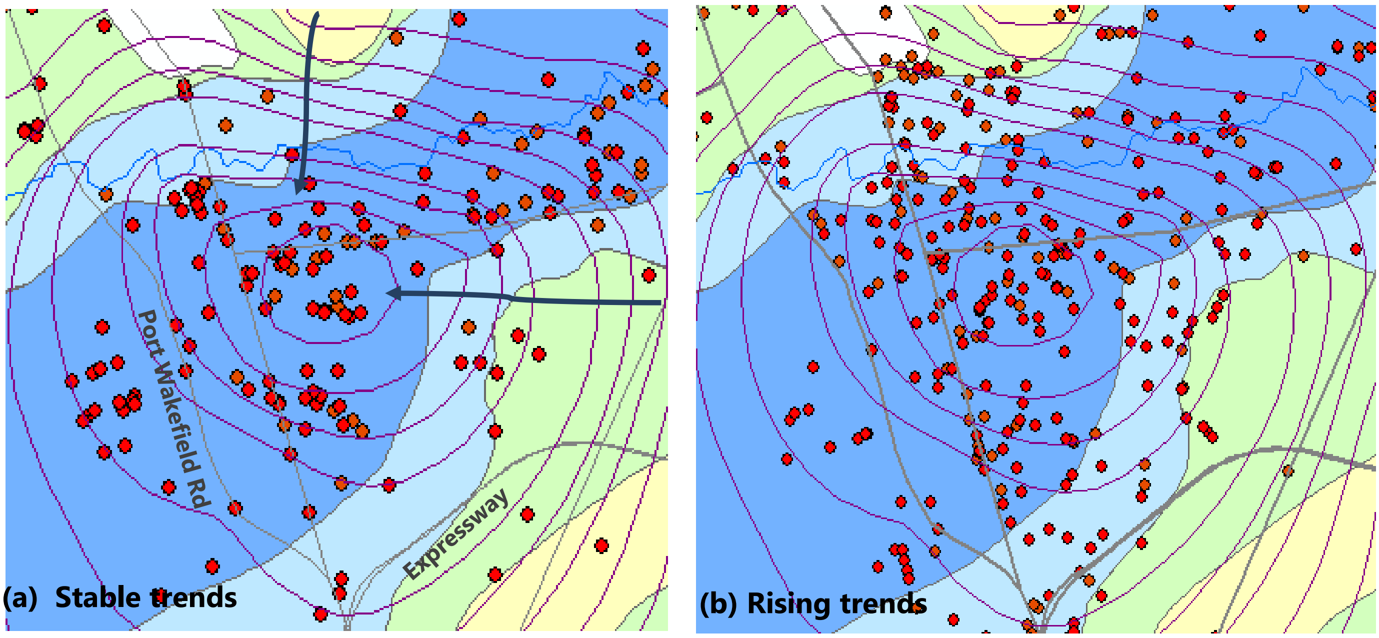


Figure 33. Salinity trends for the T2 aquifer near Virginia

7 Conclusions

A comprehensive evaluation of long term salinity monitoring results in the Northern Adelaide Plains and Central Adelaide Prescribed Wells Areas has increased the understanding of the processes that may cause salinity increases in the T1 and T2 aquifers and enabled an assessment of the likelihood of them occurring.

Comprehensive monitoring of irrigation wells in the NAP PWA has indicated the movement of plumes of more saline groundwater originating from leaky wells presents the highest risk of salinity increases, even in pressure cemented PVC cased wells. Although 651 wells display a rising trend, many of these may experience a declining trend in the future as the higher salinity plumes moves downgradient past the wells. Similarly in the CA PWA, leaky wells and associated higher salinity plumes present the highest risk of salinity increases, but this risk is restricted to the western suburb golf courses which have a long and on-going history of groundwater use.

The widespread occurrence of long term stable trends (in all types of well construction) in areas of heaviest extraction from both aquifers indicate that the likelihood of salinity increases occurring from regional processes such as vertical inter-aquifer leakage is low in both the NAP and CA PWAs. The hydrogeological setting also contributes to this low likelihood through the presence of very thick confining layers between the T2 and T3-4 aquifers and the historical upward leakage of low salinity groundwater from the T1 aquifer to the Quaternary aquifer before irrigation development occurred. The distribution of salinity trends also indicate that the lateral flow of more saline groundwater has not been the obvious cause of any observed salinity increases.

The risk of sea water intrusion is difficult to assess in both the NAP and CA PWAs because the location of the salt water interface in both confined aquifers is unknown. However the likelihood is considered low because of the thick protective cover of the Hindmarsh Clay and the highly probable flow of fresh groundwater westwards under the ocean when the sea level was historically about 120 m lower than it is today would suggest that fresh groundwater in both T1 and T2 confined aquifers extends a considerable distance offshore. In recent years, the risk of sea water intrusion has diminished significantly because of the closure of some industries and the resultant cessation of pumping which has resulted in a strong recovery of the cone of depression in both T1 and T2 aquifers between Outer Harbour and West Lakes.

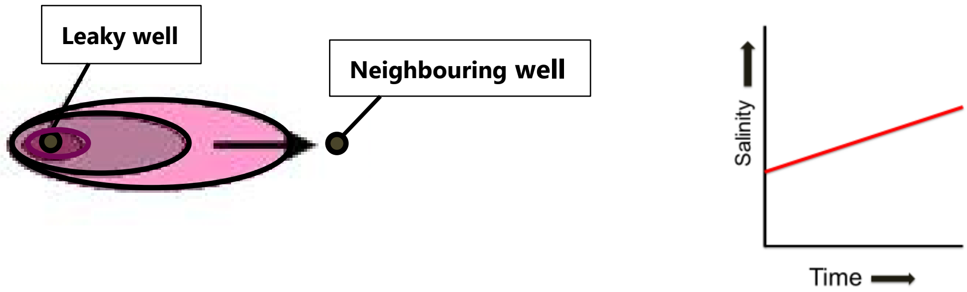
8 Appendices

A. Saline plumes

Saline plumes are created by a leaky well that introduces saline water into the aquifer which then moves downgradient and undergoes dilution and dispersion. This process has been extensively studied by contaminant hydrogeologists around the world. The following information comes from the EUGRIS web portal for soil and water management in Europe which uses well-described and investigated cases.

Expanding plume

Leaking well is active and the introduction of salt is greater than the assimilative capacity of the aquifer. A neighbouring well would show a steadily rising salinity trend.



Stable plume

Leaking well is active but there is no significant change in the plume dimensions and mass. A neighbouring well would show a steadily rising salinity trend followed by a stable trend.

Detached and fading

Leaky well has been backfilled or rehabilitated and is no longer a source of salt. The plume migrates downgradient with a reduction in plume mass due to dilution and dispersion. A neighbouring well would show a rising salinity trend followed by a falling trend.

B. Groundwater flow velocity calculations

The velocity of groundwater flow can be calculated using the following formula.

$$V = \frac{K \times Í}{\Theta}$$

where V = average water particle velocity

K = hydraulic conductivity

Í = hydraulic gradient

ϴ = porosity

For the T1 aquifer, a hydraulic gradient at the coast near West Lakes was calculated to be 0.0063. A hydraulic conductivity of 2 m/day and a porosity of 0.1 are assumed.

Therefore $V = \frac{2 \times 365 \times 0.0063}{0.1} = 46$ m/yr

For the T2 aquifer, a hydraulic gradient at the coast near St Kilda was calculated to be 0.0017. A hydraulic conductivity of 2 m/day and a porosity of 0.1 are assumed

Therefore $V = \frac{2 \times 365 \times 0.0017}{0.1} = 12$ m/yr

Given natural variations in aquifer properties, a ranges of groundwater velocities should be considered as follows.

T1 aquifer – 30 - 50 m/yr

T2 aquifer – 5 - 15 m/yr

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