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Effects of Gnangara allocation scenarios on groundwater acidification from exposed acid sulfate soils

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Department of Water and Environmental Regulation
168 St Georges Terrace
Perth Western Australia 6000
Telephone +61 8 6364 7600
Facsimile +61 8 6364 7601
National Relay Service 13 36 77
www.water.wa.gov.au

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Contents

Figures

Tables

Appendices

Summary

Acid sulfate soils (ASS) underlie more than half of the Gnangara groundwater management area and pose a risk to the water quality of groundwater users where these are exposed by declining a watertable. These soils contain sulfuric acid stored below the watertable in the mineral pyrite that is released and starts to leach when exposed to air. The acid release can trigger a cascade of other changes in soils that flow on to influence the quality of shallow groundwater including leaching of iron, aluminium and other metals in soils, salts and arsenic. While near surface ASS are typically concentrated in wetlands and lakes, there are extensive areas of Bassendean sands where ASS are associated with the shallow watertable on Gnangara mound.

This report assesses the likely extent and risks to groundwater users of poor water quality due to acidification from watertable decline under different abstraction scenarios (interventions) modelled in PRAMS. Future risks are predicated by an assessment of the status of shallow soil and groundwater acidification prior to 2013. Modelling of no intervention consisted of no changes to private licenced and unlicensed pumping, but redistributed pumping for public water supply. All interventions consisted of both reducing private and public pumping and were modelled with a projected drying climate and changes in land use (increased urbanisation and change in pine plantation management).

Collation and analysis of data from over 220 bores sampled between 2003 and 2010 indicates there is shallow groundwater acidification beneath an area of over 380 km^2 with a further 425 km^2 where impacts are emerging. This reflects acidification impacts caused by watertable decline over previous decades.

Risks of acidification impacts to groundwater users increase in many inland subareas of the Gnangara groundwater management area with unchanged pumping and changes in land use in a climate that continues to dry (no intervention). At least 10.9 GL of pumped water is at risk of impacts from poor water quality caused by drying ASS. The volume of the resource impacted is likely to be an order of magnitude greater. Users at risk in the urban subareas are a mix of smaller garden bores and licenced irrigation bores in the subareas Ballajura, Bayswater, Bassendean, Stirling and Swan North. Outside of this, there are risks to small stock and domestic bores and larger licenced irrigation bores in the semi-rural subareas of Deepwater Lagoon South, Lake Mungala, Neaves, North Swan and Reserve.

Reducing pumping lessened the risks to users in all subareas with the greatest reduction avoiding all risks in the urban subareas. Reduction in pumping by 63 GL in intervention option 4 avoids impacts to 10 GL of pumped water with less reduction of 45 GL in intervention option 3 avoiding impacts to 6.9 GL of pumped water. The benefits of avoiding impacts are to a combination of licenced users, garden bores and self-supply users in both urban and semi-rural subareas.

This assessment highlights that regional reduction in pumping can minimise future risks to users of poor groundwater quality caused by drying ASS and where future

monitoring and investigations are best focused to manage residual risks. Significant improvements in water quality monitoring is urgently required – both regionally and for specific classes of users. This can be achieved through joint activities of monitoring water quality trends with licenced users with regional surveying of shallow groundwater quality in the areas at highest risk of impacts. Significant risks to mainly users with garden bores in urban subareas are uncertain and can be clarified with further monitoring and investigation. In contrast, regional monitoring with site specific investigations and development of models can clarify the nature and progression of risks in semi-rural areas.

1 Introduction

The sustainability of the Gnangara groundwater system is being compromised by declining rainfall, which is predicted to continue. Over many years, while Perth has adjusted to the drying climate, more water was abstracted than recharged, leaving the system over-allocated and its long-term reliability at risk. The department is preparing to develop the next allocation plan for the Gnangara groundwater system, which will aim to bring the system back into balance and match the drying climate to 2030. Part of this will be reducing abstraction and water allocations. This will protect the quantity and quality of water for use and support the groundwater-dependent environment into the future.

With water being such an important part of businesses, we need to assess the impacts of allocation options and any continued water level declines on the quality of water being used for a variety of purposes. This involves considering the economic costs of existing private users of non-potable groundwater substituting their use with scheme water or re-drilling and equipping bores deeper in the aquifer. These costs occur when significant deterioration of water quality either limits shallow groundwater use for irrigation or causes problems with bore operation (fouling, clogging) or integrity (corrosion).

Water quality impacts of declining watertable include exposure of acid sulfate soils (ASS) and acidification of shallow groundwater in vulnerable areas of Gnangara mound. ASS contain fine grained pyrite minerals that if exposed to air react with oxygen to release sulfuric acid. Oxidation of ASS and acidification can leach aluminium and arsenic to groundwater and increase concentrations in the Superficial aquifer. The chemical reaction also releases high concentrations of soluble iron that can reduce the quality of water and oxidise to form sludge that clogs bores.

Acidification and deterioration of water quality in wetlands is a well-known consequence of drying ASS. Wetlands such as Lake Gnangara and Lake Mariginiup have acidified, with Lake Jandabup experiencing an intermittent period of acidification (Sommer and Horwitz 2009). Sediments and shallow groundwater have acidified at a much larger number of wetlands, mostly those in the Bassendean sands (Degens et al. 2018; Department of Water 2011a, d; McHugh et al. 2011). Soil investigations have found acidifying thin lenses of oxidising ASS in other wetlands (e.g. Yonderup and Loch McNess; Department of Water 2011 b, c). This is coupled by monitoring at wetlands such as Loch McNess and Lake Goollelal showing changes in water quality such as reduced alkalinity and increasing sulfate concentrations that are consistent with an influence of drying and oxidising ASS (Judd and Horwitz 2017).

Deterioration of shallow groundwater quality by acidification is likely to influence use of groundwater where water is drawn from near the watertable, but can also result in deterioration of quality throughout the aquifer where pumping results in significant drawdown and mixing (e.g. noted in the Mirrabooka borefield by Appleyard and Cook 2008). Impacts from a drinking water quality perspective have been limited to the hardening of water (WorleyParsons 2012; Water Corporation 2015), but may also result in corrosive conditions around the outside of production bore casing.

Oxidation of ASS in drying wetlands (high ASS risk areas) will also result in poor quality shallow groundwater down-gradient to mid-depths of the superficial aquifer. Deterioration in water quality extend beyond acidification (low pH and hardness) to include high iron concentrations and occasionally arsenic. Recharge through drying and acidifying ASS at Lake Mariginiup has led to poorer quality groundwater down-gradient of the wetland, including elevated soluble arsenic (Searle et al. 2010). A similar process has also occurred at Lake Gwelup from up-gradient oxidation of ASS (Clohessy 2012). This analysis does not extend to assessment of contaminants such as arsenic or metals mobilised by increased oxidation of ASS.

To support the Department's decision making, this report presents the status of acidification in the Gnangara groundwater system and development and application of a method to estimate the impacts of water level declines on the quality of water taken by licensed and exempt domestic bores.

2 Objective

This assessment provides:

- The status of groundwater acidification in the Superficial aquifer of the Gnangara groundwater system
- A relative estimate of the volume of groundwater use (licenced and exempt) in the Superficial aquifer on Gnangara groundwater system mound affected by changes in quality (acidification) arising from future regional water level decline with different allocation intervention options consisting of:
    - **No intervention -** with changes in land use (expanded urbanisation and changes in the pine plantations) and 281 GL abstraction.
    - **Intervention option 1 -** with abstraction reduced to 266 GL and changes in land use (as per no intervention).
    - **Intervention option 2 -** with abstraction reduced to 247 GL and changes in land use (as per no intervention).
    - **Intervention option 3 -** with abstraction reduced to 236 GL and changes in land use (as per no intervention).
    - **Intervention option 4 -** with abstraction reduced to 218 GL and changes in land use (as per no intervention).
- Map guidance for managing acidification impacts on water quality.

3 Methods

The assessment was carried in several stages consisting of assessing the regional characteristics of shallow groundwater acidification on Gnangara mound and using this as a basis for developing an approach to extrapolate acidification impacts from regional water level outputs from PRAMS.

3.1 Assessment of ASS impact on groundwater quality

Soil and groundwater quality data from multiple investigation programs was collated to assess the evidence for ASS impacts on shallow groundwater quality in the Superficial aquifer.

Soil testing data (Figure 1) was compiled from the Perth Shallow Groundwater System (SGS) investigation program (2007 – 2010) and ASS mapping program carried out by DEC on the southern Gnangara mound (2008 – 2009; Singh et al. 2012a). Evidence of acidification was rated for each site based on field pH testing above or at the watertable and evidence and depth of potential ASS below the watertable as per Degens and Wallace-Bell (2009). Evidence of acidification was broadly based on where pH <4, which is deemed to be indicating oxidising ASS (commonly termed actual ASS) if associated with residual unoxidised ASS in the same profile (Sullivan et al. 2009).

Water quality data across Gnangara mound was collated (Figure 1) and analysed to benchmark the regional status and extent of shallow groundwater quality in relation to likely ASS impacts. Data was obtained from a regional hydrochemical investigation spanning (2003 – 2005; Yesertener 2010), the Perth SGS program (2007 – 2010) and DEC program on southern Gnangara (2007 – 2011; Clohessy et al. 2012). While some of this data is more than a decade old, the regional pattern and status of water quality is useful to provide a baseline for any future assessment. The water quality data were subject to quality assurance checks including assessment of charge balance and comparison of duplicates before being included in the analysis.

Rating bores by depth intersected below watertable

Bores were categorised by the length and depth of the screen inlet below the watertable to weight the extent to which water samples from the bore (and therefore the chemistry of these) reflected water quality at or near the watertable (Table 1). Water level data at the time of sampling was used to determine the saturated thickness and depth sampled by each bore. For the GWAN bores, this was conducted by matching water level at or near the time of sampling because this was not recorded with the water chemistry data.

The majority of bores providing the best indication of water quality near the top of the aquifer were purpose built for specific wetland investigations (the SGS bores in Table 1) or regional acidification (the DEC bores in Table 1; after Clohessy et al. 2013).

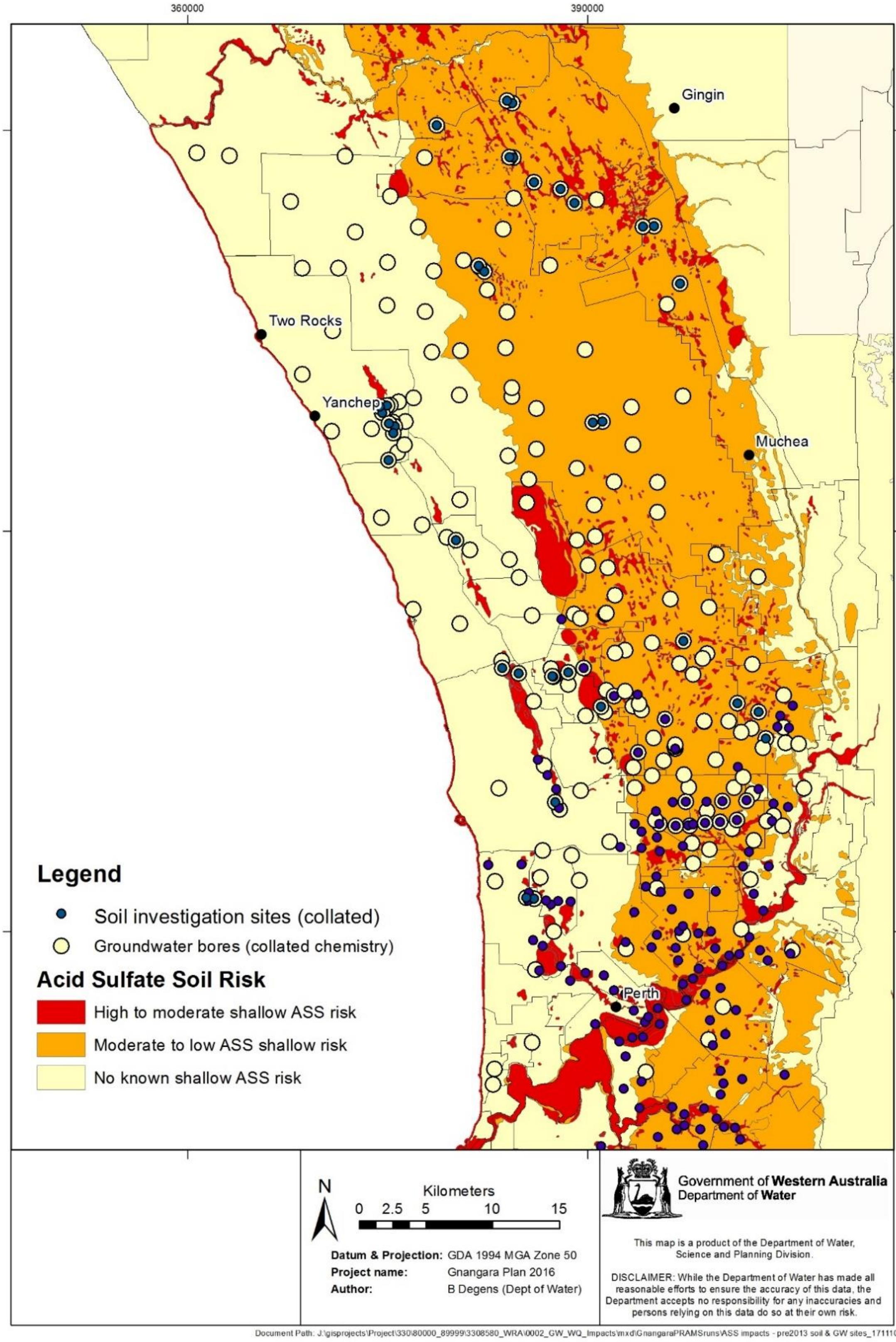


Figure 1: Collated data for soil and groundwater investigation sites

Most of the DEC and SGS bores were constructed with inlets crossing the watertable to a depth of 2 – 5 m below the watertable. In contrast, there were few bores (14) in the regional monitoring network (GWAN) that could be considered to reflect watertable chemistry. Other similar bores probably exist (that are owned by DoW) but were not sampled at the time. An additional 36 regional bores were considered to provide information for the shallow aquifer (Table 1), providing a mixed sample of water quality for a large interval (5 to 10 m thickness) near the top of the aquifer. Any acidification front progressing below the watertable at these sites may not be detected in the bores if this has progressed less than 5 m. Regional monitoring bores considered to provide information for the sub-shallow aquifer zone mostly intersected more than 10 m of the aquifer with nine intersecting 4 – 5 m of aquifer at more than 5.5 m below the watertable (Table 1). While a poor indicator of watertable acidification, these may provide some evidence of ASS impacts where the effects extend deep into the aquifer.

Table 1: Classification scheme for the extent to which bores (and therefore the samples from these) indicate shallow groundwater quality.

Category	Aquifer zone sampled by the bore	Thickness of aquifer intersected (based on inlet length) and depth in relation to watertable	Number of bores		
			GWAN bores[1]	SGS bores	DEC bores[2]
1	Watertable and shallow aquifer zone	< 5 m aquifer thickness intersected and watertable in screens or less than 1 m above top of inlets	14	38	44
2	Shallow aquifer zone	5 – 10 m aquifer thickness intersected and watertable in screens OR < 5 m aquifer thickness intersected with top of inlet < 2 m below the watertable	36	None included	10
3	Sub-shallow aquifer zone	5 – 10 m aquifer thickness intersected and watertable less than 1 m above top of inlet OR < 5 m aquifer thickness intersected with the top of inlet < 4 m below the watertable	9	None included	1
4	Mid aquifer zone	> 10 m aquifer thickness intersected OR < 6 m thickness intersected at > 5 m below the watertable	47	None included	None
5	Deep aquifer zone	Top of screen inlet is > 10 m below the watertable	23	None included	None

[1] As sampled in Yesertener (2010)

[2] As reported in Clohessy et al. (2013)

Evidence of ASS oxidation rating

Water quality data was analysed and assigned a rating as to signs of oxidising acid sulfate soils influencing quality. Best assessment of the influence of ASS oxidation is achieved by interpreting trends in groundwater chemistry. The limitations of a single point interpretation applied here are discussed later. Evidence of ASS influencing water quality was classed into three levels each reflecting the confidence of the assessment (Table 2).

Several factors were considered together in assessing the water quality data for the influence of ASS oxidation including pH and alkalinity as well as the amount of SO_4^{2-} relative to other ions (Table 2). Other factors such as increasing soluble iron can also be an indicator but was measured in few bores. These properties are based on the progressive changes in groundwater chemistry that can result when ASS begin to oxidise with a decline in pH following other changes (Knutsson 1994).

Oxidation of pyrite in ASS exposed to air is the main process driving a number of reactions summarised after Appelo and Postma (2007) as :

$$4FeS_2 + 14H_2O + 15O_2 \rightarrow 16H^+ + 8SO_4^{2-} + 4Fe(OH)_3$$

When the pH falls below 4, the precipitation of iron oxide ($Fe(OH)_3$) slows in which case the reaction at the top of the aquifer may progress with iron remaining unoxidised in soil pore water as:

$$2FeS_2 + 2H_2O + 7O_2 \rightarrow 4H^+ + 4SO_4^{2-} + 2Fe^{2+}$$

In the early stages of oxidation, the release of acidity (as H^+) in the soil above the watertable consumes any buffering capacity (ie lowering of alkalinity levels) such as carbonates (see reaction below) and displaces exchangeable cations. This is seen in water quality as increased leaching of cations such as Ca, Mg, K and Na with declining alkalinity (Knutsson 1994).

$$2H^+ + CaCO_3 \rightarrow Ca^{2+} + H_2O + CO_2$$

With advanced oxidation, leaching of rainfall recharge to groundwater carries the acidity and other products of oxidation such as SO_4^{2-} and dissolved Fe to the shallow aquifer where further chemical reactions can occur as the leachate waters mix.

In broad terms, groundwater influenced by ASS oxidation will become gradually enriched in SO_4^{2-} with this typically transported faster through the aquifer than any acidification front. Progression of acidity into the aquifer is slower due to reactions with dissolved alkalinity in groundwater and exchangeable ions in the aquifer. Consequently, alkalinity is a more sensitive indicator of acidification than changes in pH, although it is difficult to interpret acidification from alkalinity alone because this property of water can naturally vary over a wide range.

Several corresponding aspects of water quality (ie low alkalinity in combination with elevated sulfate) were considered strong indicators of ASS oxidation (Table 2), using the logic of ASS influences on recharge water chemistry discussed above. Bore water quality exhibiting the strongest indications of ASS oxidation was based on pH, alkalinity and enrichment of SO_4 whereas weaker indications of ASS oxidation were where the weight of evidence was limited to one or two aspects of water quality. Interpretations of each water quality criteria are outlined below.

Acidification of groundwater is clear with pH < 4.5 where groundwater contains no alkalinity (Table 2). Under these conditions the chemistry of the aquifer is corrosive to infrastructure and becomes dominated by geochemical reactions involving dissolution of minerals and large changes in trace metal behaviour. It is possible that some groundwater is naturally acidic as a product of consequent of leaching in podzol soils (Prakongkep et al. 2012), though most exhibited a high SO_4:Cl ratio. Groundwater in the range pH 4.5 – 5.5 with low alkalinity (< 20 mg $CaCO_3$/L) was also considered an indicator of ASS oxidation in this assessment, but only in combination with a high SO_4:Cl ratio. Some groundwater on the southern part of Gnangara groundwater system may naturally be pH 5 – 6 based on reports of water quality before significant development in the 1970's (Allen 1981; Appleyard and Cook 2009; Martin and Harris 1982). Low pH (~4.6) can also arise from naturally high concentrations of carbon dioxide in subsoils with no mineral buffering (Knutsson 1994; Appelo and Postma 2005) and high concentrations of dissolved organic matter (Oliver et al. 1983).

The ratio of sulfate to chloride (SO_4:Cl) was used as a key indicator of ASS oxidation where pH and alkalinity evidence of acidification was less conclusive (ie classification code 2 in Table 2). High SO_4:Cl does not exclusively reflect ASS oxidation and can sometimes be caused by leaching of SO_4 from fertilizer use. This is likely to result in false interpretations of impacts for some bores, but be limited in number because of most significant horticulture is limited to areas on the western side of the mound such as Carabooda and Wanneroo.

A SO_4:Cl greater than 0.5 was considered to indicate a significant additional source of SO_4 to groundwater relative to background levels in rainfall and groundwater. This ratio is several times that of recent rainfall. Rainfall sampling at Floreat from 2007 – 2011 found a ratio of 0.18 (Crosbie et al. 2012) which is similar to the previous ratio of 0.14 for Yanchep in 1973 (Hingston and Gailitis, 1976). In contrast, previous SO_4:Cl ratios in rainfall collected in Perth range from 0.34 in 1973 (Hingston and Gailitis, 1976) to 0.08 measured in 1989 to 1990 at the same site by Farrington et al. (1993). In contrast, groundwater SO_4:Cl ratios that represent a pre-disturbed condition are likely to be less than rainfall.

Sulfate reduction is common in the Bassendean sand formation where most ASS risk occurs which lowers SO_4:Cl. The ratio at the watertable on the fringes of the mound around wetlands is typically less than 0.2 where ASS oxidation has not been found in shallow sediments (Degens et al. 2012; Degens et al. 2018; Department of Water 2011a; McHugh et al. 2011). Pre-development ratios in the shallow aquifer across most of the southern part of Gnangara were also frequently less than 0.2 (Bawden 1991; Martin and Harris 1982).

Table 2: Classification scheme for the extent to which water chemistry shows signs of recharge through oxidising ASS.

Classification	Class code	Features of the water quality	Parameter ranges used to class water quality
Strong evidence of oxidising ASS influencing water quality	2	Very acidic with no alkalinity and significant extra SO_4	pH < 4.5, alkalinity <5 $CaCO_3$/L and SO_4:Cl > 0.5
		Very acidic with no alkalinity and extra SO_4	pH < 4.5, alkalinity <5 $CaCO_3$/L and SO_4:Cl 0.2 – 0.5
		Acidic with significant extra SO_4, low alkalinity	pH 4.5 – 5.5, alkalinity 5 – 20 $CaCO_3$/L and SO_4:Cl > 0.5
		Acidic with significant extra SO_4, low to moderate alkalinity	pH 4.5 – 5.5, alkalinity 20 – 30 $CaCO_3$/L and SO_4:Cl >0.5
		Mildly acidic with low alkalinity, significant extra SO_4	pH 5.5 – 6, alkalinity 20 – 30 $CaCO_3$/L and SO_4:Cl >0.5
		Very significant extra SO_4 but circum-neutral	SO_4:Cl > 1.4 but pH 6.7 – 7 (alkalinity > 50 $CaCO_3$/L)
Some evidence of oxidising ASS influencing water quality	1	Acidic with extra SO_4 and moderate alkalinity	pH 4.5 – 5.5, alkalinity 30 – 40 $CaCO_3$/L and SO_4:Cl 0.2 – 0.5
		Significant extra SO_4, but mildly acidic to circum-neutral (varying alkalinity)	SO_4:Cl >0.5, pH 5.5 – 7 (alkalinity 25 – 260 mg $CaCO_3$/L)
		Slightly increased SO_4 with low alkalinity in mildly acidic water.	SO_4:Cl 0.1 – 0.5 but with alkalinity < 30 mg $CaCO_3$/L and pH 5 – 6.5
No evidence of oxidising ASS influencing water quality	0	Mildly acidic with often moderate alkalinity and no evidence of extra SO_4	pH 5 – 6.5 and SO_4:Cl < 0.2 with alkalinity 30 – 110 $CaCO_3$/L
		Circum-neutral water with moderate alkalinity and no evidence of extra SO_4	pH > 6.5 and alkalinity often > 60 mg $CaCO_3$/L with SO_4:Cl typically < 0.3

Alkalinity has been previously used to assess acidification impacts and applied in combination with SO4 (Swedish Environmental Protection Agency 2000; Department of Environment Regulation 2015). Alkalinity criteria are used to assess susceptibility to further acidification, however the derivation of the criteria appears arbitrary. Analysis of alkalinity:sulfate has also been proposed as an indicator of ASS oxidation influence on water quality where less than 5 (Swedish Environmental Protection Agency 2000; Department of Environment Regulation 2015). This was considered as a secondary indicator in this assessment, but threshold levels used to interpret where ASS oxidation may be influencing water quality are unverified. Over 50% of bores with water quality contained alkalinity:SO_4 < 5 despite showing no evidence ASS oxidation influences using pH, alkalinity or SO_4:Cl criteria (Table 2). This indicator is also prone to errors because of the sensitivity to measurement of alkalinity in low alkalinity environments. Most available water quality data comprises laboratory analyses of alkalinity which can decrease after collection from bores.

There are uncertainties to interpreting ASS impacts from a snapshot of alkalinity and pH even in combination with SO_4:Cl and the ratings applied in this assessment are to build a regional assessment rather than allow interpretation of hot-spots of ASS impacts.

In a final analysis, the depth of acidification for a sub-set of bores was also compared with watertable decline. These bores contained clear evidence of ASS impacts, that is very acidic groundwater, with no alkalinity and highly enriched in SO_4 (Table 2). Watertable decline in the decades prior to the date of sampling was calculated from the hydrograph for each bore.

Mapping shallow groundwater acidification

The combined evidence from groundwater monitoring, wetland investigations and soil mapping were used to map the regional extent of shallow aquifer acidification from ASS oxidation. Two categories of status were mapped: acidified at the watertable or emerging acidification. The mapping used water quality data spanning 2003 to 2010 (see above) with most of the aerial coverage representing the status between 2005-2007. Areas with a high incidence (>70%) of monitoring bores showing clear evidence of acidification (see Table 2) near the watertable (see Table 1) were mapped as being acidified. Areas where most monitoring information (> 70% monitoring bores) indicated emerging impacts of ASS oxidation acidification (Table 2) either at or just below the watertable were mapped as emerging.

3.1 Outline impact risk assessment

The assessments of acidification risks and impacts were conducted using a spatial calculation model run in GIS. Calculations for each scenario were conducted with gridded drawdown data derived from regional watertable contours or from drawdown in the watertable (Layer 1) from PRAMS 3.5.2 scenarios (Hall et al. 2016).

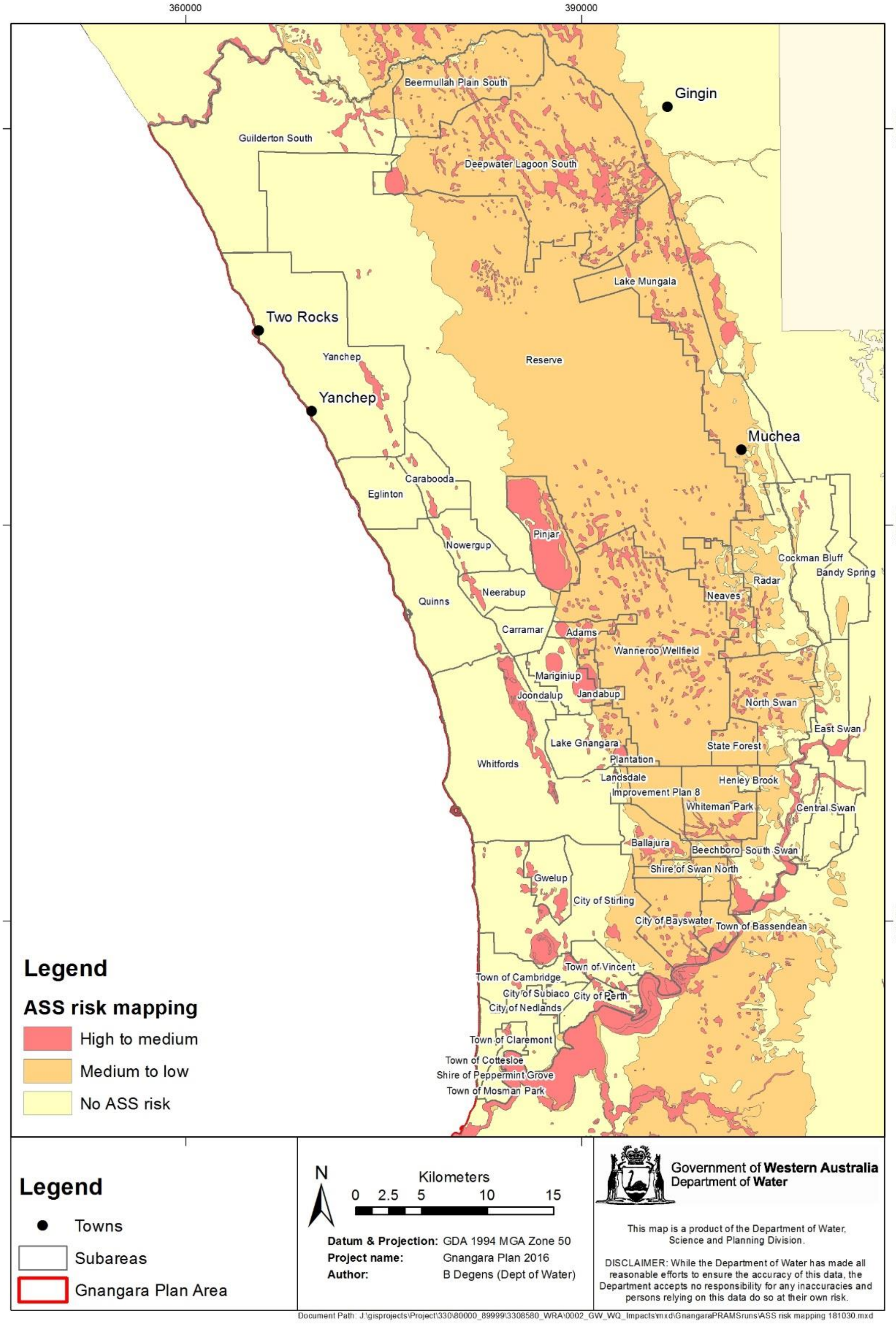


Figure 2: ASS risk mapping for the Gnangara groundwater system

Calculations were carried out in several stages outlined below and described in detail in the following sections:

- Extrapolating aquifer acidification from watertable decline: Drawdown in watertable levels for the Gnangara Mound were used to calculate the long-term average depth of acidification in the **acidification hazard area** (see below) using a linear relationship with depth of ASS exposed.
- Estimating Volumes of Use at Risk: Impacts were calculated for licenced and exempt groundwater users
- GIS methodology: Collation of results to display (spatially and as tables) volumes of groundwater at risk of pumping poor water quality for each user category (licenced or exempt) and the average number of bores affected.

3.1.1 Extrapolating aquifer acidification from watertable decline

The effect of watertable change on shallow groundwater quality was calculated in **acidification hazard areas**. This area was extrapolated from acid sulfate soil risk mapping which identifies where there is a risk of acid generating soils (acid sulfate soils) forming if exposed by a decline in the watertable. The hazard areas combined areas of medium to high ASS risk mapping (Figure 2). The medium to high ASS risk areas combined both broadly distributed low sulfide (<0.03% reduced S) containing poorly buffered Bassendean sands (Singh et al. 2012a) and sediments associated with wetlands that often contain higher concentrations of sulfides (see Degens et al. 2018; Department of Water 2011a; McHugh et al. 2011, Searle et al. 2010). Assessment of water quality impacts from previous watertable decline are generally consistent with this hazard posing a risk to water quality (see later sections).

Impacts other than acidification can also occur such as high iron concentrations and occasionally arsenic. These frequently extend to the west of high ASS risk areas in lakes and wetlands, for example Lake Mariginiup (Searle et al. 2010) and Lake Gwelup (Clohessy 2012). These down-gradient impacts are estimated to extend up to 1 km down-gradient over a 20 year time-span. This estimate is based on down-gradient groundwater flow velocities of 40 – 150 m/year (0.7 to 2.9 km/20 years) calculated for Lake Mariginiup, Lake Gwelup and North Lake (assuming hydraulic conductivity values as per Davidson 1995). Actual transport of iron and other products of acidification will be slower than the flow of groundwater as these react with the aquifer. This effect is partly accounted for by assuming that most reaction products arbitrarily move half as fast as the rate of groundwater flow (0.35 – 1.5 km / 20 years).

The average depth of aquifer acidification following exposure of acid sulfate soils was empirically derived by estimating the long-term average depth of acidification below the watertable (at least 10 years after the decline). Poor water quality was calculated as a depth of groundwater acidified which was assumed to be linearly related to every metre of decline in areas in acidification hazard. The applied relationship was:

Estimated average acidification depth = watertable decline x 5

In essence, each metre thickness of exposed ASS can generate acidity that results in acidification to an average depth of 5 m below the watertable when the acid is flushed with recharge to groundwater.

Several lines of evidence support the assumption of maximum acidification depth based on watertable decline:

- Investigations indicating that acidification fronts from < 1 m watertable decline in the Bassendean sand formation could extend more than 4 metres below the watertable (Clohessy et al. 2013; Appleyard and Cook 2008)
- Reactive transport modelling indicating a 1 m decline in the watertable exposing ASS north of Whiteman Park results in acidification extending at least a 3 m below the watertable in the 4 years following the decline (Salmon et al. 2014), and
- Acid mass balance calculations (see Appendix A) showing acidity from a 1 m decline in minimum watertable potentially leaches 1 to 32 m below the watertable in the Bassendean sand formation.

Additional verification of the assumption was also obtained by assessing acidification depth caused by ASS exposure by historic watertable change in regional monitoring bores. This was carried out only using bores where groundwater was extremely acidic (pH<4) with strong evidence of this being caused by ASS oxidation (ie highly sulfate enriched with average SO_4:Cl >1.3). Water level change over the previous decades was determined for the bore and plotted against the acidification depth at the time of sampling (based on the bottom depth of the bore inlet) + the previous watertable decline.

3.1.2 Estimating volumes of use at risk

Groundwater users at risk of impacts from acidification of shallow groundwater were identified on the basis of unlicensed (exempt) use, annual licensed allocations and the likely depth of pumping bores and screen lengths (Table 1). Larger licences for uses like horticultural or POS irrigation most likely involved bores pumping from greater depths in the aquifer whereas pumping for self-supply and general smaller irrigation would generally involve bores pumping from shallower depths in the aquifer. The closer to the watertable that pumping occurs the greater the likelihood of pumping shallow groundwater influenced by acidification caused by watertable decline. Furthermore, as an acidity front propagates below the watertable, impacts on users are likely to be greatest after this passes the mid-point of the screened inlet of bores.

Determining where water is pumped from based on inlet depth below the watertable requires a number of assumptions since little data was readily available on construction of licenced bores. Analysis of bore depth data for licenced drawpoints in COMPASS (formerly the WRL database) indicated that half of most bores pumping from the Superficial aquifer were drawing from within 20 m of the minimum 2013 watertable (Appendix B).

Table 3: Minimum screen depths and lengths of screens for pumping bores in the Bassendean Sand formation categorised by annual pumping volume and use.

Category of pumping bore	Annual Vol pumped (ML)	Depth range of top screens (m below WT)	Screen / slot length (m)
Garden bore (unlicensed)	<0.4[a]	0 to 10	4 to 6
Household supply + garden (unlicensed)	<1.5	3 to 15	4 to 6
Household supply + garden (includes unlicensed and licensed)	1.5 to 15	5 to 25	6 to 18
Irrigation (parks, horticulture etc) – all licensed	>10	>15	6 to 30 [b]

[a] Recent metering indicates most garden bores use <0.4ML/annum (Department of Water 2014)

[b] Water Corporation production bores in the Pinjar, Mirrabooka, Wanneroo and Lexia borefields have screens lengths of between 10 to 30 m.

For exempt use it was assumed that bores had inlets evenly distributed to 15 m below the watertable in any groundwater subarea and therefore the volume pumped can be assumed to be distributed evenly to 15 m depth. This is based on most backyard garden and self-supply bores typically being drilled to a depth of less than 20 m below the watertable and with screens in the order of 10 m length. As indicated above, the mid-screen depth of bores is deemed the point where any change in water quality at that depth will dominate the groundwater pumped by the bore. Therefore, use at risk of any changes in maximum acidification depth is assumed to be distributed between the watertable (where there would be some bores with screens across this) to 15 m below the watertable (representing the mid-screen depth of 5 m above the maximum bore depth of 20 m). In reality, pumping would result in accelerated drawdown of any acidified groundwater near the watertable and mixing of this with deeper water either in the aquifer or in the bore during pumping.

For bores where there is no depth information in COMPASS (formerly WRL) the proportion of water use affected was represented as a cumulative function (Appendix B). The approach is the same as assigning bore depths to individual drawpoints using the cumulative distribution.

Impacts on users were summed and presented by sub-area in several metrics:

- Volumes of use at risk of pumping poor water quality caused by ASS being exposed were summed by sub-area for licenced and exempt use.
- Average number of bores affected – this is the sum of licenced bores with known depths that were calculated to be affected, an estimated number of

licenced bore from those where depths were not known and estimated number of exempt bores based on average use per bore (from WAP estimates)

3.1.3 GIS methodology

Calculations of impacts on volumes of use were carried out in ArcGIS using several datasets and the methods below.

Spatial datasets used for this assessment were:

- ASS risk mapping (DER, Swan Coastal Plain 2006),
- ASS hydrochemistry assessment (B. Degens, 2014 unpublished dataset)
- Watertable drawdown datasets – 500 x 500 m gridded outputs of watertable drawdown (ddn layers) for Layer 1 between 2013 and 2033 for different PRAMS model scenarios.
- Water-use datasets:
    - Exempt use – Calculated for each groundwater subarea at 2030 by WAP as tabulated data (after Evans et al. 2014; see Table A8 in Appendix D). This exempt use includes growth in use as a simple proportional increase but does not account for growth due to urban expansion. For this assessment, use is assumed to be spread evenly for areas excluding where land use at 2030 was classified as pines or Banksia (PRAMS V3.5.2 codes 1, 2, 22 and 23 for Banksia and codes 6, 7, 8, 17 and 18 for pines). Exempt use is assumed to be in areas coded as pasture (typically semi-rural and rural land use activities), urban, market gardens or industrial. This is a reasonable assumption for most pasture area at 2030, except where pines where harvested and converted to pasture that will not become part of expanded semi-rural or rural activities. Most of the pine to pasture change will be in the Wanneroo Wellfield, Reserve and State Forest sub-areas which have no exempt use, except for a small amount in the State Forest sub-area.
    - Licensed use – Licenced use for drawpoints obtained from a snapshot of the COMPASS (formerly Water Resource Licensing or WRL) database for the Superficial aquifer (as at June 30 2013). Where drawpoints contain depth information (25% of bores), this was assumed to be the bottom of the well. This information was used to estimate the distribution of pumping with depth in the Superficial aquifer and applied to the 75% of bores were depth information was not available (see Appendix B).

The following calculation steps were conducted in ArcGIS :

- Creation of acidification risk area polygon from ASS risk mapping (DER dataset, 2006) with an extended risk area downgradient of high risk areas. This effectively created an extended acidification risk area of 1 km length downgradient of high risk areas. In the course of this mapping, several areas of no known ASS risk were remapped as class 2 (moderate to high ASS risk; see Appendix C).

- Extraction and processing of WL change data from raster datasets from PRAMS scenario outputs. Cleaning of the raster values to exclude no-cell and extreme values (>9999 values). Clip to acidification risk area including only pixels with the centre of these falling in risk area.
- Calculation of estimated average depth impact of acidification for each grid cell as acidification impact = 6 * WT decline. This incorporates the acidity in the depth exposed by watertable decline (1 x WT decline) and the depth below the watertable that the acidity is transported (i.e. 5 x WT decline see Section 3.1.1 for modelling rationale).
- Append tabulated exempt use data to Gnangara sub-area polygons (corporate dataset).
- Cut Gnangara groundwater sub-areas polygons with PRAMS grid and exclude cells that are in areas with Banksia or Pines (see processing of water use dataset in 3.1.3 above).
- For each PRAMS scenario impacts on each category of use were calculated as -
  - **Exempt use**: PRAMS cell area x metres depth acidification x (use per m^2/15). The PRAMS cell area was nominally 250 000 m2 (500 x 500 m) except for parts of cells falling truncated by the boundary of subareas. This assumes the exempt use (calculated as use/m^2) in each PRAMS cells is drawn evenly over 15 m from the top of the aquifer (see section 3.1.2). For average acidification depths > 15 m the calculated impact was capped at 15 m to prevent calculation of impacts greater than the use in the subarea. The number of bores impacted was estimated using the use/bore estimates assumed for each subarea (Table A8 in Appendix D; WO144925).
  - **Licenced groundwater use (where bore depths are known):** calculated as the sum of licenced use for bores were average acidification depth > bore depth – 5 m (where impacts are evident in the mid-inlet depth of bores as discussed in section 3.1.2). A count of bores impacted was used for statistics.
  - **Licenced groundwater use (where bore depths are unknown)**: calculated by appending average acidification depth to data for each drawpoint, calculating proportion of each licenced use affected (using cumulative function defined as Equation 2 in Appendix B) and summing water use values for all draw points in Superficial aquifer. The estimated number of impacted bores was estimated using the **Equation 3** in Appendix D.
- Calculate statistics on each user category (exempt, licenced and the breakdown of licenced with depth data and licenced with no depth data).

3.2 Application to PRAMS model scenarios

This report assessed how acidification impacts in the Superficial aquifer are predicted to respond by 2042-43 under a range of future pumping scenarios modelling in PRAMS (Table 4). The 2042-2043 time horizon is when all effects of pumping and land use change have stabilised in the unconfined and confined aquifer system (Yu et al. 2018). Calculations of acidification under each scenario were conducted with modelled water level outputs representing the watertable as described in section 3.1.3 above. The impacts on users from the predicted depth and distribution of acidification were then determined for each category of use (licenced and exempt).

All scenarios were modelled with different pumping volumes and distributions with:

- a future dry climate rainfall pattern (Yu et al. 2018)
- future increases in urbanisation as per the draft Green Growth Plan (Yu et al. 2018), and
- future pine plantation management as per the draft Green Growth Plan (Yu et al. 2018).

The exception to this was the basecase scenario (BOOd) which was modelled with a future dry climate but with no change in land use or pumping from 2013 (Table 4).

Pumping for the no intervention scenario beyond 2013 contains projected changes to pumping beyond 2013. These include increased pumping for public water supply in the North West growth corridor (Yanchep and Eglinton subareas) and garden bore use of 1% (Yu et al. 2018) with decreased pumping due to land use change in the East Wanneroo area effecting pumping in the Lake Gnangara, Mariginiup and Joondalup subareas (Yu et al. 2018).

3.3 Assessing impacts of scenarios

Impacts were reported as:

- Volumes of use at risk of pumping poor water quality caused by ASS being exposed summed by sub-area for licenced and exempt use.
- Average number of bores affected by acidification – this is the sum of licenced bores with known depths that were calculated to be affected, an estimated number of licenced bore from those where depths were not known and estimated number of exempt bores based on average use per bore (see Appendix D for calculations)

Table 4: PRAMS model scenarios used to calculate seawater intrusion impacts (Yu et al. 2018).

Scenario & reference code[1]	**Future abstraction (GL)**				
	Public water supply (IWSS)				
	Baseline licences	**North West coastal reserves**	**Private**	**Exempt**	**Total**
Basecase (BOOd; W10S1D)	111	0	121	37	269
No intervention (W33_01)	111	18	110	43	282
Intervention option 1 (W34_01)	101	18	104	43	266
Intervention option 2 (W34_04)	91	18	99	39	247
Intervention option 3 (W34_02)	81	18	98	39	236
Intervention option 4 (W34_03)	81	18	90	29	218

[1] PRAMS scenario codes as per Yu et al. 2018.

3.4 Limitations & sources of uncertainty

The assessments based on calculations in this report are conservative and contain a number of assumptions:

- There are uncertainties to interpreting ASS impacts from a snapshot of water quality (alkalinity, pH and SO_4:Cl) which mean that individual bores may not indicate hot-spots of ASS impacts however collectively indicate a regional status of impacts.
- Previous acidification of the shallow aquifer does not affect use from 2013 to 2030 where water levels **rise** or amplify the acidification impacts where levels **decline**. Acidification prior to 2013 may persist initially in areas where water levels rise but are likely to dissipate by 2030. Impacts in areas with acidification prior to 2013 is therefore likely to be greater than assessed here.
- Average likely acid propagation below the watertable is not modelled but represented by an approximate empirical function. This approximation is equivalent to representing the recharge in PRAMS as a single average rainfall recharge % across the whole of Gnangara Mound when recharge, acid leaching and aquifer reactions are often an order of magnitude more complex

than modelling aquifer hydraulics. Empirical representation of maximum acidification depth may equally over-estimate impacts in some areas and under-estimate this in other areas.

- Depth of impact is the average depth of changes in water quality <u>at 2030</u>. This generally means the depth of where groundwater pH falls below 4.5 due to leaching from exposed ASS. Other impacts may extend below this depth such as hardening of the groundwater (increased Ca and Mg) and increased salinity (due to increased Ca or Mg and sulfate).
- Propagation of the acidification front below the watertable is not influenced by recharge volumes or quality. Areas with greater recharge where the watertable is falling (e.g. low density Banksia or pasture areas on the centre of the mound) may result in the average depth of acidification being greater. Conversely where recharge is less, the average depth of acidification may be less and concentrated shallower in the aquifer (e.g. under pines).
- Propagation of the acidification front below the watertable is not influenced by the buffering capacity of the aquifer. The acid buffering capacity of the aquifer is likely to vary spatially (see section 3.1.1 and Appendix A) therefore maximum acidification depth may be less where buffering is greater (where the Guildford formation occurs towards the scarp) or less (Bassendean sands with limited coffee rock).
- Impact occurs when the average depth of acidification reaches the mid-inlet depth of bores. Impact may be greater at bores where regular pumping causes local mixing of groundwater, but this depends on the alkalinity of deeper groundwater and buffer capacity of the aquifer.
- Impacts on most licenced users is based on modelling the probability of the use of any one bore being affected. Depth is not recorded for over 75% of licenced bores in COMPASS (formerly WRL). Modelling of the probability of impacts may tend to over-estimate impacts for drawpoints with larger volumes but under-estimate impacts for areas with drawpoints with smaller volumes.
- Future impacts on exempt use may be underestimated where there are increased sub-division of blocks in semi-rural areas with no reticulated supplies. Sub-divisions potentially result in greater number of shallow groundwater users at risk of acidification impacts.
- Impacts on use downgradient of wetlands assume these extend from the watertable but may be deeper if originating from drying wetlands up-gradient. This means the impact on groundwater use down-gradient of drying wetlands may be understated. As wetlands dry, the recharge and influence of these on groundwater quality may extend to mid-depths of aquifers (e.g. Searle et al. 2010).

- Impacts on GDEs is not accounted for and is included as part of determining Environmental Water Requirements for wetlands (see Degens et al. 2018; Department of Water 2011a, b, c, d; McHugh et al. 2011; Searle et al. 2010).
- We assume exempt use is concentrated in areas mapped for PRAMS as non-pines or Banksia. This is reasonable for most areas except where pasture is mapped in some areas of known Banksia (e.g. Reserve and Deepwater Lagoon South).

4 Results & Discussion

4.1 Regional status of shallow groundwater acidification on Gnangara mound

Scattered information on deep soil pH and groundwater quality in the Gnangara groundwater system provides an indication of acidification from previous watertable decline. This section presents a broad analysis of the evidence for acidification in soils and shallow groundwater from a collation of data collected between 2004 and 2011. This consists of soils information collected during ASS mapping by DEC (2008-2009; Singh et al. 2012a) and for the DoW Perth SGS (2007-2010). Groundwater quality data was from the DoW and DEC shallow groundwater acidification investigations.

Extent of soil acidification from previous watertable decline.

Soil testing information shows little oxidation above the watertable from previous water level decline with this mostly being noted around wetlands outside of urbanised areas. Drilling at 31 sites near 19 wetlands on Gnangara mound for the SGS program found 45% of sites had acidic soil zones above the watertable for nine wetlands (Figure 3). In contrast, less than 10% of the 87 inter-dunal depressions investigated for ASS by DEC on the southern part of Gnangara (Figure 3) contained evidence of acidification (pH< 4) of the unsaturated zone near the watertable (Appendix E, Singh et al. 2012a). However, a further 10% of sites (9 sites) showed a trend of decreasing soil pH to the watertable (Figure 3). Acidic surface soils in damplands have also been identified on the eastern flank of Gnangara mound in the Muchea area (Toms, 2012).

The DEC investigations also indicated that potential ASS distribution was sporadic. Almost a third of sites investigated in areas where ASS hazard broadly occurs (mapped as high and medium ASS risk) had no potential ASS up to 6 m below the surface.

The absence of soil acidification at many inter-dunal (mostly Bassendean Sand) sites in the southern Gnangara area might be due to potential ASS materials being absent near the recent watertable or that recharge has neutralised or leached the acidity. The regional watertable at most of the inter-dunal sites had declined more than 0.5 m in the 15 years prior to the date of coring, with declines of more than 2 m at some sites. This would be expected to have exposed and allowed oxidation of ASS, if the watertable decline was less than the historic (pre-development) minimum. The depth of potential ASS is marginally below the pre-development long-term minimum watertable (Degens 2009). In parts of Gnangara mound, the watertable has changed since the 1970’s rising with the clearing of native vegetation and falling with the subsequent growth of pine plantations (Yesertener 2008). Urbanisation also results in a rise in the watertable. The level at the time of the soil investigations may have been above that of the original pre-development watertable thus potential ASS materials

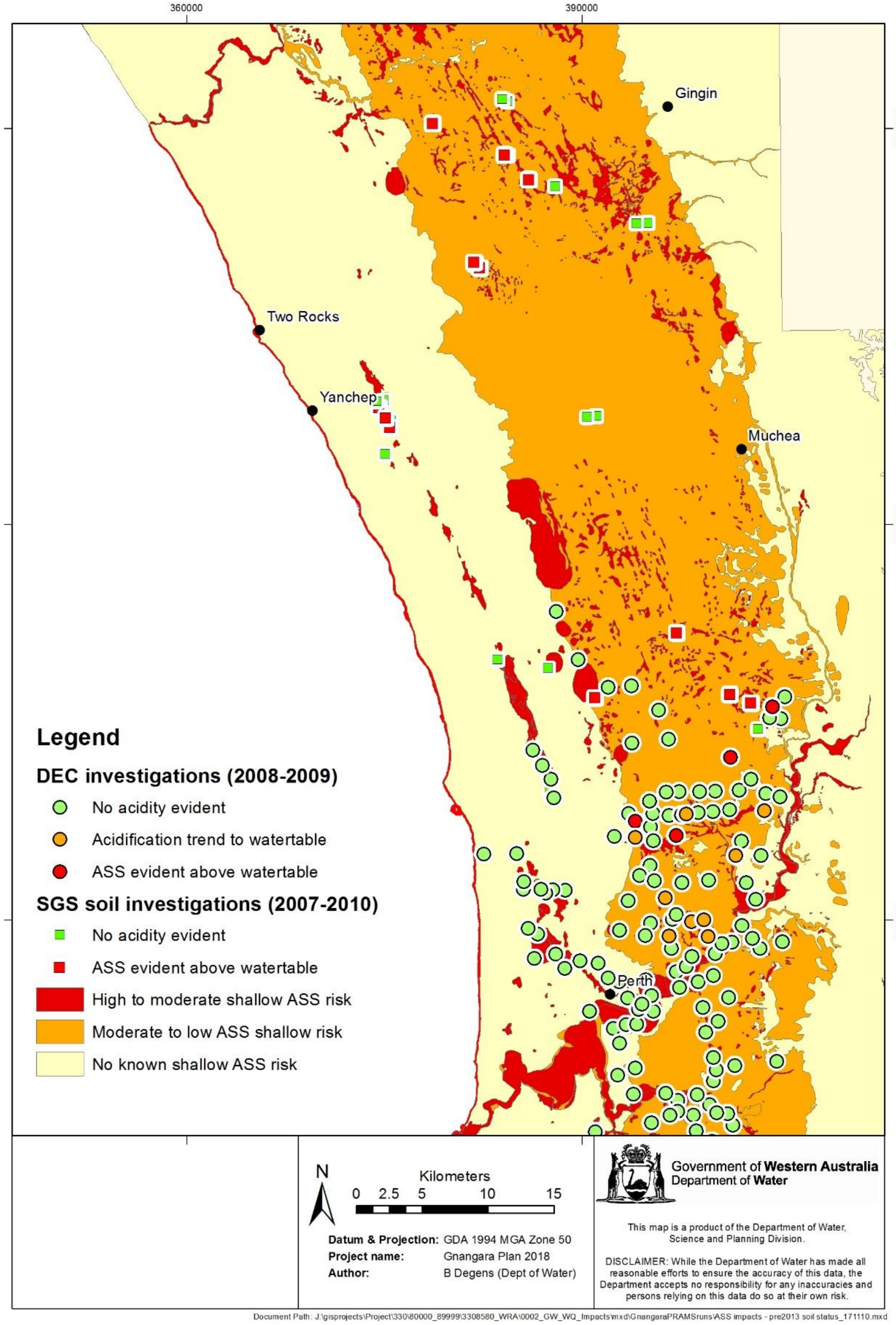


Figure 3: Classification of soil acidification status using data from collated soil investigations (2007 – 2010)

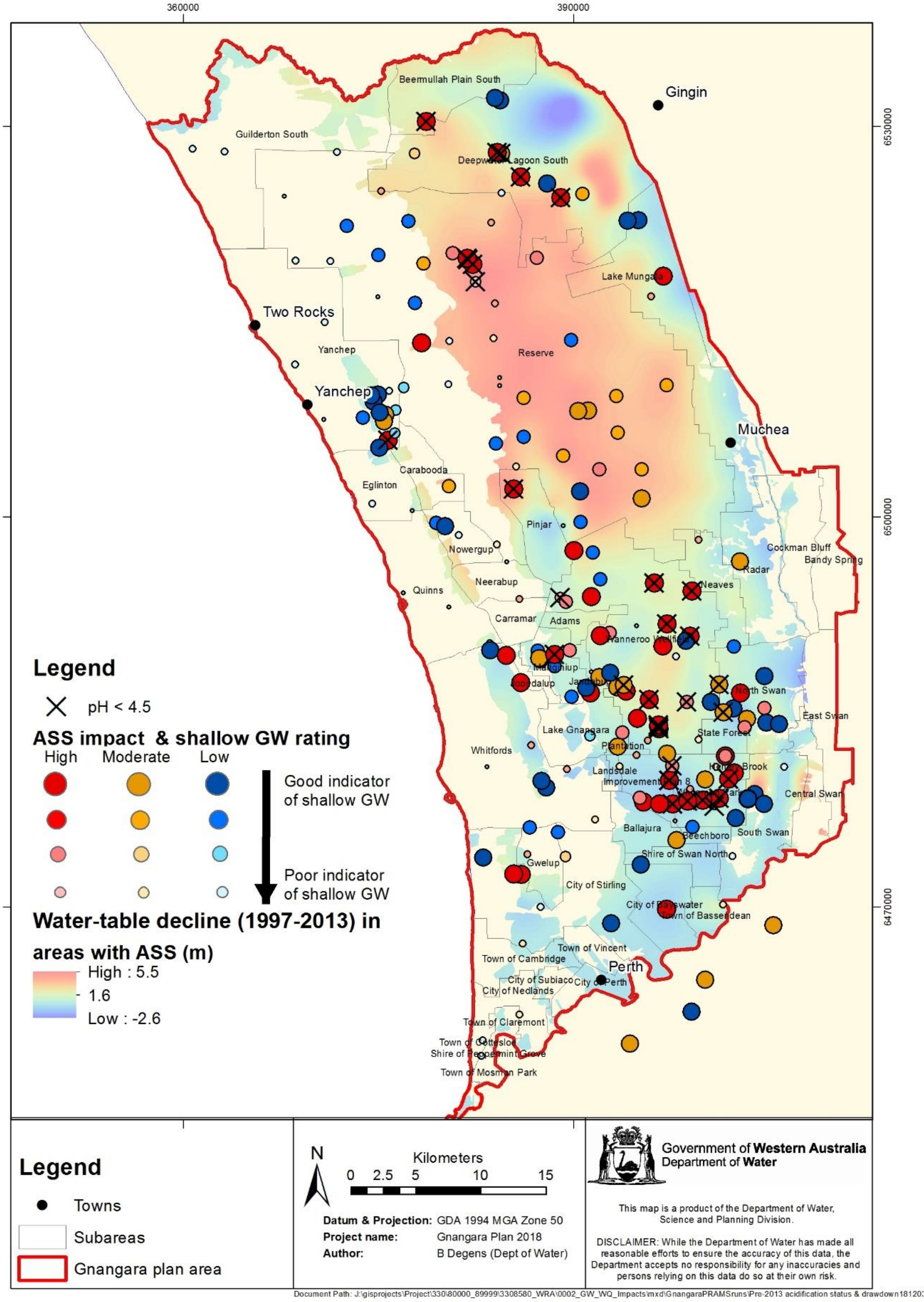


Figure 4: Status of ASS impacts on groundwater quality from monitoring (2003 – 2010) in relation watertable decline from 1997 – 2013

have remained undisturbed or have previously oxidised and leached from the soil profiles.

A second possibility is that acid generation from some oxidising ASS is neutralised by recharge from surface soils or readily leached to the shallow groundwater. Clear illustration of this was at a site north of Ballajura (near the southern part of the Mirrabooka borefield; 616-01-32) where there was a decreasing trend in soil pH to 5 at the water-table, but nested bores show the aquifer to be acidified to at least 2 m below the watertable (Appleyard and Cook 2009). Since most of the ASS data was collected for soils in urban areas frequently in parks, the soils were probably well leached by recharge from the surface.

Extent of wetland acidification from previous watertable decline.

Several large lakes have acidified on Gnangara mound since the 1990’s with acidifying trends noted in several others. Lake Gnangara acidified in the late 1970’s (Appleyard and Cook 2009) and Lake Mariginiup has progressively acidified since the late 1990’s reaching pH < 4.5 after 2007 (Sommer and Horwitz 2009; Searle et al. 2010). Lake Jandabup began to acidify in 1998 but supplementation halted this by preventing further drying (Sommer and Horwitz 2009). Elsewhere, there is evidence acidification trends in the water quality at Lake Goollelal (Judd and Horowitz 2017).

There is often little surface water quality data for other seasonal wetlands with many having transitioned to damplands with the decline in water levels for example Quin Swamp (Degens et al. 2018), Tangletoe Swamp (Department of Water 2011a) and the Lexia wetlands (Department of Water 2011d).

Extent of shallow aquifer acidification from previous watertable decline.

ASS impacts on shallow groundwater quality are evident across most of the central part of Gnangara consistent with the footprint of watertable decline from 1997 to 2013. Over 25% of the water quality in monitoring bores sampled between 2004 and 2011 showed signs of ASS impacts near the watertable and a further 10% indicate that an acidification front is propagating from the soil to the shallow aquifer in places (Table 5). Most bores intersecting shallow highly acidic groundwater were around 25 wetlands on Gnangara Mound (SGS bores). These contained water with pH <4.5, no alkalinity and elevated sulfate concentrations. In contrast, 8% of regional bores between the wetlands were highly acidic (Table 5). A further 18% of bores in the shallow aquifer between wetlands showed signs of ASS oxidation but without acidification being evident as pH < 4.5 (Table 5). This is the point where groundwater is devoid of alkalinity that would buffer acidification. These bores may be where neutralisation has occurred or where the acidification front is yet to reach below the surface few metres of the aquifer.

The bores showing signs of ASS oxidation were more widely spaced across the mound and frequently indicated water quality up to 10 m below the watertable (at the time of sampling). The pattern of impacts on water quality were patchy with some bores not showing any signs of ASS impacts on water quality adjacent to bores with a clear signal particularly towards the top of the mound (Figure 4).

The results depict a pattern of groundwater quality ranging 7 to 15 years ago (2003 – 2011). It is likely that the pattern of acidification impacts has progressed with further development and leaching of acid products to the watertable.

The combined information from soil, wetland and groundwater data indicated that 811 km^2 of the shallow Superficial aquifer has either been acidified or is showing emerging acidification. This comprises 386 km^2 where there is strong evidence of acidification at the watertable and a further 425 km^2 where acidification is emerging (Figure 5). This mapping represent the conservative status at mostly before 2009 and has likely expanded with continued groundwater decline across most of the Gnangara mound since then.

Acidification at the watertable is evident in two distinct areas across the Gnangara plan area. An area of 237 km^2 is acidified in the southern flank of the mound where regional groundwater flow is towards the south (Figure 5). This area is beneath semi-rural areas of Pinjar, Mariginup, Jandabup, Lexia and Whiteman extending towards the suburb of Ellenbrook. A slightly smaller area (148 km^2) is acidified to the north of the mound largely beneath the Yeal Nature Reserve where the regional groundwater flow is towards the coast (Figure 5).

Table 5: Summary classification of the evidence of oxidising ASS impacting groundwater quality with depth in the aquifer.

Evidence of ASS oxidation[1]	Depth in aquifer[2]				Total by ASS status
	Watertable	Shallow	Sub-watertable	Mid and deep aquifer	
Strong evidence	57	19	2	14	92 (42%)[3]
Moderate evidence	16	7	2	10	35 (16%)[3]
No evidence	33	21	5	35	94 (42%)[3]
Total by depth category	106 (48%)[3]	47 (21%)	9 (4%)	59 (27%)	221

[1] Assessment of ASS influence on water chemistry as per Table 2

[2] Classification of depth below the watertable that rating applies based on Table 1

[3] % of bores in each category

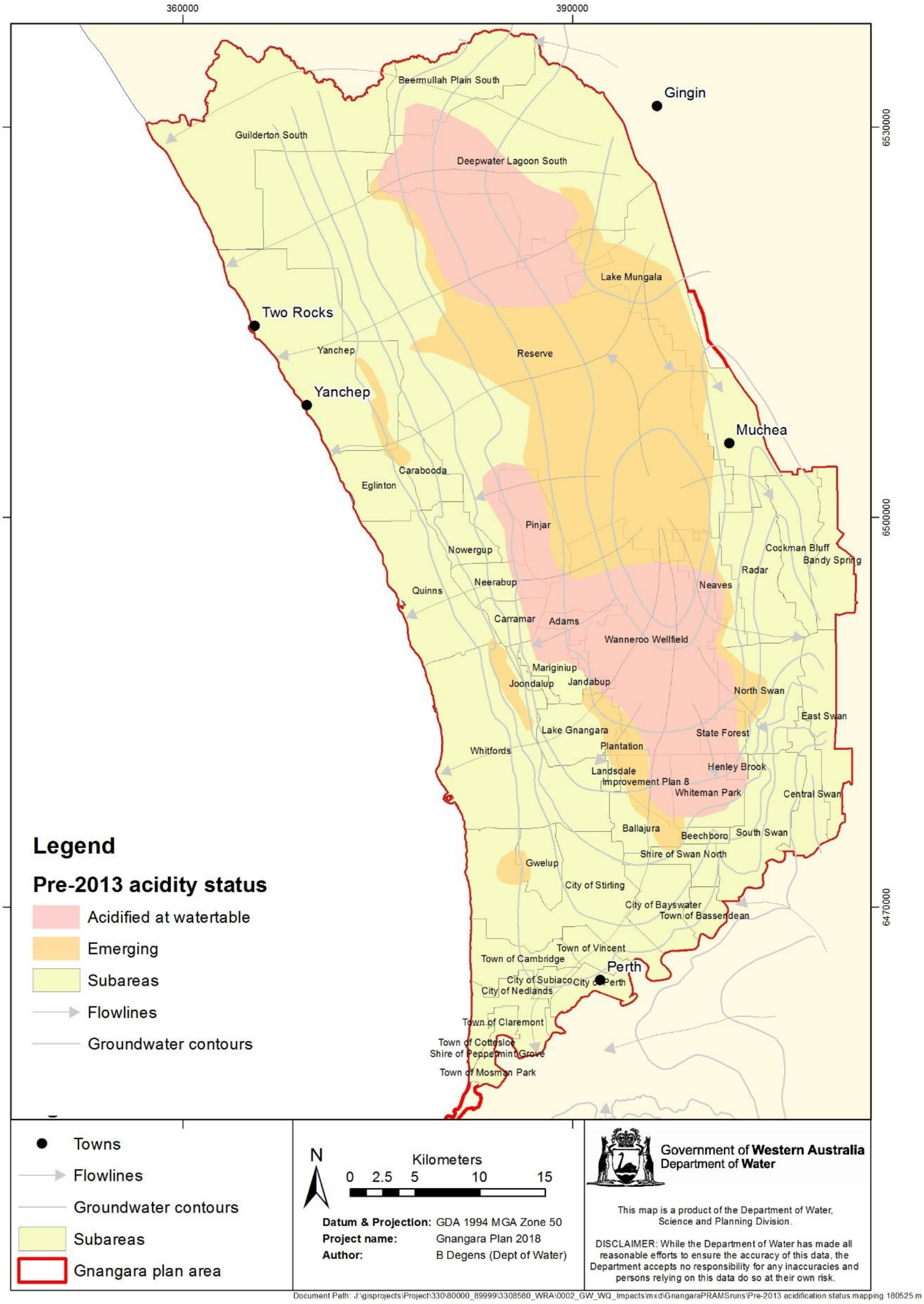


Figure 5: Regional mapping of shallow groundwater acidification status in the Superficial aquifer

The future propagation of the acidification front with depth in the aquifer and downgradient of the source area is uncertain. Local geochemical modelling indicates that acidification may not extend far below the watertable (Salmon et al. 2014), however this greatly depends on the recharge, that effectively transports acidity to the watertable and buffering capacity of the aquifer materials (including carbonates). Much of the Bassendean sand formation is devoid of carbonates (Bastian 1996; Prakongkep et al 2012; Singh et al. 2012a,b) and has limited cation-exchange capacity (Prakongkep et al 2012; Singh et al. 2012b) that would provide some capacity to neutralise the acidification front. Column investigations also indicated that very small amounts of acidity from what is regarded as minor concentrations of sulfide minerals (<0.03%S as pyrite) were also capable of causing very low pH (Singh et al. 2012b).

Severe acidification from previous watertable decline over more than 20 years could extend to at least 13 m below the watertable (Figure 6). Highly acidic groundwater (pH often less than 3.8) was found at 16 sites on Gnangara with very enriched sulfate (average SO_4:Cl >1.3) indicating ASS oxidation. Greater depth of acidification below the historic watertable (based on the inlet depth of the bores) broadly corresponded with greater watertable decline since the 1970's. Acidification probably extended below the depth of the bores with most indicating acidification fronts greater than several metres below the watertable at the time of sampling (Figure 6). This finding confirms other evidence from modelling (Salmon et al. 2014) and monitoring (Clohessy et al. 2013; Appleyard and Cook 2008) of acidification fronts extending at least 5 m following every metre of watertable decline. In comparison, previous investigations in 1986 (Cargeeg et al. 1987) and 1992 (Hirschberg and Appleyard 1996) reported only two few bores on Gnangara mound with highly acidic groundwater (pH < 4.5) and neither contained elevated SO_4 concentrations.

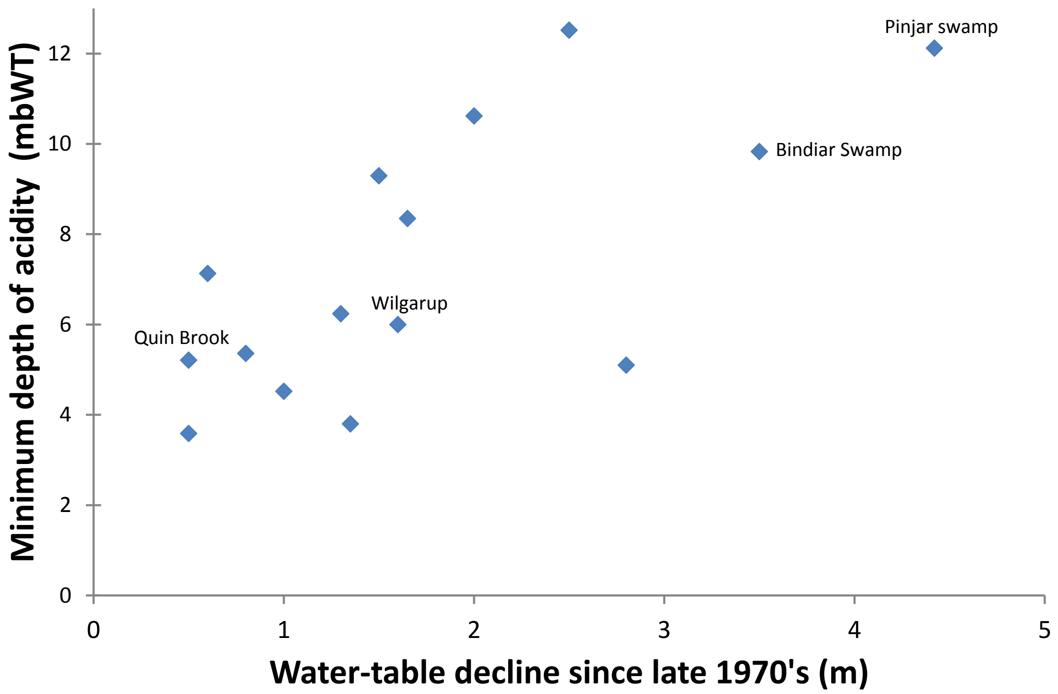


Figure 6: Acidification below the historic watertable in relation to watertable decline

A re-survey of groundwater quality would provide an updated status of the acidification status with most previous information being from more than a decade ago. The best practice for detecting changes in regional water quality status is to monitor trends over time considering alkalinity, pH, nutrients and all major ions. The ionic composition is useful to detect Ca + Mg and SO4 enrichment whereas trends in nutrients (including enrichment of K) can assist in isolating changes in quality that may be due to fertilizer leaching. Analysis of stable isotopes in groundwater ($\delta^{2}H-H_2O$ and $\delta^{18}0-H_2O$) and sulfate ($\delta^{34}S-SO_4$ and $\delta^{18}0-SO_4$) would greatly assist in determining the origin of groundwater and dissolved sulfate.

Further resolution of the shallow aquifer acidification status requires drilling new bores with shorter screen inlets, although this investigation found that the existing bore monitoring network indicated regional acidification. The best bore design for sampling changes in water quality at the watertable is with short inlet length (< 2 m) at or near the watertable (see Clohessy et al. 2013). Short inlets at greater depth below the watertable are useful for sampling discrete changes in water chemistry with depth. Many existing bores owned by DoW were constructed more than 20 years ago often with longer inlets (often >5 m) because these were not intended for monitoring of water quality. However, the data from some of these bores still provided an indication of the water quality in the shallow Superficial aquifer. Over 48% of these sampled the top 5 m of the aquifer and at least provide a mixed sample across this thickness.

Implications of shallow aquifer acidification.

The acidification indicated by regional monitoring would be expected to cause problems to users of groundwater, shallow buried infrastructure and the environment.

Impacts of acidification on users of groundwater will range from corrosion of pumps, household piping and hotwater systems, leaching of metals in these systems (risking lead contamination), staining of baths, basins, toilets and showers to poor plant growth and burning of leaves of grass and vegetables under irrigation.

Current evidence of impacts on users of groundwater range from acidification of exempt bores to declines in the water quality of public water supply bores. These impacts are consistent with evidence of the regional acidification footprint mapped in this investigation. Users near Lake Mariginiup have reported acidification of shallow water supply bores. Elsewhere, west of Muchea, farmers have anecdotally reported acidification of bores used for stockwater and increasing iron settling from pumped water. Water quality in public water supply bores also shows ASS acidification being drawn towards the base of the aquifer where these bores draw from. Monitoring of bores in the Mirrabooka borefield (in the Improvement Plan 8 and Whiteman Park sub-areas; Figure 2) shows many bores in the acidification risk area have rising hardness and sulfate concentrations often with declining alkalinity (Water Corporation 2015). These trends indicate there is acidification at the watertable that is being drawn deeper into the aquifer with pumping. Bores in other nearby borefields such as Lexia and Wanneroo (in the Wanneroo Wellfield) also show similar impacts (Water Corporation 2015), although less water quality information is available.

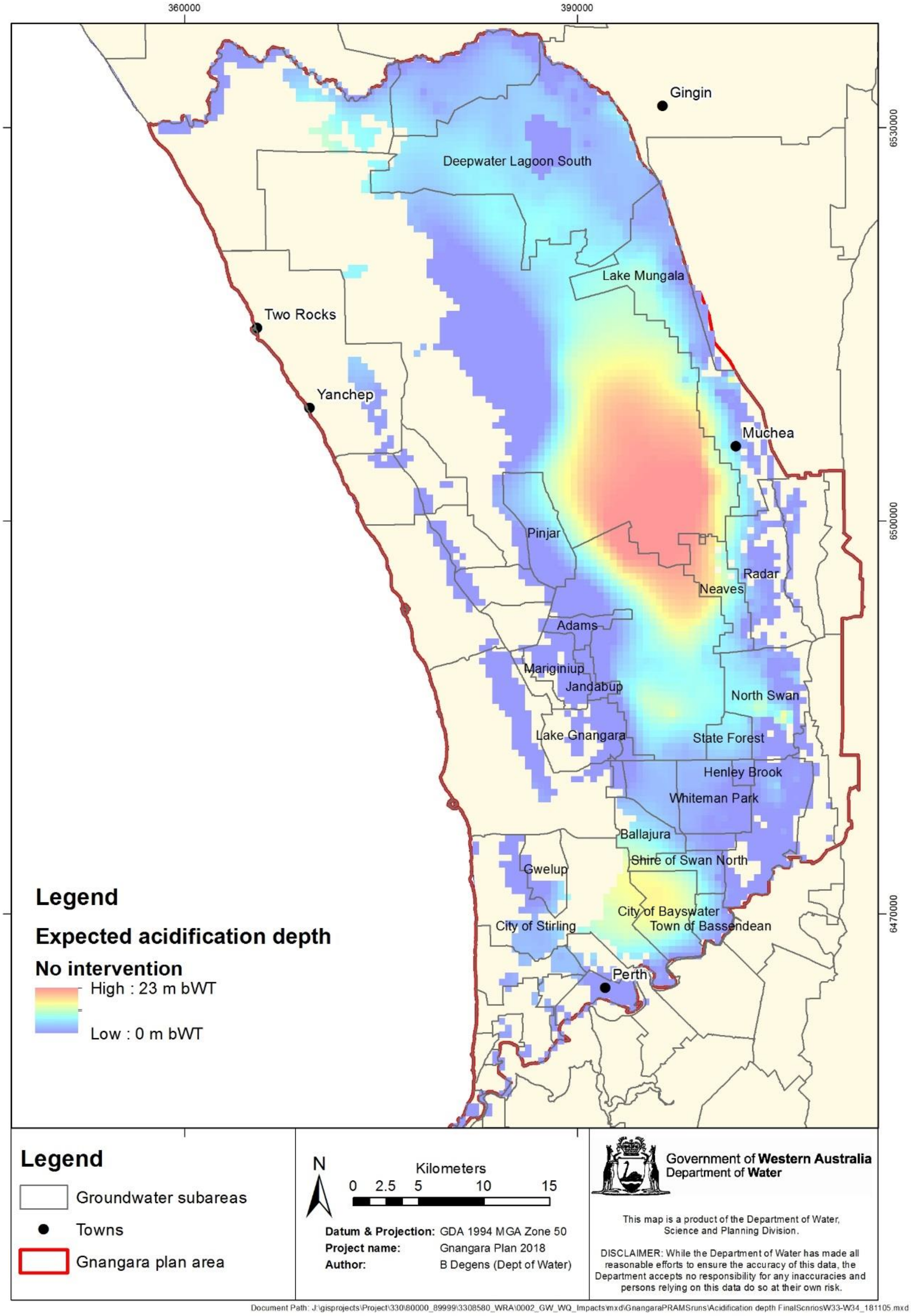


Figure 7: Average depth (metres below watertable) of acidification calculated for 2030 based on PRAMS modelling for the no intervention scenario.

Most users may be unaware of changes in groundwater quality if they are not routinely checking quality. Deterioration in water quality is likely to occur gradually over a number of years to decades as acidification progresses. Changes in chemistry can be slow to show without detailed analysis of groundwater quality but suddenly hit once an acidification front reaches the depth of a bore. These begin as trends in ionic composition (with increasing sulfate and sometimes increasing calcium concentrations) with a decline in alkalinity until there is breakthrough of acidity. Any gradual changes in quality causing corrosion could easily be misattributed to wear and tear, aging of bore casing, pumps, plumping, tanks and hot water systems.

4.2 Modelling acidification of the Superficial aquifer

Modelling of acidification depth with watertable decline in the acid hazard areas was carried out for two base scenarios (with and without landuse change) and 4 scenarios with increasing levels of intervention to reduce pumping (see Table 4). Across all of the scenarios, the, depth of acidification was up to 23 m on the top of the mound but is generally less than 11 m. Future average acidification depth is greatest in the Reserve subarea for all the scenarios, corresponding with the greatest reduction in watertable levels (Figure 7).

The estimated average depth of acidification is less with reduced pumping, but remains at least 10 m across most of the central part of the mound (see Appendix F for all figures). In urban subareas such as Bayswater, Bassendean and eastern City of Stirling, there is no acidification expected with greatest reduction in pumping in intervention option 4. However, with slightly greater pumping in intervention option 3 the estimated average depth of acidification is mostly less than 6 m (see Appendix F). With no intervention, the depth of acidification in these urban subareas increases to as much as 13 m (Figure 7).

4.3 Distribution of acidification impacts at 2030 under the basecase and no intervention scenarios

Over 13 GL of water use is at risk of acidification under the basecase scenario that is reduced to 11 GL with land use change, growth in pumping of garden bores and some redistribution of licenced pumping in the no intervention scenario (Table 6).

With no intervention, most of the impacts (>8.2 GL) are in urbanised subareas (Bayswater, Ballajura, Bassendean, Stirling & Shire of Swan North) effecting up to 15,500 bores. Most of the remaining impacts (1.9 GL) are extensive in rural sub-areas such as Reserve, Neaves, North Swan and Lake Mungala (Table 6; Appendix F) effecting up to 350 bores (Appendix H).

By contrast, the basecase scenario highlights the effects of land use change but no changes in pumping with a future drying climate. Without removal of the pines and increased urbanisation (in areas such as East Wanneroo) there are impacts to more than 4.4 GL of use in semi-rural areas such as Adams, Lake Gnangara, Mariginiup Pinjar and Wanneroo Wellfield effecting over 1200 bores (Figure 8; Appendix H). However, with no growth in garden bore use, impacts in urban subareas such as

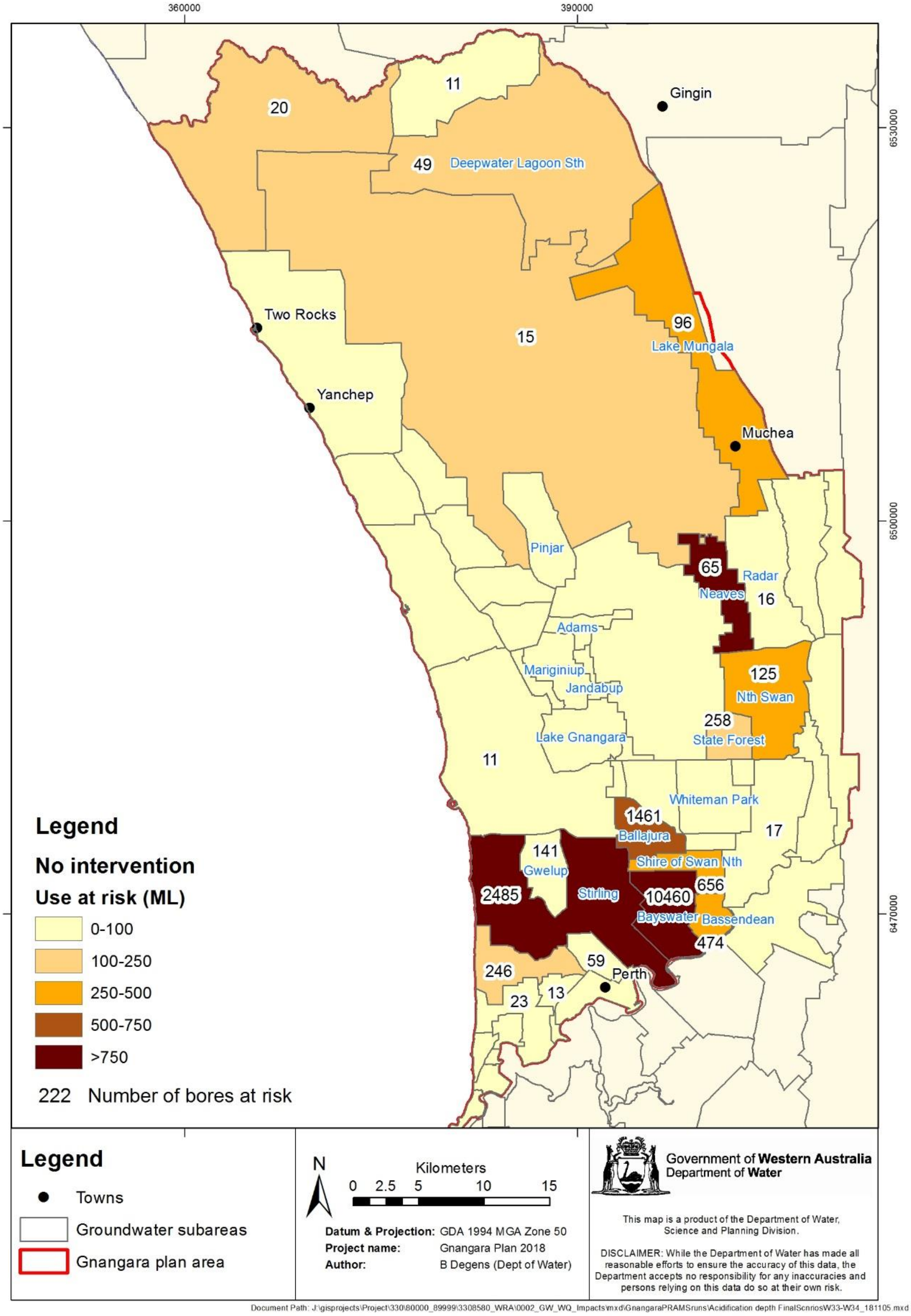


Figure 8: Groundwater use (licenced and exempt) corresponding number of bores at risk of increased acidification for the no intervention scenario.

Bayswater, Bassendean, Stirling and Shire of Swan North are 2.9 GL less in the basecase (Table 6).

Risk of impacts increases where water levels decline within the area where there is an acidification hazard, which is often in areas with previous acidification or emerging quality impacts from previous watertable decline (Figure 5). Water level decline for the no intervention scenario mostly occurs in the central and southern parts of Gnangara mound and in urbanised areas (see Yu et al., 2018). The resource volume impacted is not calculated here but is many times greater than the volume of impacted use.

The volume of use in the urbanised sub-areas at risk of impacts with no intervention is mostly garden bores (in the exempt category). This use is comprised of many smaller, shallow bores ranging between 400 in Bassendean to over 10000 in Bayswater (Figure 8; Appendix H). There is little to no previous groundwater quality information in these areas to confirm whether acidification is a risk, however previous DEC soil investigations (2011) have noted potential ASS materials are within 1 m of the watertable in these areas.

Use at risk in the semi-rural sub-areas mostly consists of licenced use estimated using a probability distribution (because of a lack of information on pumping bore depths). The proportion of licenced use at risk ranges from 61% in Lake Mungala to 95% in Neaves of which >75% of this in both areas is estimated for bores with no depth recorded in WRL. The increased risk to the quality of pumped groundwater is where water is used for drinking and there are no piped supplies. In North Swan, the risks to use are mostly in the north of the subarea which is the southern part of the future Brabham development where available groundwater is constrained for future development. Acidification of the aquifer from watertable decline to 2013 in these subareas (see Figure 5) will amplify the sensitivity of the aquifer to future acidification impacts in these areas.

4.4 Distribution of acidification impacts at 2030 under the reduced pumping intervention options

Intervention to reduce pumping reduced users at risk of impacts by between 1 and 10 GL. Use at risk of acidification was minimised to less than 0.8 GL (Table 6; Appendix G) effecting less than 140 bores in intervention option 4 (Figure 12) with greatest reductions in pumping. By contrast, 9.7 GL of use remained at risk (effecting over 15000 bores) with slight reduction in pumping in intervention option 1 (Table 6; Figure 9). Reductions between these in intervention options 2 and 3 resulted in impacts to less than 4.4 GL of use (Table 6; Appendix G) effecting over 5 900 bores (Figure 10, Figure 11, Appendix H).

Urban subareas with greatest risks of water quality impacts under all intervention options are concentrated in Ballajura, Bayswater, Bassendean, Stirling and Swan North. These are progressively reduced with less pumping from over 7.8 GL in intervention option 1 (Figure 9) to less than 3 GL in intervention options 2 and 3 (Figure 10; Figure 11) and avoided altogether in option 4 (Table 6; Figure 12). Under intervention option 1, these impacts were estimated to effect over 15 000 bores that were mostly (>95%) garden bores with the number of effected bores reducing to less than 6 000 with options 2 and 3 and no bores effected in option 4 (Appendix H).

The largest risks to pumped water in semi-rural subareas under all intervention options are concentrated in Deepwater Lagoon South, Lake Mungala, Neaves, North Swan and Reserve. These are progressively reduced with less pumping from almost 1.4 GL in intervention option 1 to less than 0.7 GL in option 4 (Table 6; Appendix G) with over 60% of use at risk being licenced. These volumes are estimated to put at risk water use from up to 60 bores under intervention option 1 reducing to 36 bores in intervention option 4. While the volumes of exempt use at risk were much less (<0.3 GL) this is estimated to impact over 200 users in these subareas under option 2 progressively halving to less than 100 under option 4. Most of this water is used for a combination of stock watering, garden irrigation and domestic self-supply.

Table 6: Annual volumes (GL) of pumped groundwater (exempt and licenced) at high risk of poor water quality from acidification under different regional intervention options.

Subarea name	Basecase	No intervention	Intervention option 1	Intervention option 2	Intervention option 3	Intervention option 4
Adams	0.36	0.01	0.00	0.00	0.00	0.00
Ballajura	0.77	0.71	0.63	0.05	0.04	0.00
Bandy Spring	0.00	0.00	0.00	0.00	0.00	0.00
Beechboro	0.01	0.01	0.00	0.00	0.00	0.00
Beermullah Plain Sth	0.07	0.06	0.05	0.04	0.04	0.03
City of Bayswater	2.85	4.81	4.75	2.13	2.05	0.00
City of Nedlands	0.01	0.01	0.01	0.00	0.00	0.00
City of Stirling	1.12	1.77	1.74	0.58	0.51	0.00
City of Subiaco	0.01	0.01	0.01	0.00	0.00	0.00
Cockman Bluff	0.00	0.00	0.00	0.00	0.00	0.00
Deepwater Lagoon Sth	0.26	0.22	0.16	0.14	0.10	0.07
Guilderton South	0.13	0.14	0.07	0.07	0.07	0.02
Gwelup	0.04	0.09	0.09	0.00	0.00	0.00
Henley Brook	0.08	0.01	0.00	0.00	0.00	0.00
Improvement Plan 8	0.03	0.00	0.00	0.00	0.00	0.00

Subarea name	Basecase	No intervention	Intervention option 1	Intervention option 2	Intervention option 3	Intervention option 4
Jandabup	0.10	0.00	0.00	0.00	0.00	0.00
Lake Gnangara	2.23	0.00	0.00	0.00	0.00	0.00
Lake Mungala	0.33	0.30	0.24	0.20	0.17	0.13
Landsdale	0.07	0.00	0.00	0.00	0.00	0.00
Mariginiup	0.79	0.00	0.00	0.00	0.00	0.00
Neaves	0.90	0.86	0.63	0.55	0.49	0.30
North Swan	0.32	0.27	0.17	0.14	0.12	0.07
Pinjar	0.20	0.03	0.01	0.00	0.00	0.00
Plantation	0.07	0.01	0.00	0.00	0.00	0.00
Radar	0.05	0.05	0.04	0.02	0.02	0.01
Reserve	0.24	0.22	0.19	0.15	0.12	0.11
Shire of Swan North	0.28	0.39	0.37	0.13	0.12	0.00
South Swan	0.14	0.09	0.02	0.00	0.00	0.00
State Forest	0.36	0.20	0.01	0.00	0.00	0.00
Town of Bassendean	0.18	0.36	0.35	0.14	0.13	0.00
Town of Cambridge	0.05	0.13	0.09	0.00	0.00	0.00
Town of Claremont	0.00	0.00	0.00	0.00	0.00	0.00
Town of Vincent	0.01	0.04	0.03	0.00	0.00	0.00
Wanneroo Wellfield	0.82	0.09	0.00	0.00	0.00	0.00
Whiteman Park	0.02	0.00	0.00	0.00	0.00	0.00
Whitfords	0.29	0.01	0.00	0.00	0.00	0.00
Yanchep	0.01	0.00	0.00	0.00	0.00	0.00
Totals	13.20	10.91	9.68	4.36	3.99	0.75

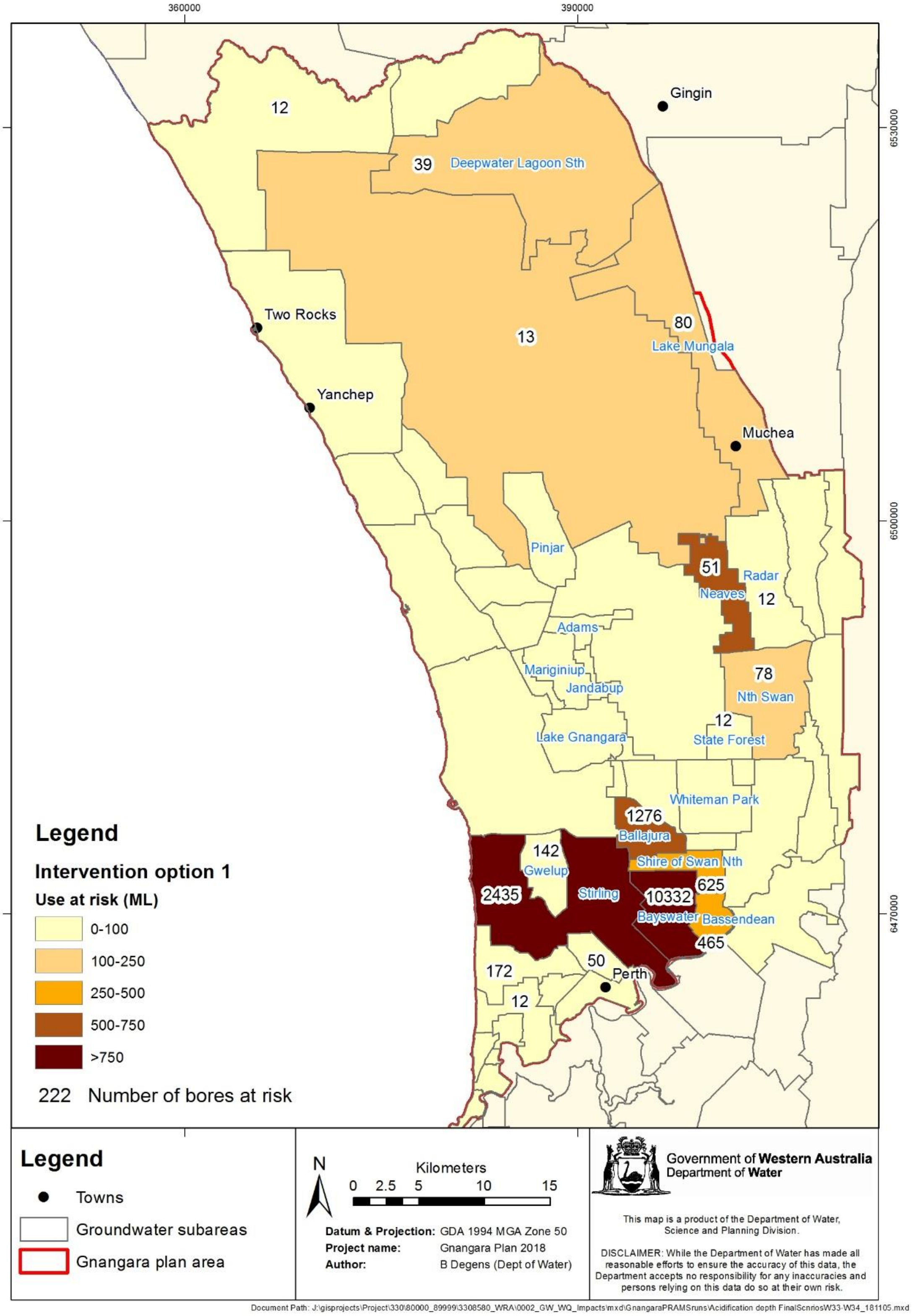


Figure 9: Groundwater use (licenced and exempt) corresponding number of bores at risk of increased acidification for intervention option 1.

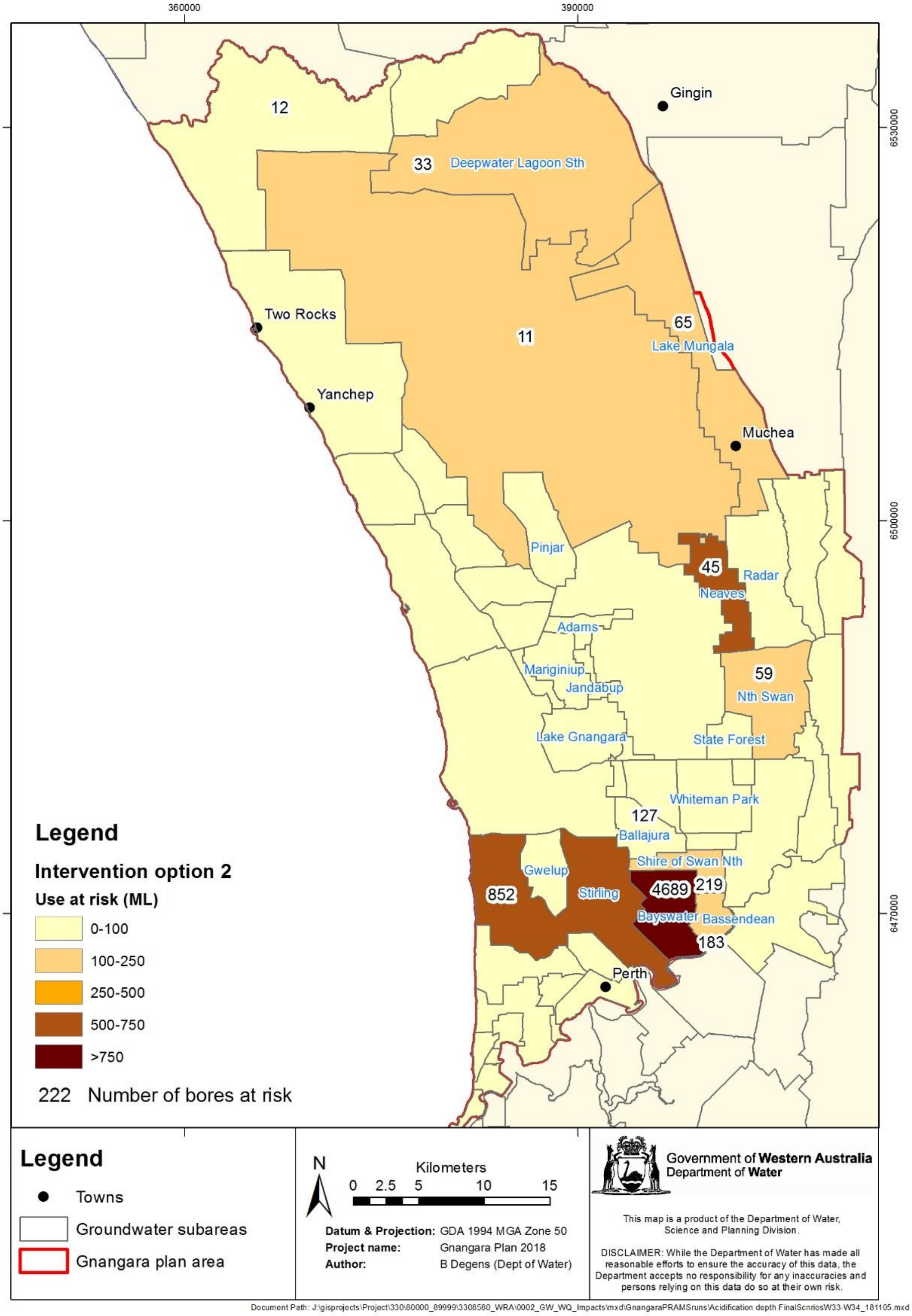


Figure 10: Groundwater use (licenced and exempt) corresponding number of bores at risk of increased acidification for intervention option 2.

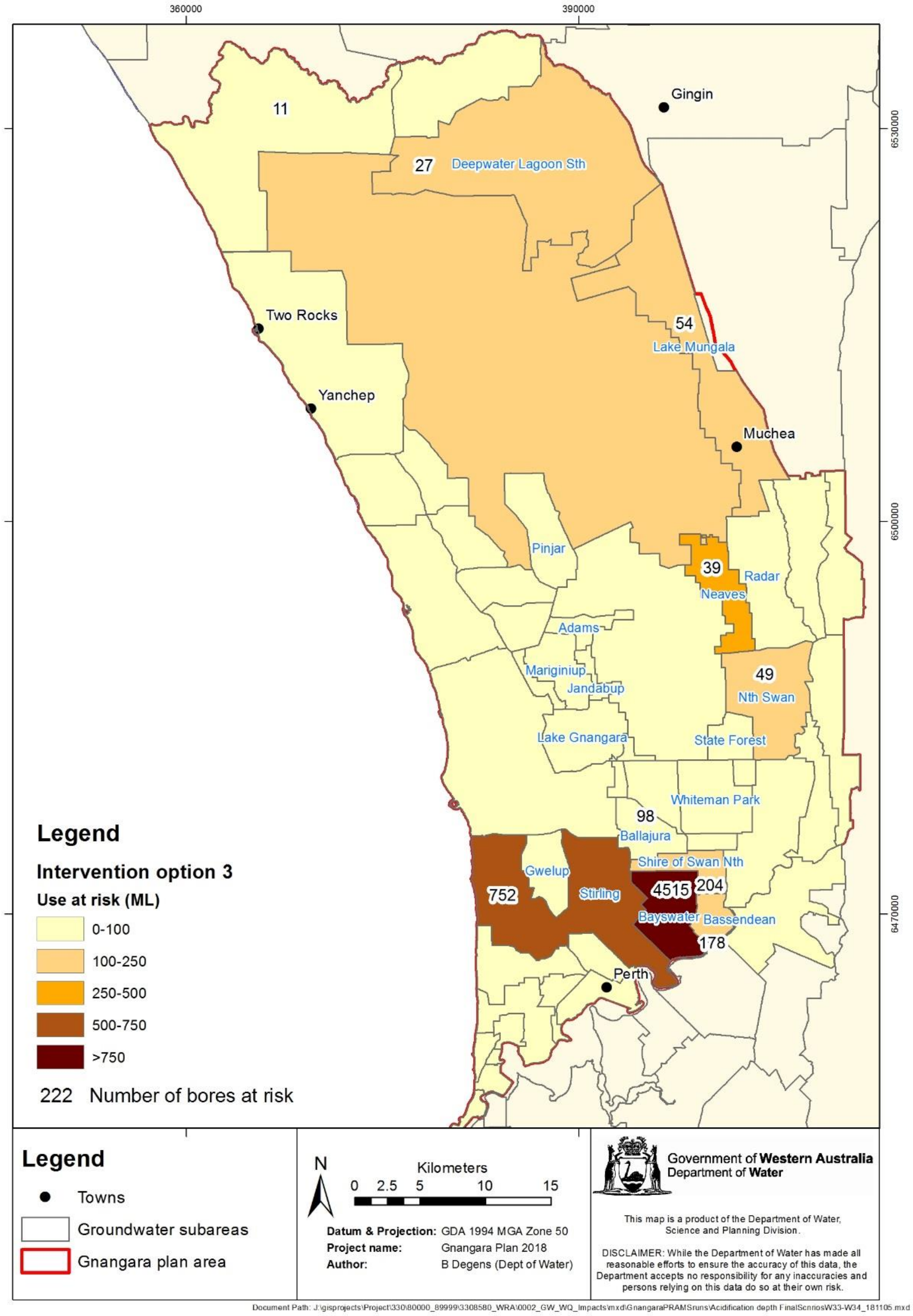


Figure 11: Groundwater use (licenced and exempt) corresponding number of bores at risk of increased acidification for intervention option 3.

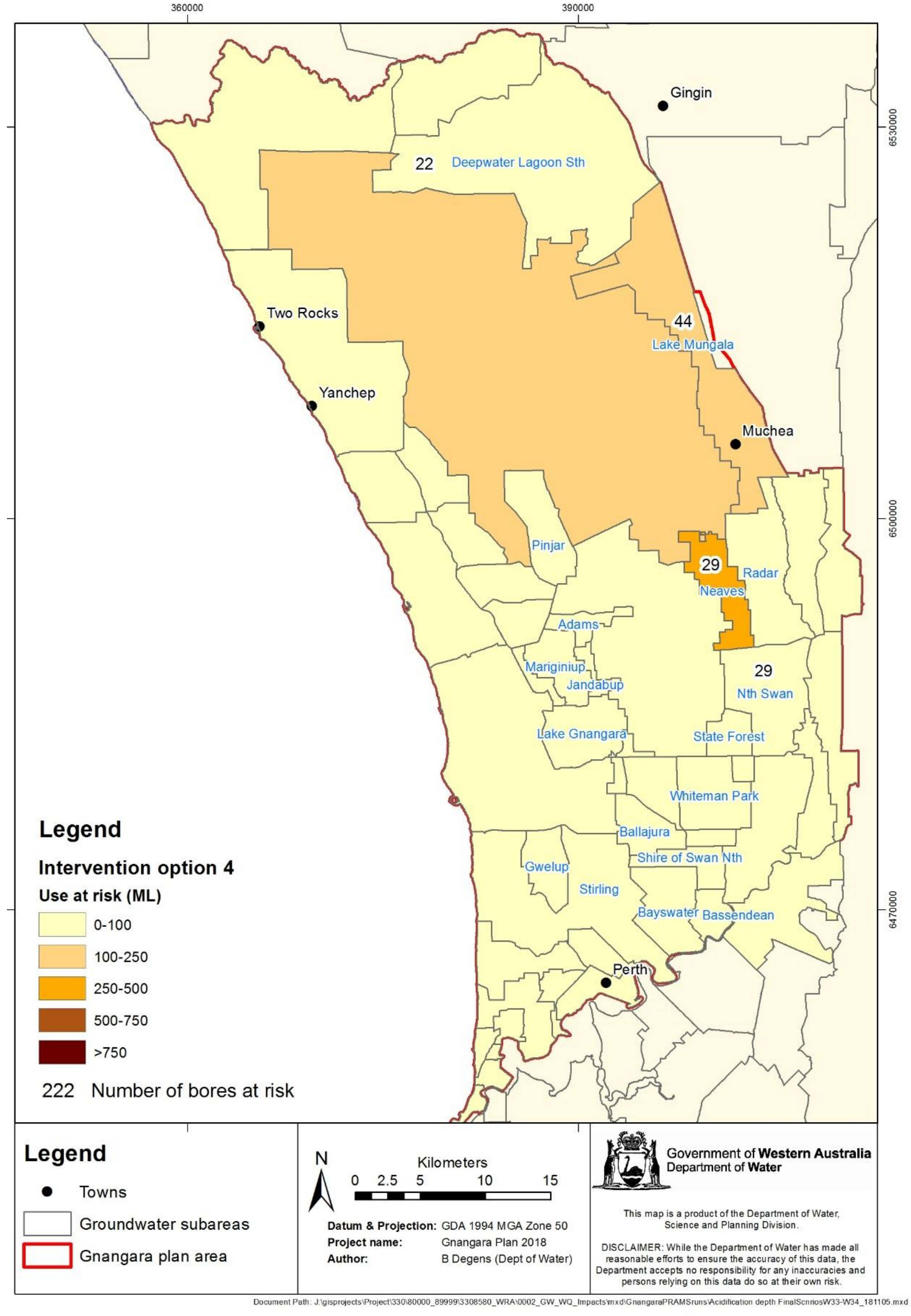


Figure 12: Groundwater use (licenced and exempt) corresponding number of bores at risk of increased acidification for intervention option 4.

5 General discussion

Shallow acidification of the Superficial aquifer in the Gnangara Groundwater area is extensive but regional risk modelling indicates that future expansion of this impact can be minimised with reduced pumping. Watertable decline over previous decades has led to an acidification footprint spanning over 380 km^2 with a further 425 km^2 where impacts are emerging. This area corresponds with areas mapped as medium ASS risk broadly corresponding with the distribution of the Bassendean sand dunes. Calculations of future impacts from the no intervention scenario modelled in PRAMS estimate that 10.9 GL of pumped water will be at risk of poor water quality. Reduction in pumping by 63 GL in intervention option 4 avoids risk of impacts to 10 GL of pumped water with less reduction of 45 GL in intervention option 3 avoiding risks to 6.9 GL of pumped water. The benefits of avoiding impacts are to a combination of licenced, garden bore and self-supply users in both urban and semi-rural subareas.

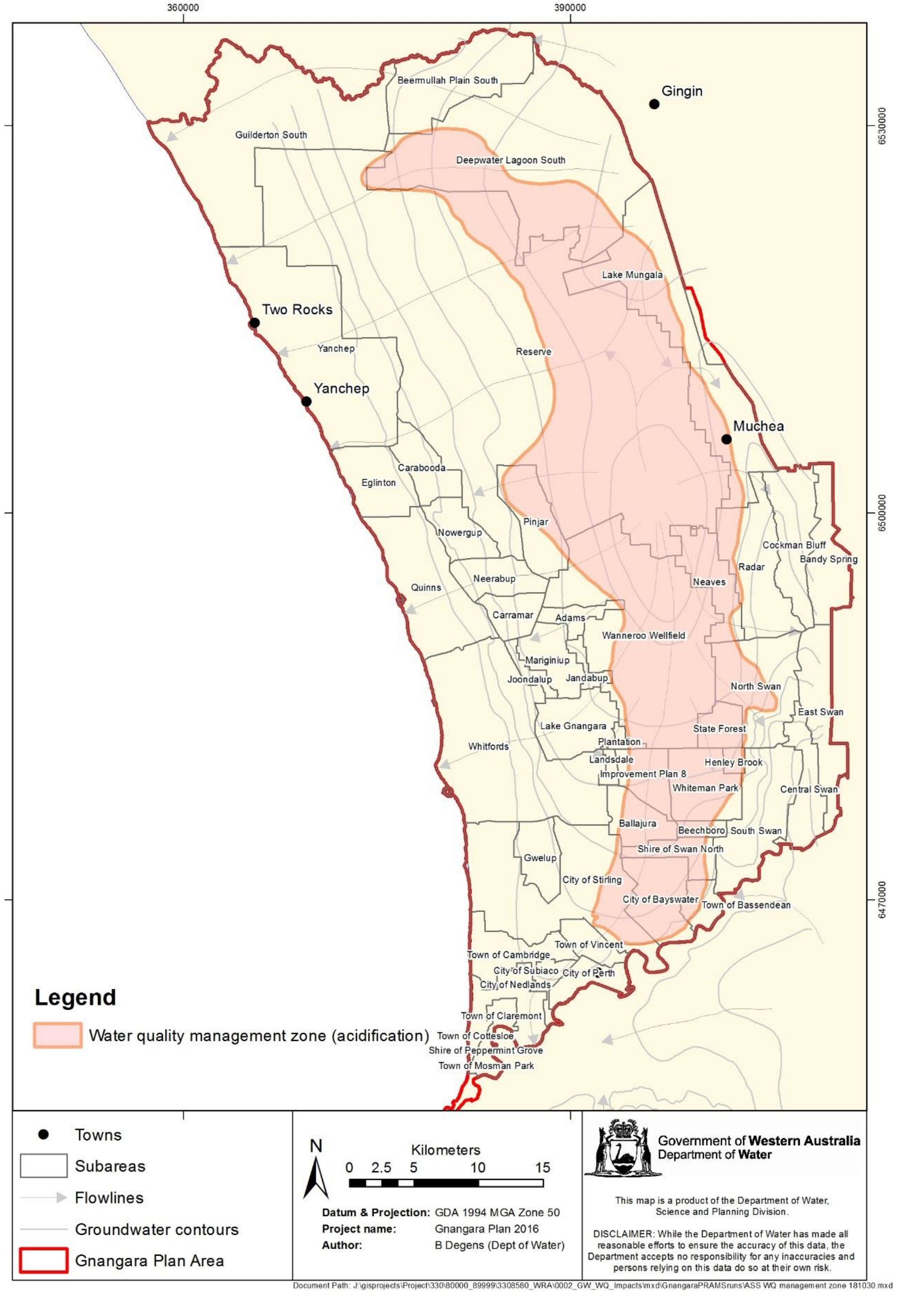
5.1 Residual risks to groundwater users

Residual risks remain in each reduced pumping scenario, which are where future impacts on users are likely given the projected drying climate and mitigating effects of land use change. Management depends on the varying nature of the acidification risks in each area across the Gnangara groundwater system and the depth that users draw water from the Superficial aquifer. There are greater risks to exempt users who often have bores that draw from shallower depths than licensed users. The exception to this are risks down-gradient of drying wetlands, where impacts on water quality can extend to the middle of the aquifer and potentially effect bores with inlets many metres below the watertable.

Residual risks remain in some semi-rural subareas even with the greatest reduction in pumping. Reduced pumping can minimise but does not avoid risks to groundwater users in Deepwater Lagoon South, Lake Mungala, Neaves, North Swan and Reserve. The risks to use in some of these areas may be greater than calculated where monitoring indicates acidification from previous watertable decline (Figure 5). Previous acidification is likely to amplify the effects of future acidification by increasing the propagation of additional acidification into the aquifer. Most impacted volumes are a combination of licenced use (mostly for irrigated horticulture) and exempt stock and domestic. Impacts to stock and domestic users carry direct risks to public health where water is used for household self-supply in addition to impacts on livestock (horses, cattle or sheep) or garden irrigation. It is unclear how many exempt users in these subareas use water in households. These users can be at risk of potential contaminants such as arsenic down-gradient of wetlands (see later discussion) and risks associated with acidic water in potential mobilisation of lead in household plumbing systems (Harvey et al. 2016; Ljung et al. 2000). Corrosion of household piping can also contribute to increased copper in water that can stain sinks, baths and toilets.

Interventions with lower reductions in pumping are coupled with higher risks to mostly garden bore users in the urbanised subareas such as Ballajura, Bayswater, Bassendean, Stirling and Swan North. These users are numerous and significant uncertainties remain around the likely magnitude of the impacts. These may be less than is calculated. ASS in some urban areas may be below that of the present watertable and therefore not at the same risk of generating acidity with watertable decline. The depth of ASS in relation to the present watertable was noted in the collated soil data presented earlier (see discussion in section 4.1). Increasing alkalinity in surface soils and therefore in recharge chemistry with urbanisation may also modify the acidification risk. There is very little groundwater quality data available for these urban areas and further investigation is required to substantiate the extent of future risks to shallow groundwater users in the urban subareas.

The areas where management is best focused to address risks to the resource and users of this can be mapped from existing acidification extent and areas of predicted impacts for each of the intervention scenarios (


360000
390000
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Gingin
Two Rocks
Yanchep
Muchea
Beermullah Plain South
Guilderton South
Deepwater Lagoon South
Lake Mungala
Reserve
Carabooda
Eglinton
Pinjar
Nowergup
Cockman Bluff
Bandy Spring
Radar
Neaves
Quinns
Neerabup
Carramar
Adams
Wanneroo Wellfield
Mariginiup
Joondalup
Jandabup
North Swan
East Swan
Lake Gnangara
State Forest
Whitfords
Plantation
Landsdale
Henley Brook
Improvement Plan 8
Whiteman Park
Central Swan
Ballajura
Beechboro
South Swan
Shire of Swan North
Gwelup
City of Stirling
City of Bayswater
Town of Bassendean
Town of Vincent
Town of Cambridge
City of Subiaco
City of Perth
City of Nedlands
Town of Claremont
Town of Cottesloe
Shire of Peppermint Grove
Town of Mosman Park
Legend
Water quality management zone (acidification)
Towns
Subareas
Flowlines
Groundwater contours
Gnangara Plan Area
N
Kilometers
0 2.5 5 10 15
Datum & Projection: GDA 1994 MGA Zone 50
Project name: Gnangara Plan 2016
Author: B Degens (Dept of Water)
Government of Western Australia
Department of Water
This map is a product of the Department of Water, Science and Planning Division.
DISCLAIMER: While the Department of Water has made all reasonable efforts to ensure the accuracy of this data, the Department accepts no responsibility for any inaccuracies and persons relying on this data do so at their own risk.
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Figure 13).

Persistent acidification impacts in the long-term are not expected with watertable rise or stabilisation in a number of subareas including Adams, Jandabup, eastern Lake Gnangara, Mariginiup, Pinjar, State Forrest and Henley Brook. However, these are areas where watertable acidification has been mapped and may experience adverse changes in water quality in the short term with transition to higher water level. Increased recharge, with increased urbanisation and removal of pine plantations, leading to a rise in water level may locally accelerate leaching of acidic materials (protons as well as aluminium, iron and other metals) to the watertable as well as inundation of acidic layers near the watertable. The greater recharge will also increase the dilution and mixing of the water with deeper alkaline groundwater in the aquifer. The net effect and duration of these processes is not readily predictable in the absence of soil and water chemistry near the watertable and deeper in the aquifer in these areas.

5.2 Variation in potential ASS impacts depending on location

The progression and nature of water quality impacts from exposed ASS will vary depending on how much acidity is stored in the drying soils, how fast this is washed into the aquifer and the mixing in the aquifer. Wetlands often contain the most concentrated acidity near surface typically exceeding 0.2% S as pyrite (e.g. Lake, Mariginiup - Searle et al. 2010; Tangletoe – Department of Water 2011a; Lexia - Department of Water 2011d and Nowerup - Searle et al. 2011). In contrast, between these in Bassendean sands acidity is typically just below the watertable, less concentrated (often <0.03% S as pyrite) but in sands underlying large areas that can be rapidly acidified to very low pH (Prakongkep et al. 2012; Singh et al. 2012b). Impacts of continued acidification at different locations include:

- **At wetlands:** acidification and poor water quality contributing to loss of species diversity. The sediments can generate more highly odorous sulfur-based gases with transition to drying state (with occasional wetting) (Kinsela 2007; Environment Protection and Heritage Council and the Natural Resource Management Ministerial Council, 2011). In the dry phase, the wetlands may also generate greater amounts of wind-blown dust from the fine salts that can form on the acidified drying sediments (Environment Protection and Heritage Council and the Natural Resource Management Ministerial Council, 2011; Ljung et al., 2000). Acidification in the pheatic zone may also place additional stress on surrounding wetland vegetation as roots access this for water.
- **Downgradient of wetlands:** greater mobilisation of iron in the aquifer can lead to problems for groundwater users ranging from increased staining to iron clogging. As wetlands dry, there can be greater mobilisation of arsenic and metals to groundwater down-gradient (see Searle et al., 2010; Clohessy 2012). Drying wetlands containing peat in particular can leach significant concentrations of arsenic (Appelyard et al. 2006) and these are distributed around the Gnangara groundwater system (Seminiuk and Seminiuk 2006). In addition, as the net acidity of groundwater increases (along with a decline in

pH) this can increase corrosion of bores and pumps. For soils irrigated with acidic waters the impacts may range from trace element deficiencies to leaf burn.

- **Extensive acidification (between wetlands):** Oxidation of subsurface ASS may lead to increased iron concentrations and increasingly net acidic bore water leading to staining of irrigated surfaces, iron accumulation on pump impellers and in pipes, corrosion of concrete with any buried infrastructure (deep foundations, sewer pipes, bore grouting), corrosion of bores and pumps and impacts on irrigated soils (trace element deficiencies & leaf burn). These impacts will are likely to be more evident for shallow stock and domestic or garden bores than bores drawing from deeper in the aquifer (typically at licenced bores).

Water quality impacts of acidification from previous watertable decline have not been documented and were likely not noticed by many users. Few groundwater users routinely monitor water quality apart from the Water Corporation. The Corporation has seen steady changes in water chemistry for production bores most clearly in the Mirrabooka borefields but also evident in the Wanneroo and Lexia borefields (Appleyard and Cook 2009; Water Corporation 2015). These bores draw from the bottom of the aquifer that can be traced to changes near the watertable (Appleyard and Cook 2009). Without regular monitoring most users are unlikely to detect changes in water quality until there are extreme changes such as severe acidification to the extent of complete burn-off of irrigated plants. This is what happened when acute acidification was caused by dewatering in Stirling during an urban development in the early 2000’s (Appleyard et al. 2004). Early changes in groundwater chemistry with acidification impacts can be slow to show without detailed analysis of groundwater quality until the plume of acidification in the aquifer reaches the bore inlet resulting in a sharp plummet in water quality. Other impacts such as corrosion might be misattributed to wear and tear and problems with iron can emerge slowly such that people ignore these.

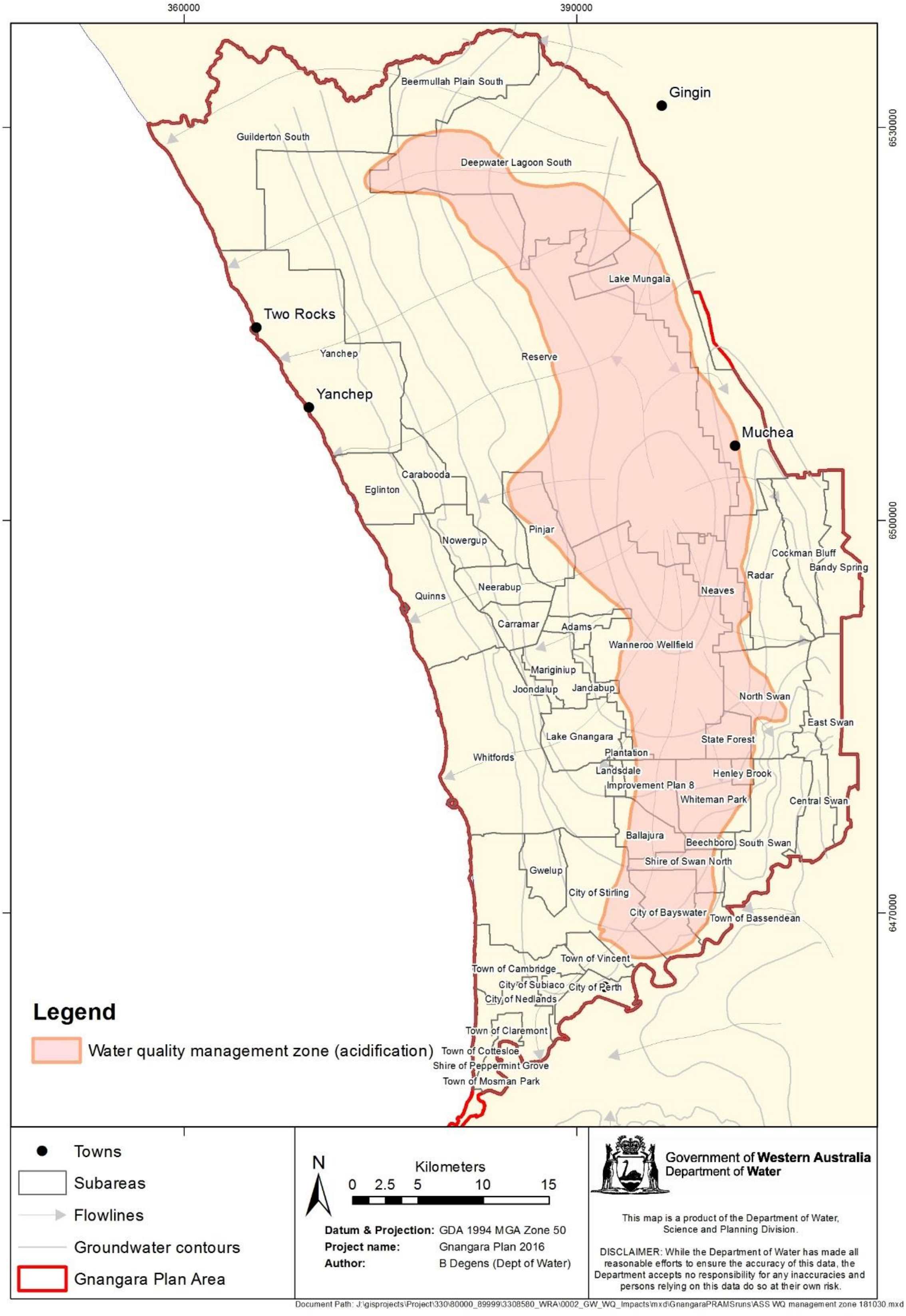

Figure 13: Water quality management zone for acidification impacts.

Another factor masking detection of the problem by groundwater users is that water is often drawn from more than 10 m below the watertable. This means that acidity can be hidden through the mixing of shallow water with deeper aquifer water during pumping. Drawing water from deeper in the Superficial aquifer can avoid most of the impacts of shallow acidic water but does not manage the problem at the surface.

5.3 Existing acidification extent

The spatial extent of acidification impacts mapped in this report has most likely expanded with further development and leaching of acid products to the watertable from the time most of the water quality was sampled. Regional mapping of acidification is based on collated groundwater quality surveys ranging 8 to 15 years ago (2003 – 2011) and is unlikely to have reflected a stable state with the continued drying climate and groundwater decline in many areas. Water quality information is very limited water quality information in a number of subareas such as Lake Mungala, Neaves, Pinjar, Lake Gnangara and North Swan where acidification impacts are projected to increase even with the greatest modelled reduction in pumping (intervention option 4).

The mapping and monitoring of acidification impacts does not include all impacts on water quality down-gradient of wetlands. The influence of exposed ASS in lakes on water quality down-gradient of lakes is broadly known from site specific investigations at Lake Mariginiup (Searle et al. 2010) and to a lesser extent Nowergup (Searle et al. 2011). These lakes contained significant surface concentrations of oxidising ASS that had an influence on groundwater quality extending to the mid-depth of the Superficial aquifer (>20 m) on the down-gradient margin of the lake. The extent of this influence down-gradient is unknown and depends on reactions with the aquifer lithology and mixing with both down-gradient recharge and throughflow from up-gradient of the lakes. Further investigations are needed to enable modelling of the fate of plumes of ASS oxidation products from drying wetlands.

6 Recommendations

The following further work would improve tracking the status of acidification impacts and improve future prediction of water quality impacts from watertable decline.

- Monitor water quality trends in licenced bores in the semi-rural subareas at highest risk of water quality impacts and shallower licenced bores in subareas with marginal risk using water quality management zones mapped in this report.
- Confirm progression of regional trends of acidification evident in pre-2009 data by a 5 yearly regional snapshot of all available bores with screens within 5 m of watertable identified in this investigation. This should also include in-fill sampling of additional suitable bores in the Neaves, Lake Mungala, State Forest and North Swan subareas where acidification has previously been mapped and greatest on-going impacts are likely on **users**. Sampling should focus on seasonal low and high watertable and focus on accurately determining field pH, alkalinity (titrated in the field), major ions, nutrients (total and soluble) and dissolved metals (Al, Fe, As, Cu, Pb, Zn, Cr and Ni) with selective analysis of δ34S-SO_4 to verify the acidification source for high SO_4:Cl waters.
- Investigate likelihood of acidification in the urban subareas of Ballajura, Bayswater, Bassendean, Stirling and Swan North should water levels decline. This requires strategic sampling of bores and soils through recommissioning of existing monitoring bores or drilling of new bores at points distant from the influence of urban drainage infrastructure.
- Conduct strategic investigations of acidity transport and reactions in the Superficial aquifer (drilling, bore construction, lithological analysis, hydrochemical sampling including reactive transport and age tracers) in priority subareas of Deepwater Lagoon South, Lake Mungala, Neaves, North Swan and Reserve as well as other areas depending on re-surveying of regional water quality (above).
- Develop local scale reactive transport models for representative parts of these subareas to serve as sites where local scale characterisation of geochemical processes can be modelled and used to upscale to a regional reactive transport model.
- Develop conceptual models and identify upscaling for regional scale reactive transport modelling that couples with the next version of PRAMS for regional acidification modelling to inform future allocation planning.
- Conduct strategic investigations in subareas where previous acidification impacts have been mapped to confirm progression/recovery of water quality with projected rising or stabilising water levels in these area (e.g. Adams, Jandabup, eastern Lake Gnangara, Mariginiup, Pinjar, State Forrest and Henley Brook).

- Improve cataloguing of bore depth data for drawpoints in the COMPASS database:
    - Record bore inlets or screen lengths for all new or redrilled bores
    - Extracting screen depth data from hard-copy form L records to accompany drawpoint entitlement data.

Appendices

Appendix A — Acid mass balance to estimate extent of aquifer acidification from acid sulfate soils

Acid mass balance calculations were applied to a simple soil model (Figure A14) to estimate the likely acidification of the shallow aquifer by leaching of acidity from the oxidation of sulfide minerals in a 1 m depth of soil above the watertable. This calculation uses the acid-base accounting approaches applied to assess acidification risks for acid sulfate soils (Ahern et al. 2004) and accounts for alkalinity as either soluble alkalinity in the shallow groundwater or as cation exchange capacity (CEC).

The calculations assumed:

- A 1 m soil layer with a density of 1.6 tonnes/m^3 (typical for Bassendean sands)
- Stochiometric generation of 623.7 moles H^+/tonne for every 1 %S (w/w)
- Sulfide concentration in the exposed soil layer of between 0.01 to 0.03% S w/w which is typical of that found in Bassendean sands distant from wetlands on Gnangara mound (Prakongkep et al 2009; Singh et al. 2012a)
- Sulfide minerals occur immediately below the summer minimum watertable at similar concentrations with depth in the aquifer. This is typical of ASS in Bassendean sands on Gnangara mound near wetlands (e.g. Department of Water 2011c, Degens et al. 2018) and elsewhere in the Perth basin (Degens and Wallace-Bell 2009; Degens 2009). However this is less so in the Perth metropolitan area (Singh et al. 2009a) possibly because watertables were greater than historic minimum.
- The majority (90%) of acidity from sulfide oxidation is leached vertically with recharge and interact with aquifer materials
- The neutralising capacity (pH buffer capacity) of the aquifer ranges from 0.1 to 70 moles H^+/tonne extrapolated from CEC (Prakongkep et al 2009; Singh et al. 2012b), and,
- No existing acidification or depletion of buffer capacity

The basis of some of these assumptions are discussed in more detail below.

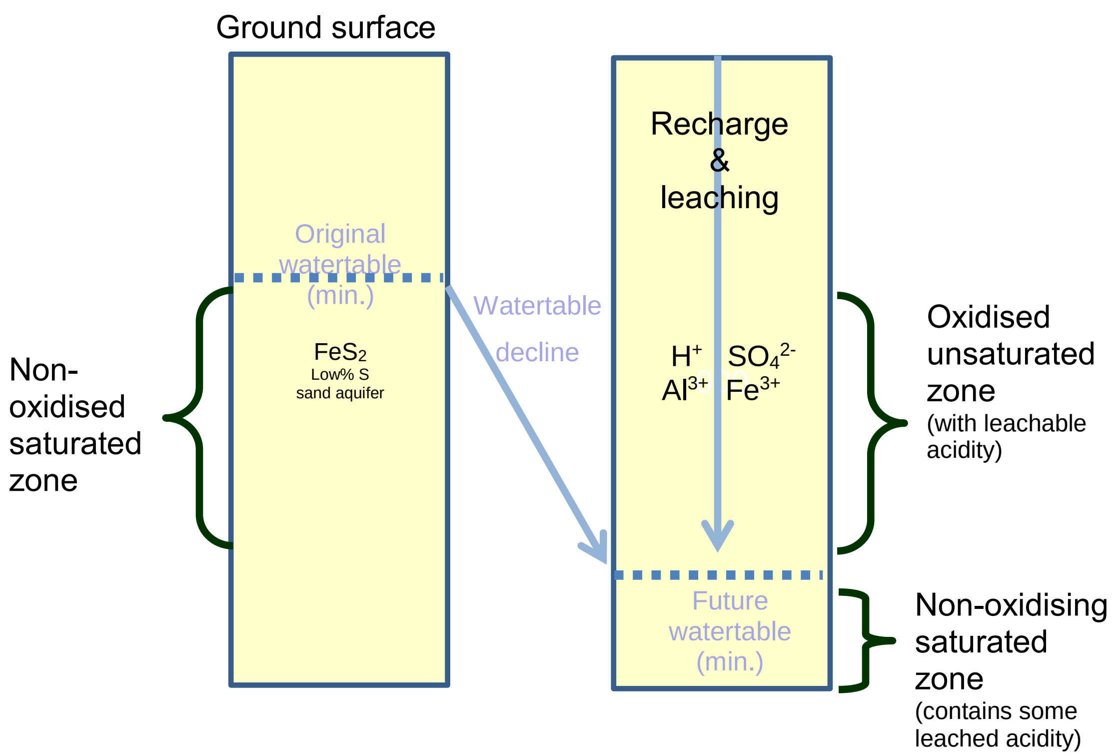

Figure A14: Simplified model of acid generation based on oxidation of pyritic materials (Potential ASS) exposed below the minimum watertable

The acid buffer capacity can vary widely between horizons in deep leached Bassendean sands. CEC is a strong determinant of pH buffer capacity in Bassendean sands and can range from <0.1 to 6.9 cmoles/kg for subsoils in the Perth region (Prakongkep et al. 2012). Organic matter can be contribute significantly to the greater CEC of some soil horizons, particularly where greater than 1%C in dark, brown sands and coffee rock horizons (Prakongkep et al. 2012). Maximum acid buffer capacity can be calculated from CEC assuming all exchangeable surfaces could buffer H^+ as 1 cmole/kg CEC = 0.01 moles H^+ adsorption/kg = 10 moles H^+ buffer capacity/tonne. However, a proportion of the buffer capacity is frequently exhausted by historic acidifying processes with part of the exchangeable cations often comprising of protons (H^+) depending on pH and the ionic strength of the soil solution. Measured buffer capacity (before pH falls below 4) for acid titrations of eight Bassendean sand samples indicate H^+ buffer capacity of less than 0.8 moles H^+/tonne in low organic C content horizons to 22 moles H^+/tonne in coffee rock (Prakongkep et al 2009). Buffer capacity is often low with lower pH samples indicating partial exhaustion of buffer capacity because of previous acidification processes. Titration of soils with weak NaOH found that buffer capacity in soils with pH 4.5-5 were in the order of 2 to 10 moles H^+/tonne less than at pH>5.5, except for coffee rock which was an order of magnitude greater (Prakongkep et al. 2009).

The mass balance calculations of acidity indicated that the acidification depth in the aquifer for 1 m oxidation has a maximum range of 0.2 to 52 m and is most sensitive to the likely acid buffer capacity of the aquifer (Table E7). For the range of acid buffer capacity previously measured for Bassendean sands in the Perth area (approximately 1 to 20 moles H^+/tonne), the depth of acidification ranged from 0.7 to 32 m for sulfide contents ranging 0.01 to 0.03% (Table E7). In general, a nominal 5 m depth of acidification below the acidifying 1m layer is likely for low to moderate sulfide content sands with various acid buffer capacities. The calculations assumed no depletion in buffer capacity by previous ASS oxidation. In many parts of Gnangara mound there is evidence in the groundwater that leachates from oxidising ASS above the watertable have acidified groundwater up to 1m below the watertable (Figure 6 in section 4.1).

Table E7: Calculated maximum depth of leached acidity (where pH < 4.5) from complete oxidation of a range of sulfides 1 m thickness of sandy aquifer materials with a range of buffer capacity.

	Aquifer buffering (moles H^+/tonne)			
Soil sulfide (% S)	0.5	1	5	20
0.01	17	11	3	0.7
0.02	35	22	5	1.4
0.03	52	32	8	2.1

Appendix B — Analysis of bore depth data

Explanation of analysis of bore depth by abstraction volume using extract of COMPASS (formerly WRL) data.

Bore depth data extracted from a snapshot of COMPASS (formerly WRL) for June 2013 were used to estimate depth at which groundwater was pumped from the Superficial aquifer. For the 4862 drawpoints, 1095 (22%) had bottom depths which were assumed to represent the bottom of screens in the bore. A subset matched against sites in WIN (by co-ordinates) indicated that the depth data the drilled depth which indicates that the bottom of the screens is probably above the drilled depth. Only in-force licences (INF) were considered, since expired, terminated and surrendered licences may have represented bores that had not been actively pumped over the last few years or that had been removed with land development.

Half of the bores had bottom depths less than 20 m below the minimum watertable in 2013 and 30% of bores were less than 15 m from the watertable where screens were likely to be at or near the watertable (Figure A15). While there was no inlet data available in WIN this distribution is consistent with many bores being drilled to more than 10 m below the watertable and constructed with screens of at least 10 m length.

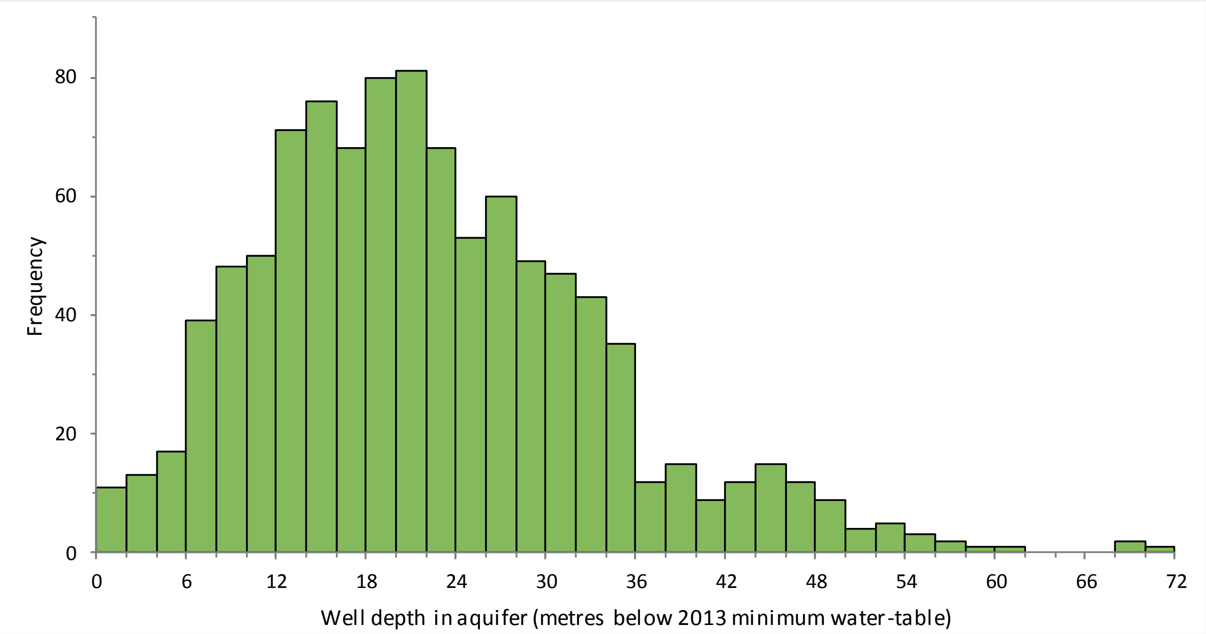

Figure A15: Distribution of licenced bores (June 2013) in the Superficial aquifer (Perth region) with calculated bottom depth of well below the minimum watertable in 2013.

Inflow from the aquifer into the bores is above the bottom depth and was assumed to be in the interval 6 to 18 m above bottom depth based on typical screens of this length (Table 3). The depth that groundwater was pumped from in the Superficial aquifer (metres below the watertable) was calculated using maximum depth to groundwater mapping for 2013 ($DTGW_{max2013}$) assuming the mid-point of the screens is 5 m above the bottom depth (for an average screen length of 10 to 12 m) as:

Pumping depth = drawpoint depth – $DTGW_{max2013}$ – 5 …………………..Equation 1

This dataset was used to determine the distribution of pumping by depth in the Superficial aquifer. Bores used for this analysis were where the calculated pumping depth was above the watertable and no deeper than 60 m corresponding with the general range of thickness of the Superficial aquifer in the Perth area of 20 to 60 m (Davidson 1995). There were 25 bores where the depth fell outside this range because of either co-ordinate errors for the bores, errors in depth records or that the bores were of the depth originally and have been redrilled.

A simple relationship between bore depth and drawpoint allocation was not evident in the data, even for bores only in sub-areas with no-limestone which might bias towards shallower bores (Figure A16). This was probably because there are numerous bores where current pumping is less than the maximum pumping capacity of the bore and bores may have been constructed deeper for a range of reasons that no longer relate to the amount currently pumped.

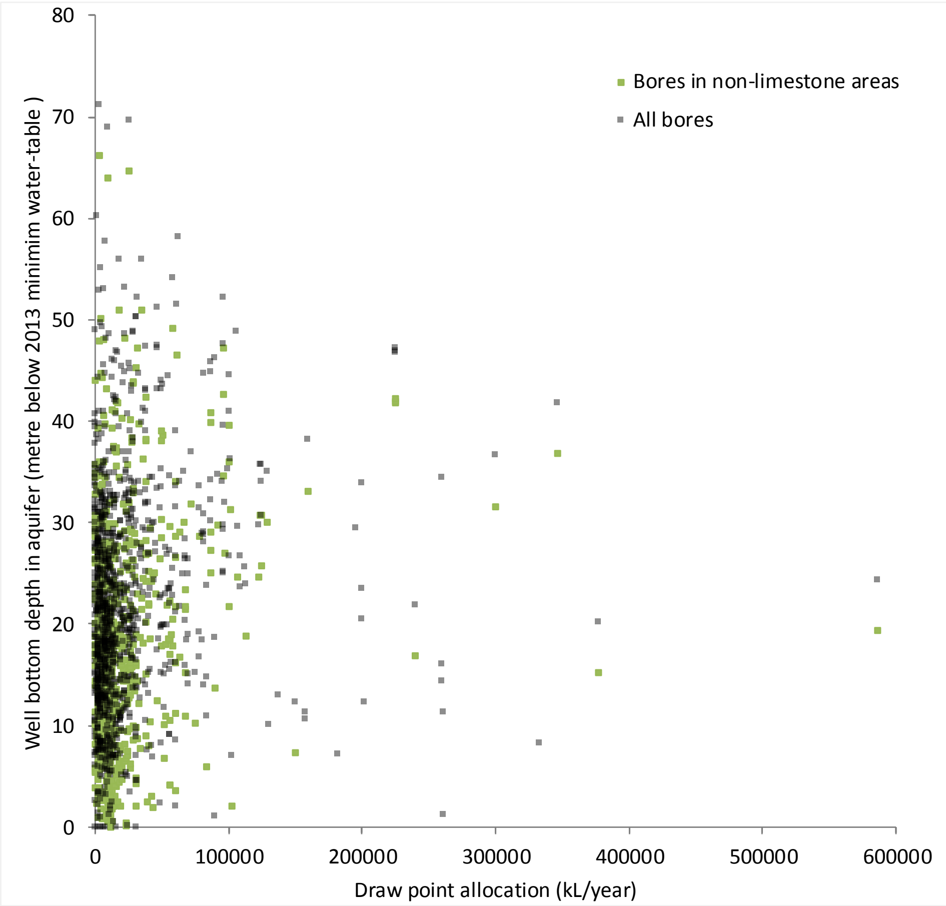

Figure A16: Bottom depth of bores below the 2013 watertable in relation to current pumping entitlement

For the majority of bores where depth data was not available depth was estimated using a cumulative use by depth function. This describes the distribution of groundwater pumping by depth in the aquifer and therefore the depths at which changes in water quality would affect use. Cumulative pumping for bores with entitlements were plotted against depth in the aquifer and a curve fitted to explain the proportion of pumped groundwater by inlet depth in the aquifer for bores using those in sub-areas without limestone (Figure A17). These bores contained less bias towards pumping from shallow depths that was apparent when considering all bore data as the deviation to the top left in the shape of the cumulative distributions (Figure A17). A polynomial function best represented the relationship between cumulative pumped volume and depth that this is pumped from the aquifer up to 45 m below the watertable (Figure A17). A linear relationship over-estimates the proportion of pumping at depths of less than 20 m (Figure A17).

Proportion of use by depth in the aquifer to 45 m (y) is given by the equation:

$$y = \frac{-176.3x^3+11714x^2+195215x}{15635312} \qquad \text{.................Equation 2}$$

where x is the bore inlet depth in metres below the watertable. This equation is based on the product of the 3rd order polynomial in Figure A17 for bores in non-limestone subareas relative to the total abstraction for these bores.

This function enables calculation of the fraction of total water pumped given the depth in the aquifer and therefore the volume affected depending on depth of acidification below the watertable. In the absence of bore depth data for most bores, this is applied to each bore effectively describing the probability of acidification impacts on each bore depending on acidification depth.

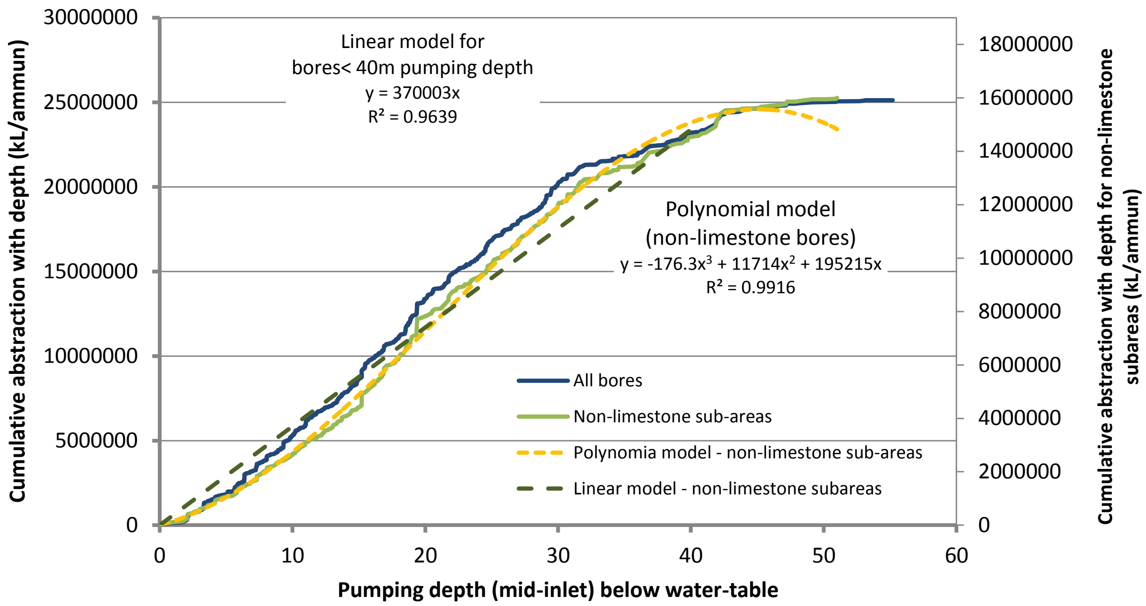

Figure A17: Regression modelling of cumulative pumping (based on entitlement) in relation to inlet depth in the Superficial aquifer for selected bores

Appendix C — Reclassification of ASS risk for selected polygons

ASS classification was revised for several map units in the ASS risk mapping dataset (2006). The original mapping was based on assessment of risk for map units in the 1:50000 environmental geology mapping for the Perth metropolitan area (GSWA 1986 ANZWA1220000175) which was used in combination with updated information for the map units to revise the ASS risk classification.

Object ID & Suburb (GIS dataset)	50K geology unit	Class	Revised Class	Justification
47 Beechborough	Mgs1 Pebbly silt with fine to coase laterite & quartz.	Class 3 – No known ASS risk	Class 2 – moderate to high ASS risk	Drilling logs for private bores in area do not indicate silt with upper horizons (approx. 3-6m) being brown sands. Likely ASS materials coupled with shallow WT as per surrounding geology.
47 Malaga	Mgs1 Pebbly silt with fine to coase laterite & quartz.	Class 3 – No known ASS risk	Class 2 – moderate to high ASS risk	No drilling logs in units or nearby, but high ASS risk area in middle of unit. Likely ASS materials coupled with shallow WT as per surrounding geology.
47 – 2 units West Whiteman Park	Mgs1 Pebbly silt with fine to coase laterite & quartz.	Class 3 – No known ASS risk	Class 2 – moderate to high ASS risk	Drilling logs for private bores in area do not indicate silt with upper horizons (approx. 3-6m) being coffee rock (1-3m), brown sands to 5m. Likely ASS materials coupled with shallow WT as per surrounding geology.

Appendix D — Estimating probable number of bores from total impacted use

Impacts reported in this assessment are for the total volume of abstracted use estimated for licenced and unlicenced (exempt) users. The approximate number of users for the impacted volumes were needed for communication purposes. These were derived independently for each category of user.

Impacts reported in this assessment are for the total volume of abstracted use estimated for licenced and unlicenced (exempt) users. The approximate number of users for the impacted volumes were needed for communication purposes. These were derived independently for each category of user.

Exempt use is based on data calculated by Evans et al. (2014) from block sizes, likely frequency of blocks with bores and the average annual volume pumped per bore on these blocks as per Table A8. The average pumping per bore was used to estimate the number of exempt users affected by acidification impacts.

Estimates of the most probable number of licenced bores were derived using empirical methods. Data for all licenced bores within the ASS risk areas with depth data were extracted from COMPASS (formerly WRL). Regression analysis was used to derive an empirical probability density function (Figure A18) that was applied to the estimates of impacts on licenced bores where the depth data were not recorded in the database.

The number of bores (y) is given by:

$$\boldsymbol{y = 0.0002x^{0.8975}} \qquad \text{................Equation 3}$$

where x is the impacted volume (kL) of licenced bore use.

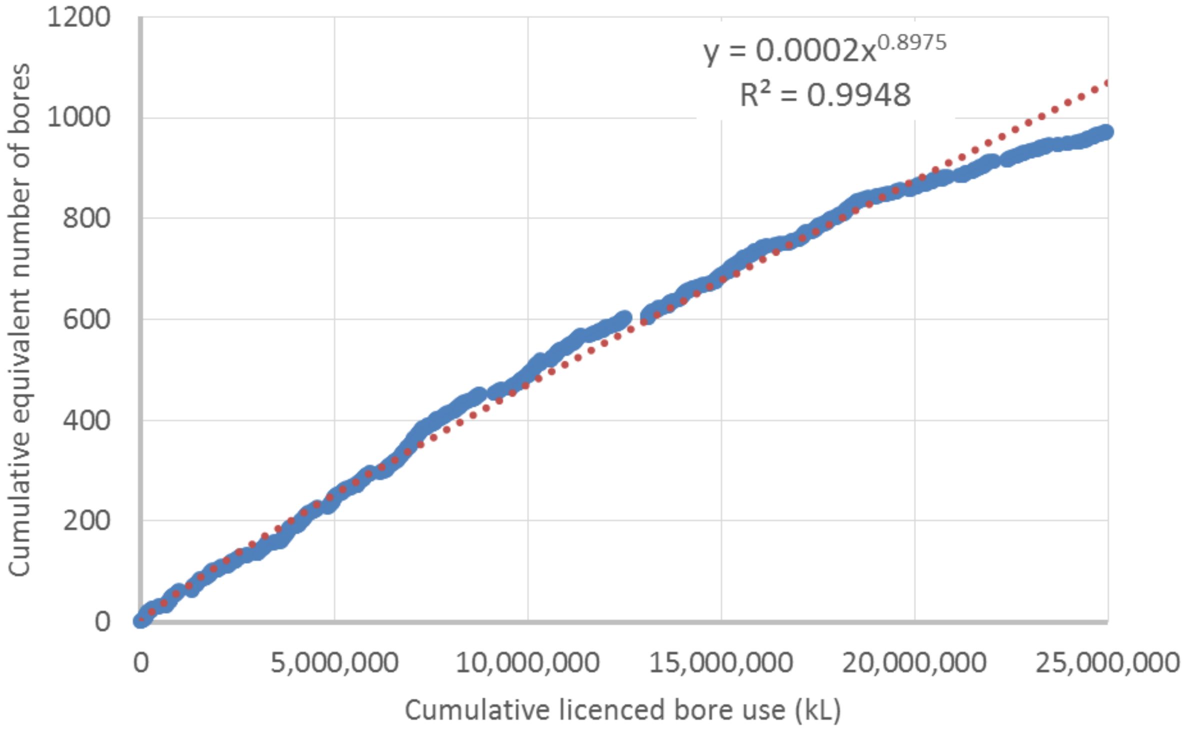

Figure A18: Regression modelling of probable number of licenced bores from total pumping volume from the Superficial aquifer

Table A8: Exempt use estimates per subarea for 2014 (after Evans et al. 2014).

Groundwater subarea (Superficial Aquifer)	**Estimated bore use ML/year**	**Estimated number of bores**
Adams	62	42
Ballajura	1 617	3 761
Bandy Spring	226	191
Beechboro	83	93
Beermullah Plain South	69	46
Carabooda	107	72
Carramar	476	893
Central Swan	551	405
City of Bayswater	5 813	13 518
City of Fremantle North	61	117
City of Nedlands	1 410	3 290
City of Perth	19	45
City of Stirling	7 863	13 463
City of Subiaco	212	494
Cockman Bluff	196	181
Deepwater Lagoon South	241	162

Groundwater subarea (Superficial Aquifer)	**Estimated bore use ML/year**	**Estimated number of bores**
East Swan	322	219
Eglinton	261	644
Guilderton South	347	231
Gwelup	1 663	3 868
Henley Brook	155	153
Improvement plan 8	16	11
Jandabup	34	22
Joondalup	31	71
Lake Gnangara	829	973
Lake Mungala	396	291
Lansdale	62	96
Mariginiup	316	408
Neaves	55	37
Neerabup	48	34
North Swan	484	662
Nowergup	23	15
Pinjar	56	38
Plantation	20	14
Quinns	485	1 197
Radar	221	175
Reserve	8	6
Shire of Peppermint Grove	127	295
Shire of Swan North	841	1591
South Swan	587	574
State Forest	374	730
Town of Bassendean	1 101	1552
Town of Cambridge	1 675	3 894
Town of Claremont	242	549
Town of Cottesloe	200	482
Town of Mosman Park	119	276
Town of Vincent	715	1 663
Wanneroo Wellfield	0	0
Whiteman Park	16	16
Whitfords	5 168	12 020
Yanchep	665	1 642
TOTAL	**36 667**	**71 222**

Appendix E — Assessment of ASS oxidation from DEC soil mapping and SGS investigations

Summary assessment of DoW ASS investigations at wetlands on Gnangara (Perth SGS Program 2007-2009) and DEC ASS investigation sites (2008-2009) in medium ASS risk areas on Gnangara mound (excludes southern part of Joondalup, Gwelup and other western investigation sites).

DEC soil mapping sites

General location	DER site number[1]	ASS status[2]	Watertable (mbgl)	Assessment of oxidation status near the watertable[3]
Vines	616-01-46	pH >6.5 above WT. PASS 0.02 to 0.09% below 4m in clayey sand (2.5m below WT)	2.5	No evidence of oxidation
Vines	616-01-43	pH >7 above WT. PASS 0.02 to 1.1% below 4m in sand (2m below WT)	2	No evidence of oxidation
Vines	616-01-44	pH >4.5 to 6 above WT. PASS 0.01% below 5m in sand (3 m below WT)	2	No evidence of oxidation
Vines	616-04-40	pH >5.5 above WT and <4 at WT. PASS 0.07 to 0.35 % below 5.75 m in sand (immediately below WT)	5.75	Oxidising at watertable
Vines	616-04-65	pH >7 above WT. No PASS identified	Dry?	No evidence of oxidation
Averley	616-04-17	pH 5.5 increasing to 7 above WT. PASS 0.03 to 0.15% below 4.5m in clayey sand (2 m below WT)	2.5	No evidence of oxidation
Ellenbrook	616-01-38	pH 4 to 3.5 above WT. PASS 0.02 % below at WT m in sand	3.8	Oxidising at watertable
Ellenbrook	616-04-66	pH 4 to 4.5 above WT. No PASS identified	Dry?	Oxidising at watertable
Landsdale (south of Lake Gnangara)	616-04-28	pH 5 to 5.5 to 2m (above WT?). PASS 0.1 to 0.2%S in peaty sand 1.75-2.75	Dry?	No evidence of oxidation

General location	DER site number[1]	ASS status[2]	Watertable (mbgl)	Assessment of oxidation status near the watertable[3]
Alexander Heights (Ballajura)	616-04-28	pH down to 4.5 above WT. PASS 0.15% in sand around WT	4	No evidence of oxidation
Alexander Heights (Ballajura)	616-02-169	pH down to 4 above WT. PASS 0.02% in sand around WT	5.5	Oxidising at watertable
Ballajura	616-02-174	pH decreasing from 6 to 4.5 down to WT. PASS up to 0.06% in sand around WT and below	3.1	Oxidising at watertable
Alexander Heights (Ballajura)	616-02-170	pH decreasing from 8 to 4.5 above WT. No %S determined but PASS within 0.5m WT	3	Acid trend with depth (possible oxidation towards watertable)
Alexander Heights (Ballajura)	616-02-173	pH >6 above WT. No %S determined	Not reported	No evidence of oxidation
Kiara	616-02-179	pH >6 above inferred WT (~1m?). PASS in sand and coffee rock 1-2m and 3-6m up to 0.24% at depth.	Not reported	No evidence of oxidation
Malaga	616-02-173	pH increases to >7 above WT. No %S determined PASS possibly >2m below WT	2	No evidence of oxidation
Whiteman Park West (Cullacarbardee)	616-01-032	pH decreases from >8 at surface to 5 above WT. No PASS	3	Acid trend with depth (possible oxidation towards watertable) Near nested bores with vertical pH trend in aquifer (Clohessy et al 2013)
Whiteman Park East	616-02-173	pH >6 to WT. PASS from >1.5m of 0.03-0.48%S	2.5	No evidence of oxidation

General location	DER site number[1]	ASS status[2]	Watertable (mbgl)	Assessment of oxidation status near the watertable[3]
Whiteman Park South	616-01-35	pH decreases from 9 to 6 at WT. PASS in thick clay bed at 4.5 above WT	5	Acid trend with depth (possible oxidation towards watertable)
Whiteman Park South - Benara	616-01-30	pH >8 decreasing to 5 at WT. PASS up to 0.04%S from 3.25 m (WT) in sand	3	Oxidising at watertable
Henley Brook	616-01-47	pH >6 to WT. PASS from 2m of 0.02-0.07%S	0.5	No evidence of oxidation
Henley Brook	616-01-48	pH >6 to WT. No PASS	3	No evidence of oxidation
Caversham	6160-04-14	pH >6 throughout. PASS from 0.75 to 2m as 0.04-0.05%S	Not reported	No evidence of oxidation
Caversham	616-01-42	pH >6 throughout. No PASS, sand over mostly clays	1.5	No evidence of oxidation
Bedford flat	616-02-12	pH deceasing from 6 to 4.8 at WT. PASS >2.5m at >1mbWT	1.5	Acid trend with depth (possible oxidation towards watertable)
Dianella	616-02-119	pH ranging >5.5 to 4.5 to WT (higher near WT). PASS >3.75m in sands 0.25mbWT	3.5	No evidence of oxidation
Noranda	616-02-177	pH increasing from 5 to >6 with depth to WT. PASS immediately below WT in sands (no %S)	2.8	No evidence of oxidation
Noranda - east	616-02-178	pH >6 with no trend to WT. PASS up to 0.03% at >0.5 mbWT	3.5	No evidence of oxidation
Noranda - north	616-04-90	pH >5.5 to inferred WT . No PASS	Not reported	No evidence of oxidation
Embleton	616-02-126	pH >4.5 to 5 from surface. PASS immediately below WT at 0.05%S	3	No evidence of oxidation

General location	DER site number[1]	ASS status[2]	Watertable (mbgl)	Assessment of oxidation status near the watertable[3]
Embleton	616-02-125	pH 5 to 8 with depth decreasing to 6 at WT. No PASS detected in 1m of WT	5	No evidence of oxidation
Morley	616-02-120	pH decreasing >6 to 5 at depth (near WT?). No PASS	Not reported	Weak acid trend with depth (possible oxidation towards watertable)
Bayswater	616-02-124	pH >7 throughout. No WT or PASS reported.	Not reported	Weak acid trend with depth (possible oxidation towards watertable)
Bayswater - south	616-02-123	pH 4.8-5 near surface increasing to >6 at depth. PASS in sand at >2m within 1m below inferred WT.	Not reported	No evidence of oxidation
Bayswater - east	616-02-127	pH 5.5 to 6. Weak decreasing trend to WT. Oxidised above WT >1m (at 1-1.5mbgl) PASS of 0.04%S at >2.75m within 0.75m of WT.	2	Weak acid trend with depth (possible oxidation towards watertable)
Bassendean	616-02-128	pH >6.5 throughout. Weak PASS in sand >4m within 1m of WT.	3	Weak acid trend with depth (possible oxidation towards watertable)
Ashfield	616-02-129	pH >6.5 to WT. Significant PASS of up to 0.29% in sands immediately below WT.	1.5	Weak acid trend with depth (possible oxidation towards watertable)

[1] Site number as per Appendix 1 bore ID values in Singh et al. 2012a.

[2] Summary extrapolated from Appendix 3, Singh et al. 2012a and soil profile data on SLIP.

[3] Acidification status in unsaturated zone determined from field pH testing of soils (Singh et al. 2012a and summary data on SLIP). pH < 4 is deemed to be an actual ASS in association with other ASS evidence (after Sullivan et al. 2009)

DoW SGS soil investigation sites

General location	DoW site number[1]	ASS status[2]	Water-table (mbgl)	Assessment of oxidation status near the water-table[3]
Lake Bambun	61710483	pH >6.5 above WT. PASS up to 0.05%S below 3.1m in grey sand (0.9m below WT)	2.2	No evidence of oxidation
Bindiar Lake	61710489	pH 3.2- 4.4 above WT in sand. No PASS detected to 8.1 m in light grey sand	8.2	Oxidising at and above water-table
	61710492	Actual acidity and PASS in surface 0.2 m. pH 4- 4.5 above WT in sand with no acid trend. No PASS detected in light brown sand to 6.4 m but evident >8.5 m.	4.9	Oxidising above water-table.
	61710493	pH 3.8-4 above WT in sand with silt lenses. No PASS detected in silty sands to 9.5m.	5.6	Oxidising at and above water-table.
Central Yeal	61710480	pH 4-4.5 above WT with no acid trend. No PASS detected below WT	2.0	Oxidised above water-table. No residual PASS.
Edgerton Seepage	61611443	pH 3.7- 4 above WT in sand with acid trend. No PASS detected to 8.0 m in light grey sand	1.6	Oxidising at and above water-table
Lake Goollelal	61611870	pH 5.8 – 7 above WT with no acid trend. Minor PASS below WT increasing with depth (>3.8m) to 0.09%S.	2.0	No evidence of oxidation
Lake Gwelup	61611876	pH above WT >6.8 with no acid trend. Minor PASS at 5 m (0.02%S) increasing to significant PASS at 5m (0.3%S)	3.1	No evidence of oxidation

General location	DoW site number[1]	ASS status[2]	Water-table (mbgl)	Assessment of oxidation status near the water-table[3]
High Hill wetland	61611863	pH 4.5-5.5 above WT in silty sand with frequent iron mottling and weak acid trend to WT. No PASS detected in silty sands to 14 m.	11.6	Oxidised above water-table. No residual PASS.
	61611861	pH 4.4-6 above WT in silty sand with frequent iron mottling and a weak acid trend to WT. No PASS detected in silty sands to 14 m.	11.3	Oxidised above water-table. No residual PASS.
Lake Jandabup	61611850	Actual acidity (pH <4.5) in surface 1 m sands above WT with no acid trend. PASS detected at and immediately below WT in brown silty sands and sand to 3.6 m but evident to 5.6 m.	2.2	Oxidising above water-table.
Lake Joondalup	61611423	pH > 6 above WT with no acid trend. PASS materials (up to 0.04%) within 0.5m of WT	3.0	No evidence of oxidation
Lexia wetlands	61611849	pH <4.5 in 0.8 m silty sand above WT with no acid trend to WT. Minor PASS (<0.03%S) detected immediately below WT in brown silty sands to 5.6 m.	2.1	Oxidising at and above water-table
	61611848	Strongly acid (pH 3.5-4) in surface 2.2 m sand increasing to pH 4 at WT. No PASS detected immediately below WT in pale brown sands to 6.4 m.	4.2	Oxidised above water-table. No residual PASS.
Lake McNess	61611847	No shallow PASS detected or acidification trends	1.0	No evidence of oxidation
	61611847	Strongly acid (pH < 3.5) in ~ 0.8 m brownish yellow sands above WT. Acid trend to WT with PASS below WT (up to 0.16%S).	2.7	Oxidising at and above water-table

General location	DoW site number[1]	ASS status[2]	Water-table (mbgl)	Assessment of oxidation status near the water-table[3]
Lake Mariginiup	61611440	pH 5.5 – 6.2 above WT with no acid trend. PASS materials (>0.02%S) slightly above WT (2.5m) and below to 8m in light brown sands	2.6	Oxidising at water-table
Lake Muckenburra	61710474	No PASS found with no evidence of acid trends to the WT	1.5	No evidence of oxidation
Melaleuca Park wetlands	61611853	pH 4-4.5 above WT but no acid trend. No PASS detected in pale brown sands to 8 m.	4.5	Oxidised above water-table. No residual PASS.
Pipidinny	61611872	pH > 7.5 with no acid trend to WT. Minor (0.03%S) PASS in thin clay & limestone near WT with significant PASS (1.6%S) at >6m	3.5	No evidence of oxidation
Quin Swamp	61710592	pH 4.5-5 above WT with acid trend to WT. No significant PASS materials below WT	2.2	Oxidised above water-table. No residual PASS.
	61710589	pH 4-5 above WT with acid trend to WT. PASS materials immediately below WT	3.2	Oxidising at and above water-table.
	Lake bed	pH 3.5-5 above WT with acid trend to WT. PASS materials immediately below WT.	0.900	Oxidising at and above water-table.
Tangletoe wetland	61710469	Actual ASS (pH 3.9-4) above WT in mottled sand with acid trend to WT. PASS materials immediately below WT.	3.8	Oxidising at and above water-table.
	Wetland bed (61710505-506_	Actual ASS (pH <4) with significant residual PASS (0.03 – 0.2%S).		Oxidising at and above water-table.

General location	DoW site number[1]	ASS status[2]	Water-table (mbgl)	Assessment of oxidation status near the water-table[3]
Lake Yonderup	61611840	Actual ASS lens (pH 4) at 1.5m above WT in mottled sitly sand with residual PASS materials (0.07-0.1%S). No acid trend to WT.	2.3	Oxidised above water-table.
	61611839	pH 6 – 8 above WT with no acid trend. No PASS materials detected in pale yellow sands.	3.2	No evidence of oxidation
	61611836	Thin actual ASS lens (pH 3.6-4.5) at 4.3 m above WT in brownish-yellow sand but no acid trend to WT detected. No significant PASS materials immediately below WT	6.8	Oxidising above water-table.
Yeal Lake	61710494	pH > 6 above WT with no acid trend. Minor PASS below WT.	2.2	No evidence of oxidation
	Lakebed (61700152-154)	Mostly pH>5-7 with one site with thin actual ASS. Minor PASS below WT	0.1	Oxidising at and above water-table.

[1] Site number as per the Water Information database AWRC number.

[2] Summary extrapolated from SGS bore completion reports and published HG reports.

[3] Acidification status in unsaturated zone determined from field pH testing of soils. pH < 4 is deemed to be an actual ASS in association with other ASS evidence (after Sullivan et al. 2009)

Appendix F — Acidification depths (m below watertable) calculated from PRAMS modelling of each intervention scenario

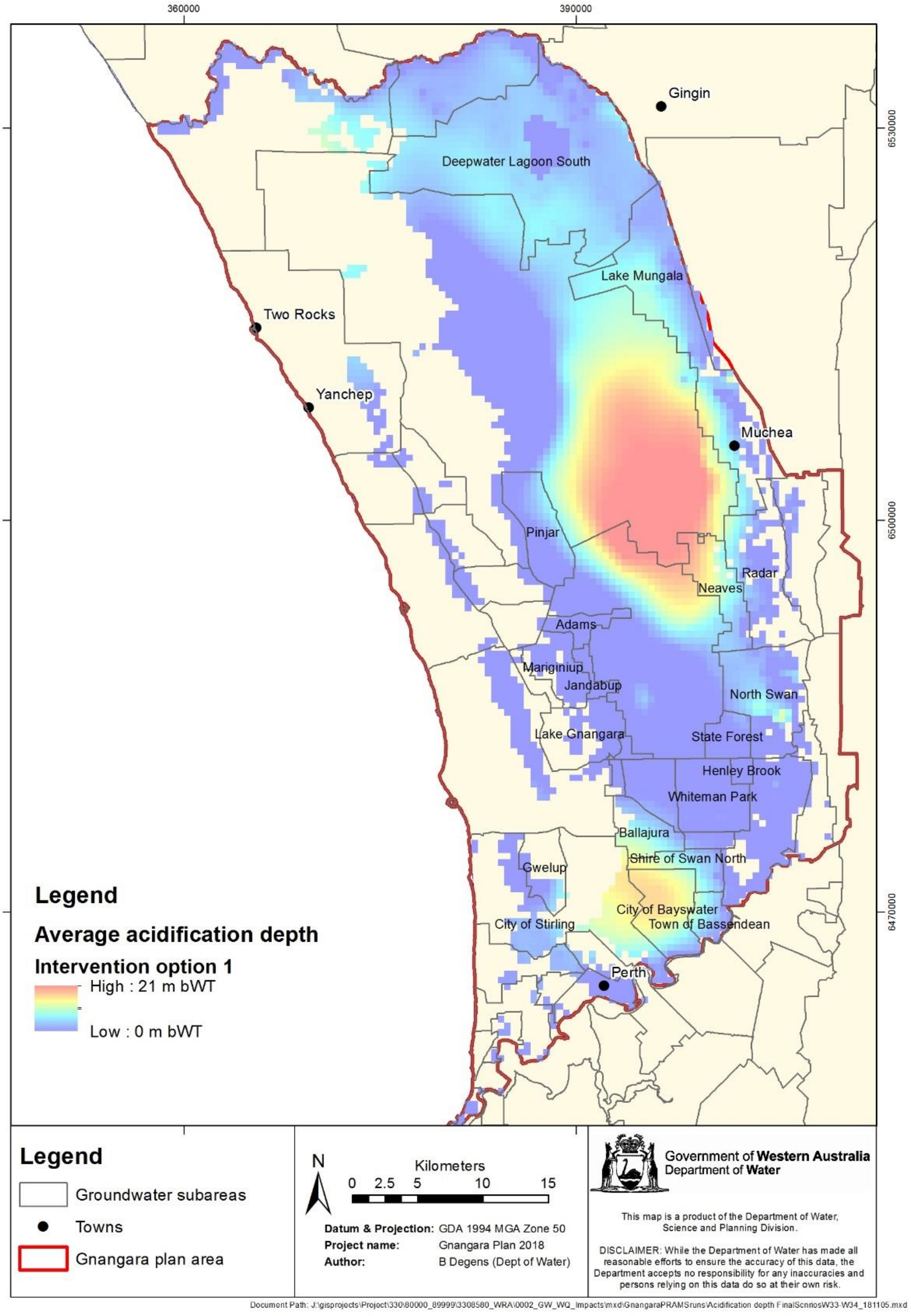

Figure A19: Acidification depth (m below WT) at 2030 for intervention option 1

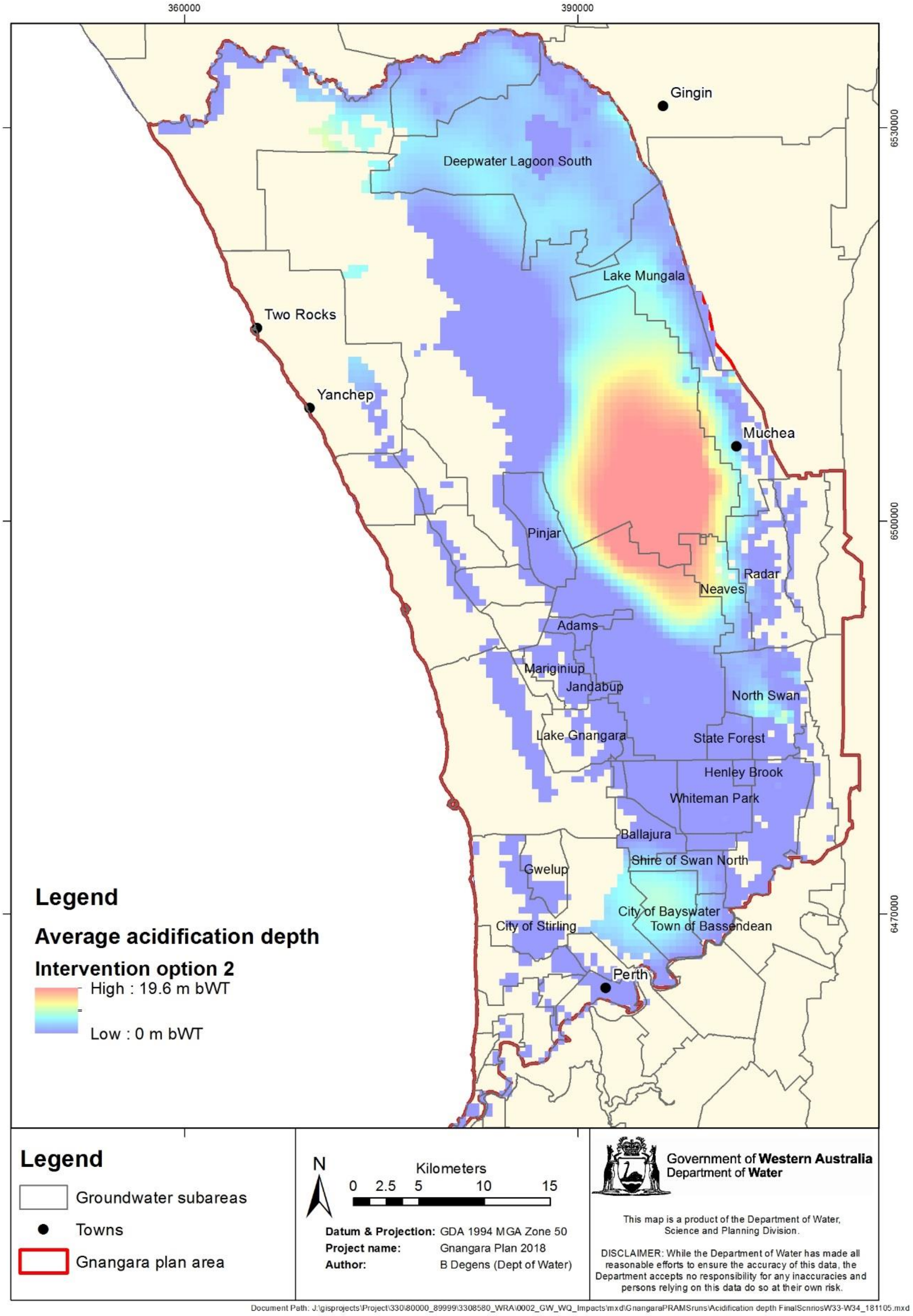

Figure A20: Acidification depth (m below WT) at 2030 for intervention option 2

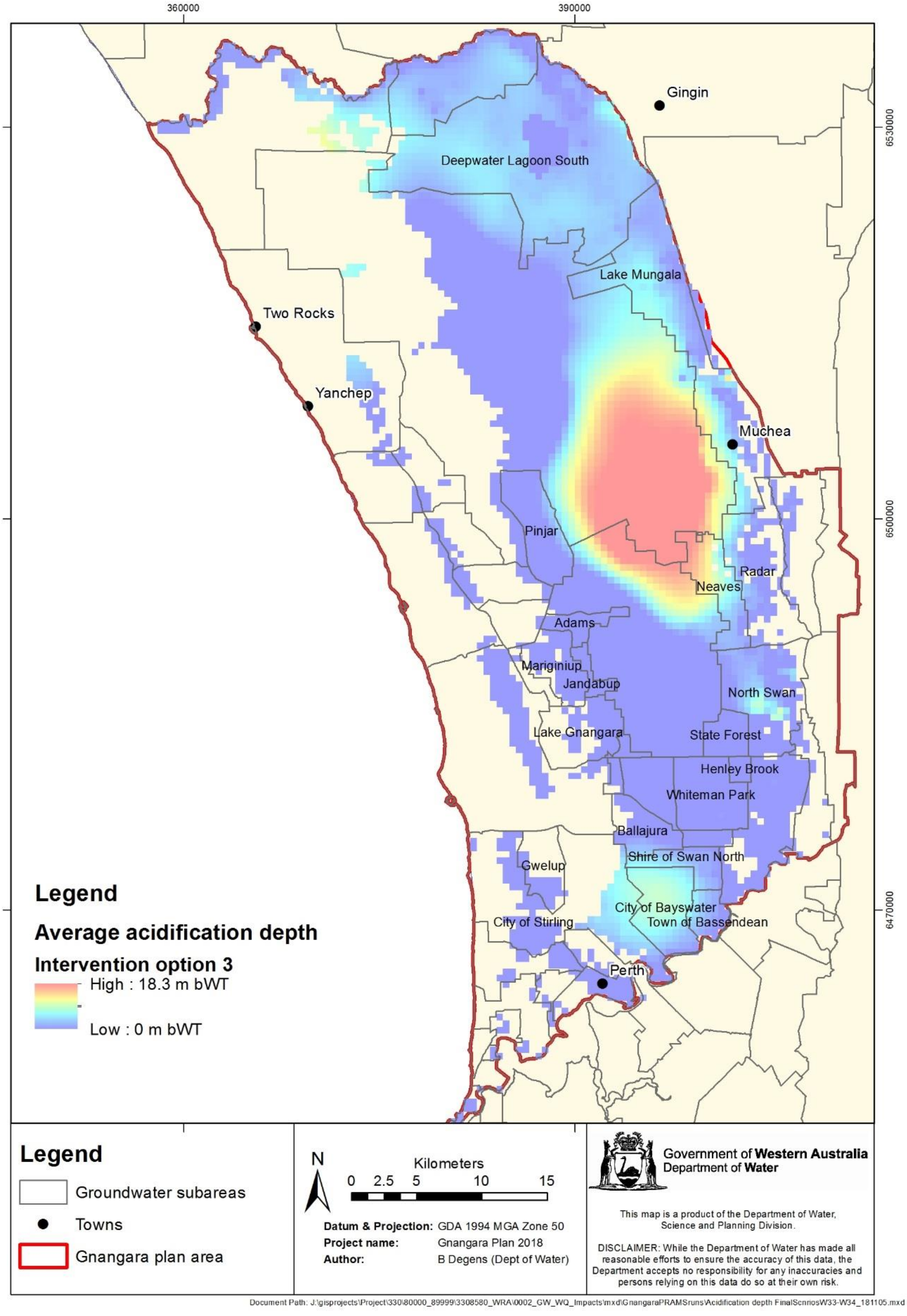

Figure A21: Acidification depth (m below WT) at 2030 for intervention option 3

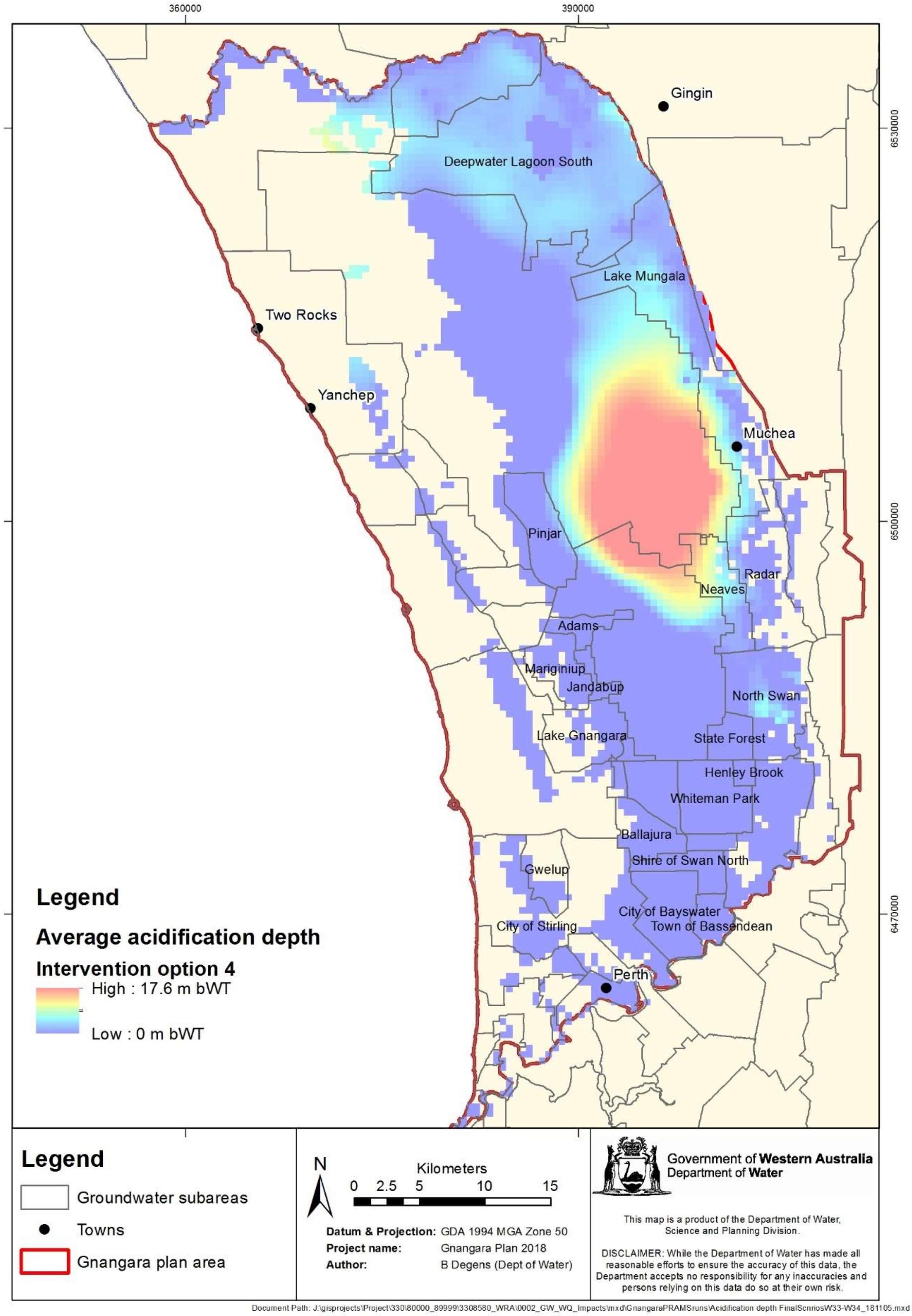

Figure A22: Acidification depth (m below WT) at 2030 for intervention option 4

Appendix G — Annual volumes (GL) of licenced (Lic.) and exempt (Ex.) groundwater pumping at risk of impacts from acidification under different pumping scenarios

Subarea [1]	Basecase			No intervention			Intervention opt. 1			Intervention opt. 2			Intervention opt. 3			Intervention opt. 4		
	Total	Lic.	Ex.	Total	Lic.	Ex.	Total	Lic.	Ex.	Total	Lic.	Ex.	Total	Lic.	Ex.	Total	Lic.	Ex.
Adams	**0.36**	0.30	0.06	**0.01**	0.01	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00
Ballajura	**0.77**	0.10	0.68	**0.71**	0.08	0.63	**0.63**	0.08	0.55	**0.05**	0.00	0.05	**0.04**	0.00	0.04	**0.00**	0.00	0.00
Beechboro	**0.01**	0.00	0.01	**0.01**	0.00	0.01	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00
Beermullah Plain South	**0.07**	0.06	0.01	**0.06**	0.05	0.01	**0.05**	0.04	0.01	**0.04**	0.03	0.01	**0.04**	0.03	0.01	**0.03**	0.02	0.01
City of Bayswater	**2.85**	0.17	2.68	**4.81**	0.32	4.49	**4.75**	0.32	4.44	**2.13**	0.12	2.01	**2.05**	0.12	1.94	**0.00**	0.00	0.00
City of Nedlands	**0.01**	0.00	0.01	**0.01**	0.00	0.01	**0.01**	0.00	0.01	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00
City of Stirling	**1.12**	0.19	0.92	**1.77**	0.33	1.44	**1.74**	0.33	1.41	**0.58**	0.09	0.49	**0.51**	0.07	0.44	**0.00**	0.00	0.00
City of Subiaco	**0.01**	0.00	0.00	**0.01**	0.01	0.01	**0.01**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00
Deepwater Lagoon South	**0.26**	0.20	0.07	**0.22**	0.17	0.06	**0.16**	0.12	0.05	**0.14**	0.10	0.04	**0.10**	0.07	0.03	**0.07**	0.04	0.03
Guilderton South	**0.13**	0.12	0.02	**0.14**	0.12	0.02	**0.07**	0.06	0.01	**0.07**	0.06	0.01	**0.07**	0.05	0.01	**0.02**	0.01	0.01
Gwelup	**0.04**	0.01	0.03	**0.09**	0.03	0.06	**0.09**	0.03	0.06	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00
Henley Brook	**0.08**	0.01	0.06	**0.01**	0.00	0.01	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00
Improvement Plan 8	**0.03**	0.02	0.01	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00
Jandabup	**0.10**	0.06	0.04	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00
Lake Gnangara	**2.23**	1.80	0.43	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00
Lake Mungala	**0.33**	0.20	0.13	**0.30**	0.18	0.12	**0.24**	0.15	0.10	**0.20**	0.12	0.08	**0.17**	0.10	0.06	**0.13**	0.08	0.05
Landsdale	**0.07**	0.05	0.02	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00
Mariginiup	**0.79**	0.58	0.21	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00
Neaves	**0.90**	0.86	0.04	**0.86**	0.82	0.04	**0.63**	0.60	0.03	**0.55**	0.52	0.03	**0.49**	0.46	0.02	**0.30**	0.29	0.02
North Swan	**0.32**	0.22	0.10	**0.27**	0.19	0.08	**0.17**	0.12	0.05	**0.14**	0.10	0.04	**0.12**	0.09	0.03	**0.07**	0.06	0.02

Subarea [1]	Basecase			No intervention			Intervention opt. 1			Intervention opt. 2			Intervention opt. 3			Intervention opt. 4		
	Total	Lic.	Ex.	Total	Lic.	Ex.	Total	Lic.	Ex.	Total	Lic.	Ex.	Total	Lic.	Ex.	Total	Lic.	Ex.
Nowergup	**0.02**	0.02	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00
Pinjar	**0.20**	0.16	0.04	**0.03**	0.01	0.01	**0.01**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00
Plantation	**0.07**	0.06	0.01	**0.01**	0.01	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00
Radar	**0.05**	0.03	0.02	**0.05**	0.03	0.02	**0.04**	0.02	0.01	**0.02**	0.01	0.01	**0.02**	0.01	0.01	**0.01**	0.00	0.01
Reserve	**0.24**	0.23	0.00	**0.22**	0.22	0.00	**0.19**	0.18	0.00	**0.15**	0.15	0.00	**0.12**	0.12	0.00	**0.11**	0.11	0.00
Shire of Swan North	**0.28**	0.02	0.25	**0.39**	0.04	0.34	**0.37**	0.04	0.33	**0.13**	0.01	0.12	**0.12**	0.01	0.11	**0.00**	0.00	0.00
South Swan	**0.14**	0.11	0.03	**0.09**	0.08	0.01	**0.02**	0.02	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00
State Forest	**0.36**	0.13	0.23	**0.20**	0.07	0.13	**0.01**	0.00	0.01	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00
Town of Bassendean	**0.18**	0.01	0.17	**0.36**	0.02	0.33	**0.35**	0.02	0.33	**0.14**	0.01	0.13	**0.13**	0.01	0.13	**0.00**	0.00	0.00
Town of Cambridge	**0.05**	0.01	0.04	**0.13**	0.02	0.10	**0.09**	0.01	0.07	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00
Town of Vincent	**0.01**	0.00	0.01	**0.04**	0.01	0.03	**0.03**	0.01	0.02	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00
Wanneroo Wellfield	**0.82**	0.82	0.00	**0.09**	0.09	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00
Whiteman Park	**0.02**	0.01	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00
Whitfords	**0.29**	0.06	0.23	**0.01**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00
Yanchep	**0.01**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00
TOTALS	**13.2**	6.65	6.59	**10.9**	2.93	7.98	**9.68**	2.17	7.50	**4.36**	1.33	3.04	**3.99**	1.15	2.84	**0.75**	0.61	0.14

[1] NB – Data is not shown for subareas in the ASS hazard zone where total impacts were <0.004 GL for all scenarios. These include: Bandy Spring, Carabooda, Carramar, Central Swan, City of Fremantle, City of Perth, Cockman Bluff, East Swan, Eglington, Joondalup, Neerabup, Shire of Peppermint Grove, Quinns, Town of Claremont, Town of Cottesloe and Town of Mosman Park.

Appendix H — Estimated number of exempt (Ex.) and licenced (Lic.) pumping bores at risk of impacts from acidification under different pumping scenarios

Subarea [1]	Basecase			No intervention			Intervention opt. 1			Intervention opt. 2			Intervention opt. 3			Intervention opt. 4		
	Total	Lic.	Ex.	Total	Lic.	Ex.	Total	Lic.	Ex.	Total	Lic.	Ex.	Total	Lic.	Ex.	Total	Lic.	Ex.
Adams	132	94	38	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Ballajura	1583	11	1572	1461	5	1456	1276	5	1271	127	0	127	98	0	98	0	0	0
Beechboro	19	11	8	6	0	6	3	0	3	0	0	0	0	0	0	0	0	0
Beermullah Plain South	31	22	9	11	3	8	10	3	7	8	2	6	8	2	6	6	1	5
City of Bayswater	6352	121	6231	10460	18	10442	10332	17	10315	4689	7	4682	4515	7	4508	0	0	0
City of Nedlands	22	7	15	23	0	23	12	0	12	2	0	2	2	0	2	0	0	0
City of Stirling	1709	128	1581	2485	19	2466	2435	19	2416	852	5	847	752	5	747	0	0	0
City of Subiaco	17	10	7	13	0	13	7	0	7	0	0	0	0	0	0	0	0	0
Deepwater Lagoon South	82	37	45	49	10	39	39	7	32	33	6	27	27	4	23	22	3	19
Guilderton South	41	29	12	20	7	13	12	4	8	12	4	8	11	3	8	5	1	4
Gwelup	74	12	62	141	2	139	142	2	140	1	0	1	0	0	0	0	0	0
Henley Brook	71	9	62	8	0	8	0	0	0	0	0	0	0	0	0	0	0	0
Improvement Plan 8	7	2	5	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0
Jandabup	40	13	27	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Lake Gnangara	691	184	507	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lake Mungala	162	65	97	96	11	85	80	9	71	65	7	58	54	6	48	44	5	39
Landsdale	49	11	38	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Mariginiup	419	150	269	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Subarea [1]	Basecase			No intervention			Intervention opt. 1			Intervention opt. 2			Intervention opt. 3			Intervention opt. 4		
	Total	Lic.	Ex.	Total	Lic.	Ex.	Total	Lic.	Ex.	Total	Lic.	Ex.	Total	Lic.	Ex.	Total	Lic.	Ex.
Neaves	74	45	29	65	38	27	51	30	21	45	26	19	39	23	16	29	17	12
North Swan	183	47	136	125	11	114	78	7	71	59	6	53	49	6	43	29	4	25
Nowergup	27	26	1	**0**	0	0	**0**	0	0	**0**	0	0	**0**	0	0	**0**	0	0
Pinjar	44	19	25	10	1	9	3	0	3	2	0	2	1	0	1	0	0	0
Plantation	28	18	10	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Radar	39	25	14	16	2	14	12	2	10	8	1	7	7	1	6	4	0	4
Reserve	13	9	4	15	12	3	13	11	2	11	9	2	9	7	2	9	7	2
Shire of Swan North	516	35	481	656	3	653	625	3	622	219	1	218	204	1	203	0	0	0
South Swan	164	132	32	17	6	11	2	1	1	0	0	0	0	0	0	0	0	0
State Forest	463	15	448	258	4	254	12	0	12	4	0	4	1	0	1	0	0	0
Town of Bassendean	258	19	239	474	2	472	465	2	463	183	1	182	178	1	177	0	0	0
Town of Cambridge	122	24	98	246	2	244	172	1	171	0	0	0	0	0	0	0	0	0
Town of Vincent	34	16	18	59	1	58	50	1	49	1	0	1	0	0	0	0	0	0
Wanneroo Wellfield	3	3	0	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0
Whiteman Park	15	11	4	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Whitfords	586	52	534	11	0	11	9	0	9	0	0	0	0	0	0	0	0	0
Yanchep	10	2	8	6	0	6	5	0	5	5	0	5	4	0	4	4	0	4
TOTALS	14114	1429	12685	16753	165	16588	15850	124	15726	6329	76	6253	5961	67	5894	151	37	114

[1] NB – Data is not shown for subareas in the ASS hazard zone where total impacts were <0.004 GL for all scenarios. These include: Bandy Spring, Carabooda, Carramar, Central Swan, City of Fremantle, City of Perth, Cockman Bluff, East Swan, Eglington, Joondalup, Neerabup, Shire of Peppermint Grove, Quinns, Town of Claremont, Town of Cottesloe and Town of Mosman Park.

Shortened forms

ASS	Acid sulfate soil
GWAN	Groundwater assessment network, which is the Department of Water regional water level monitoring bore network.
m bWT	Metres below watertable
m bgl	Metres below ground level
PASS	Potential acid sulfate soil
WRL	Water resource licensing database, reconstructed and named COMPASS in 2017
w/w	Weight of measured constituent per unit weight of soil or water
%S	Percentage sulfur by weight of soil (as pyrite in this report)

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