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Development of a System to Optimise Water Recharge and Timber Production from *Pinus pinaster* Aiton Plantations on the Gnangara Water Mound

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**Publication Details**


6. Groundwater recharge relationships to Leaf Area Index in *Pinus pinaster* Aiton on Gnangara Mound

The following issues will be addressed in this chapter:-

- What factors need to be considered in quantifying the water use of *P. pinaster* Aiton plantations?
- At what point does the LAI stop effective recharge?
- What is the most likely configuration of the LAI to recharge relationship and how does this vary with age and depth to groundwater?

**i) Banksia sp. woodland and *P. pinaster* Aiton water use on the Gnangara Mound**

Farrington et. al. (1989) measured evapotranspiration from *Banksia sp.* woodland on the Gnangara Mound. Farrington et. al. (1989) found that for this vegetation community depth to groundwater had little or no effect on evapotranspiration and that the *Banksia sp.* and *Adenanthes sp.* contributed only 36% (240mm) of the annual evapotranspiration. The site contained thick ground flora, which grows roots to a similar depth as the trees and shrubs. The shrub and herbaceous ground flora layer contributed 64% (426mm) of the site’s evapotranspiration. Where the water table was within 5.4 metres of the ground surface, roots extended to that level. Upslope, where the depth to groundwater was deeper roots were sparse below 8 metres depth. Evaporation for the whole vegetation community totalled 666 mm per year or 77% of the 863 mm annual rainfall. Hence, in their study area recharge was 23 % during the study. As this site is close to that reported in Farrington et. al. (1990), it is believed that it was burnt at the same time (6 years before the study).

Farrington et. al. (1989) points out that there are important management implications from their study. For example, ground flora evaporation is a major component of the water use of
Banksia sp. woodland. If ground flora were reduced by 50%, it would be expected to increase the recharge to 48% of annual rainfall. If prescribed burning is used to achieve this it could be expected that the regeneration of the biomass would reach a new lower plateau. A regular burning program at specified intervals would be necessary to keep the evaporation rates of the ground flora at a low level.

A further implication of the finding that the ground flora is a significant water user is that any scrub layer that recovers below pines once the canopy is opened sufficiently would significantly increase water use despite the reduction of the canopy overstory. It would be important to ensure the gains to recharge by pine thinning are not lost through understorey water use below the pine canopy.

Farrington et. al. (1990) measured evapotranspiration from vegetation growing in a small, seasonally waterlogged basin on the Gnangara Mound. It is unclear from their report how much of the Gnangara Mound these “damplands” sites occupy. They are part of the wetlands of the Bassendean dune system that are at the bottom of the interdunal swales where the water table intersects the ground surface. The site of the study was burnt 7 years prior to the study period. The dominant tree species at the site is Melaleuca preissiana Schauer with other Melaleuca sp. and Banksia sp. species being subdominant. Shrubs formed a dominant component of the community around the edge of the depression (including species of Regelia sp., Hypocalymma sp. and Pultenaea sp.) and in the waterlogged area (Leptospermum sp. and Astartea sp.). The reed Baumea articulata R.Br. is dominant in small areas where free water persists at the surface in summer. Total annual evaporation was 814 mm or 109% of annual rainfall. There was a fresh water table within 3 metres of the ground surface at all times, even at the upslope edge of the site, and some areas of free water persisted during summer.

Farrington et. al. (1990) report that there was water at the surface even in summer and the
evaporation of greater than 100% of rainfall measured at the site. This would indicate that the groundwater mound was exposed at this site and was directly evaporating away.

Raper (1998) suggests that measurements made with the ventilated chamber technique, which indicates that tree water use may exceed annual pan evaporation under highly favourable conditions, may be in error. Raper (1998) states, “at the very least they should be viewed as the extreme upper limit to tree water use under ideal conditions and extrapolating these figures to other areas or periods would be optimistic in the extreme” (p. 32).

Carbon et. al. (1982) carried out soil water measurements with a neutron moisture meter every six weeks for periods ranging from 378 to 489 days for areas of both native vegetation and *P. pinaster* ait on Gnangara mound. Carbon et. al. (1982) found that at 1200 stems.ha$^{-1}$ 14 year old *P. pinaster* Aiton plantations on the Swan Coastal Plain extracted soil water from beyond 6 metres depth and their total evapotranspiration (including interception) was between 96% and 105% of the rainfall for the measurement period. Carbon et. al. (1982) also determined the water use of native vegetation communities on the Swan Coastal Plain in 1965 to 1967. Carbon et. al. (1982) monitored the rainfall and soil moisture at three sites with average annual rainfall of 800 to 900 mm per year. A deep, permanent water table was present at 15 to 20 metres depths at each site. A forest dominated by *Eucalyptus marginata* Donn ex Sm., *E. gomphocephala* DC., and *Banksia grandis* Willd covered the first site. Evapotranspiration over the period of the study was 105% of the rainfall. The vegetation at the second site was dominated by *E. marginata* Donn ex Sm, *E. todtiana* F.Muell., and *B. grandis* Willd. Evapotranspiration over the period of the study was 70% of rainfall. The third site, dominated by *B. attenuata* R.Br. and *B. menziessi* R.Br., had evapotranspiration of 49% of rainfall. Unpublished studies on thinning trials in Myalup and McLarty plantations west of Harvey in the south west of WA, (Ian Dumbrell 2008, Research scientist Forest Products
Commission pers. comm.) also point to negligible recharge under *P. pinaster* Aiton stands greater than 500 stems/ha at age 17, 18 m$^2$ basal area. Myalup and McLarty plantations have slightly higher annual rainfall at 840mm per annum and similar evaporation to Gnangara mound. They are also on the swan coastal plain of South Western Australia and have similar depth sandy soils as Yanchep and Pinjar plantations.

Butcher (1997) reports on a study that was carried out on stands planted in 1952 with an initial stocking of 2200 stems/ha. A thinning experiment was established in 1966 to test the effect of stand density on groundwater recharge. The stands were periodically thinned to maintain the target basal area over time for four treatments of 35, 25, 11 and 7 m$^2$ basal area. Soil water content was estimated using a neutron attenuation technique from 1968 to 1975 to a depth of 6 metres. Rainfall through fall beneath the stands was directly measured and rainfall interception was then derived from these values when this was compared to open cover rainfall gauges. The stand data for this study is unpublished (Trevor Butcher 2007 Research scientist Forest Products Commission pers. comm.).

Butcher (1977) found that:

- Rainfall interception by *P. pinaster* Aiton increased from 10% in 7 m$^2$ basal area sites to 26% in 25 m$^2$ basal area sites. Butcher (1977) suggests the relationship between basal area and rainfall interception has a major bearing on the recharge below the stand. Butcher (1977) also suggests that further losses to recharge are caused by an increasing needle bed and humus layer with increasing stand density.

- No soil wetting front for the 25 m$^2$ site was recorded below 6 metres soil depth. Considerable recharge however occurred under native woodland and open pine (*P. pinaster* Aiton) stands below 7 metres soil depth. The soil moisture withdrawal for the 11 m$^2$ basal area pine (*P. pinaster* Aiton) stand was similar to the native woodland site. One major difference however, is that below 5 metres soil depth the native
woodland appears to remove more soil moisture than the 11 m$^2$ basal area pine (*P. pinaster* Aiton) stand. This may however, reflect the greater amount of soil moisture under the native woodland relative to the pine (*P. pinaster* Aiton) stand.

Sharma, Barron and Craig (1991) undertook a study on Gnangara mound, using the chlorine method, from 1983 to 1987. Sharma, Barron and Craig (1991) examined the differences in depth to water table and recharge in dense (basal area 48 m$^2$/ha) and thinned (9.5 m$^2$ basal area) pine (*P. pinaster* Aiton) stands versus *Banksia sp.* stands. 1985 was a poor rainfall year (621mm at Wanneroo) at these pine sites and this may have significantly influenced the results.

Sharma, Barron and Craig (1991) found on a deep (20m) to water table site:

- Negligible rainfall recharge occurred beneath dense (originally planted at 2200 stems/ha) mature pines (*P. pinaster* Aiton) planted in 1957. The stand of pines was 16 metres high with basal area of 48 m$^2$/ha when the study was carried out. Stands of this density are now rare on the Gnangara Mound.
- 15% rainfall recharge in *Banksia sp.* considered typical and in pristine condition. From this it could be hypothesised to be a site long unburnt. The density and structure of the *Banksia sp.* at this site is unreported in the study.
- 32% rainfall recharge beneath young pines (*P. pinaster* Aiton), planted in 1976 originally planted at 1150 stems/ha and thinned to 300 stems/ha in 1980. The stand was six metres high with a basal area of 5 m$^2$ when the study was carried out.
- Using the bromide method they calculated that recharge for their deep to water table *Banksia sp.* site averaged 7% over the five year period of the study.

On the shallow water table sites, they found:
• That for dense pine (P. pinaster Aiton) planted in 1946 with a basal area of 30 m$^2$ in 1985 and height of 15 metres, water table at 4.5 metres depth, interception was 30% of rainfall and using the bromide and chloride methods and recharge was 8% and <12% respectively.

• For the low density pine site (P. pinaster Aiton) planted in 1946 site, 9.5 m$^2$ basal area in 1985 and thinned that year to this level, 15 metres high water table at 6 metres depth, interception was 20% of rainfall and using the bromide and chloride methods recharge was 16% and <16% respectively.

• For the Banksia sp., which was sited on an area seven metres to water table (measured over a different time frame and at different water table depths making comparisons difficult), interception was 15% of rainfall and for the chloride method 31% recharge and the bromide method 32% recharge.

Sharma, Barron and Craig (1991) attributed the difference in Banksia sp. recharge between the two sites to the difference in understorey vegetation because at the deep to ground water site it was much denser. This would agree with the Farrington et. al. (1989) model of the relationship between density of ground flora and recharge. Their modelling showed that a reduction of LAI from six to one would reduce the interception from 29% to 10% and because of this reduction and lower transpiration at one LAI recharge is doubled in their model.

Farrington and Bartle (1991) estimated recharge for both Banksia sp. and P. pinaster Aiton from 1985 to 1988. The average recharge over the three years was 15% for the pine (P. pinaster Aiton) and 22% for the Banksia sp. woodland. The Banksia sp. site had 410 trees per ha with a basal area of 5 m$^2$. The pine (P. pinaster Aiton) site was established in 1967 and thinned to 750 stems/ha approx. in 1972. At the time of the study stocking was 630 stems/ha and basal area 30 m$^2$. A permanent water table at both sites was between five to eight metres below the surface. Farrington and Bartle (1991) found the throughfall was similar for pine (P.
pinaster Aiton) and the Banksia sp. Farrington and Bartle (1991) suggest that the difference was due to a combination of additional evapotranspiration by pine (P. pinaster Aiton) over Banksia sp. woodland and the presence of needle bed under the pines. This study suggests that regular underpine burning to reduce needle bed depths may be as important as thinning to increase recharge.

Butcher (1979) found that for the first 10 years after pine (P. pinaster Aiton) planting recharge was greater than in native Banksia sp. stands. It took 10 years after pine (P. pinaster Aiton) planting for the recharge below those stands to return to equivalent native levels. This would seem to agree with the formula used by Water Corporation that recharge below 0.5 LAI is 45 % and that from 0.5 to 1.5 m²/m² LAI decreases linearly (Robert Stokes 2003,Principal Engineer Integrated Water Supply, Water Corporation pers. comm.).

The important points from above can be summarised as :-

- **P. pinaster Aiton** stands that are young (under 10 years old and) or are of low basal area (below 11 m²) and hence low LAI allow ground water recharge at or greater than native vegetation on Gnangara Mound.

- At canopy closure of P. pinaster Aiton stands, ground water recharge appears to be extinguished.

- Fire impacts groundwater recharge because it reduces ground cover lowering the vegetations water usage and hence increasing recharge.

Much of the Gnangara Mound P. pinaster Aiton is now less than 250 stems/ha (Figure 60). This factor will need to be taken into account when prescribing future outcomes for recharge as many of the previous studies looked at areas with significantly larger stockings.
Figure 60. 2002 stocking levels of the Gnangara plantations

Less than 250 stems/ha
Greater than 250 stems/ha

Figure 60. 2002 stocking levels of the Gnangara plantations
ii) *P. pinaster* Aiton LAI and depth to water table at Gnangara Mound

Evidence of suppression of maximum LAI can be seen from both the 1978 and 1967 plantings. The 1978 plantings on shallow water tables in Pinjar plantation had a lower LAI of 2.6 m²/m² prior to the thinning in 2001 than the areas with deeper water tables which had an LAI of 2.96 m²/m². The 1967 plantings on shallow depths to water table have not exceeded LAI’s of 2.4 m²/m² in Gnangara plantation whereas it would have been expected it to reach 3 m²/m². It also had lower height growth on shallow depths to water as previously noted in chapter 2.

Depth to water table at the end of summer 2002 below Gnangara Mound plantations shown in Figure 12 was combined with the LAI data derived from the satellite sequence to produce a data set that shown maximum LAI for different depth to water table classes and was further subdivided into planting decades. The results are shown in Figure 61.
Figure 61. Maximum LAI expressed on Gnangara Mound in relation to depth to water table and Planting year’s class

The data in Figure 61 is for the entire Gnangara Mound. At any one time there would have been recent thinning which would have reduced LAI for those stands there would have still been other stands that would have reached their maximum LAI.

The pattern of maximum expressed LAI in Figure 61 suggests that LAI stand growth is repressed on shallow ground water areas less than 10 metres at ages below 20 years. A shallow depth to groundwater below 10 metres is inhibiting growth due to less unsaturated soil volume being available to the trees at ages below 20. This is despite many of these young
stands being at a far higher stocking density which would normally mean a greater growth of LAI (Figure 62).

The difference in maximum LAI recorded at lower and higher depths to the water table declines with increasing age. However, there are still perceivable declines at lower depths to water table in the 1960s age class. The effect in the 1950s age class is not seen probably because by the time the stands have reached 2002 they have an average stocking of only 126 stems/ha and it is likely these stands are not fully occupying the site. Large gaps between the trees at this low stocking will never be able to be occupied. Hence they are not able to fully express maximum site LAI. The difference in LAI between different depths to water table as seen in younger stands is then hidden for this age class group.

![Graph](image)

Figure 62. Area weighted average stockings for age classes of *P. pinaster* Aiton for different depths to water table in 2002 (Weighting by area has been carried out to achieve a consistent average per hectare value)
Benyon (2002) contended that there was a high degree of uncertainty in our knowledge of rates of groundwater use by plantations for sites with water tables below 10 metres from the surface. Benyon (2002) also contended that due to these gaps in our knowledge water use rates on such sites are likely to be accurate only to within hundreds of millimetres per year.

Unlike, Benyon’s (2002) observations which were that maximum LAI was highly variable for the green triangle, the maximum LAI on Gnangara Mound is in a narrow range for closed canopy stands and not highly variable. In fact maximum LAI is less on shallower depths to water. If these stands on shallow water tables were using ground water it is logical to assume that that they would have higher LAI’s based on Benyon’s (2002) observations. Benyon and Doody (2004) state that “it is evident some plantations not using groundwater were able to maintain a relatively high LAI (~3 to 4 m²/m²) through summer under conditions of mild drought stress” (p. 18). Benyon and Doody (2004) suggested that during the dry conditions over summer the trees controlled their transpiration rates by stomatal closure. Benyon and Doody (2004) further suggest that if plantations with a similar LAI were accessing groundwater they would have been able to maintain higher transpiration rates over summer through greater stomatal conductance. Gnangara mound and the green triangle climate are similar with a Mediterranean climate with long dry summers and wet winters.

All of the evidence presented on growth rates and water stress outlined above strongly suggests that the *P. pinaster* Aiton plantations on the Gnangara Mound are not using groundwater even when they would appear to have access to it. In fact shallow depth to groundwater is inhibiting growth. This is probably because there is less unsaturated soil volume available and hence less total soil water available to trees growing on these sites.
iii) Groundwater Recharge rates and LAI on the Gnangara Mound for *P. pinaster* Aiton

Young (below 20 years of age) stands of *P. pinaster* Aiton have LAI growth which has a sigmoidal growth pattern on the Gnangara Mound (See Chapter 5). This is probably caused by increasing reductions of water availability. It can then be hypothesized that the water usage is also sigmoidal. It would then follow that the recharge below the young stands with age is a negative sigmoid (Figure 63). That is it mirrors the growth rates of LAI in reverse. There would be an increasing capture of the total rainfall with increasing LAI until it reaches the site maximum LAI and then plateaus. This is significant in that it means that it will be possible to derive an LAI to water recharge relationship by combining the young stand (below 20 years of age) LAI growth and the hypothesised water usage pattern.

![Figure 63. Possible hypothesized recharge to age relationship as derived from young stand (below 20 years of age) LAI growth pattern](image)

This recharge relationship when combined with LAI growth for the same ages of young stands (below 20 years of age) results in a negative linear relationship as shown in Figure 64.
Figure 64. Combination of theorized recharge by age and actual LAI growth for age to produce a LAI to recharge relationship

It differs for the LAI to recharge relationship used in Xu, Canci, Martin, Donnelly and Stokes (2004) which proposes that above LAI 1.5 m²/m² there is a complete extinguishment of recharge (Table 6). Xu et. al (2004) come to this conclusion by using the PRAMS model. Xu et. al (2004) also cite the findings of Ellis, Hatton and Nuberg (1999) who found that the site maximum equilibrium LAI for a range of Australian sclerophyll woody vegetation types with an equivalent rainfall and evaporation is 1.62 m²/m².
Table 6. PRAMS recharge categories (Xu, Canci, Martin, Donnelly and Stokes (2004))

<table>
<thead>
<tr>
<th></th>
<th>Pine High density</th>
<th>Pine med to high</th>
<th>Pine medium</th>
<th>Pine low to medium</th>
<th>Pine low</th>
<th>Pine very low</th>
<th>Banksia High density</th>
<th>Banksia medium</th>
<th>Banksia low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recharge (mm)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>65</td>
<td>220</td>
<td>360</td>
<td>85</td>
<td>135</td>
<td>300</td>
</tr>
<tr>
<td>Recharge as a percentage of rainfall</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>28</td>
<td>45</td>
<td>10</td>
<td>18</td>
<td>38</td>
</tr>
<tr>
<td>Nominal LAI (m²/m²)</td>
<td></td>
<td></td>
<td></td>
<td>1.25</td>
<td>0.75</td>
<td></td>
<td>1.26</td>
<td>1.08</td>
<td>0.66</td>
</tr>
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If total water usage occurs at an LAI of 1.6 in *P. pinaster* Aiton then it is difficult to explain why it continues grow and to double this LAI to 3.3 m²/m². It is inconceivable that a plant would double its transpiration and rainfall interception area if it has already reached the limitation of full site water usage.

The use of a recharge relationship developed elsewhere in Australia for comparison also ignores the findings of Petheram et. al. (2000) who found that the data on water use and recharge from Gnangara Mound in Western Australia was significantly different from other places in Australia such that it required additional analysis to recognise its unique characteristics including low water retention sandy soils.

Xu et. al (2004) also found that there is a significant over prediction for water uptake by pines on sites with shallow depth to water tables when the LAI was greater than 2 m²/m² using the WAVES model. Xu et. al (2004) describe this deficiency as being caused by the assumption in WAVES that these stands were able to access saturated groundwater. Xu et. al (2004) found that the modelled “resultant large water table declines were not consistent with the observation bore data” (p. 24). Xu et. al (2004) also find difficulty in WAVES simulations for the native woodland as a part of model calibration. Calibrated nominal LAI values for the medium density Banksia are at 1.08 m²/m² and this is well over the range of 0.75-0.85 m²/m² used in PRAMS.
All of these issues put some doubt in the applicability and reliability of the PRAMS modelling process used to predict LAI to water recharge.

There is a strong relationship between water usage and growth and a sigmoidal pattern of LAI growth in young stands (<20 years old) (Figure 42) that have not been thinned. It therefore can be contended that on this basis the pattern is most likely to be as hypothesised in Figure 65 because this is able to explain the LAI to age pattern for young stands (<20 years old) whereas a full extinguishment at LAI 1.5 m$^2$/m$^2$ is not able to explain the ongoing LAI growth to 3.3 m$^2$/m$^2$.

Sharma, Barron and Craig (1991), Farrington & Bartle (1991) and Butcher (1979) also found that for sites of high pine LAI (approx 2.5 m$^2$/m$^2$) water recharge was less than 8%, 15%, and 8% respectively. This does not support the conclusion that there an extinguishment of recharge for LAI greater than 1.5 m$^2$/m$^2$ assumed in PRAMS. These values of approximately 8% are closer to that described by the hypothesis of a linear relationship between LAI and water recharge as shown in Figure 64.

If the hypothesis of a linear relationship between LAI and water recharge was correct then both the *Banksia sp.* and *P. pinaster* Aiton recharge rates may have been underestimated in PRAMS. Components of the total water balance such as the private water usage amount are not accurately measured and are a guesstimate. Give this it is possible that the calibration calculations that rely on whole system balance in PRAMS are not correct.

The exact usage of groundwater through private extraction on the Gnangara Mound is unknown but estimated at 220GL per annum (representing approximately 50% of total usage) and this could be an underestimate. There are also large differences of 100GL per annum in 9 out of the 23 years between 1980 and 2003 reported in Vogwill, McHugh, O’Boy and Yu (2008), between the measured water storage decline and PRAMS modelled decline on
Gnangara Mound. This substantial difference is far greater than has been claimed for the water usage of the Gnangara Mound pine plantations.

Vogwill, McHugh, O’Boy and Yu (2008) also state that PRAMS modelling indicates “high-density native vegetation, particularly Banksia woodland areas, are heavy water users” (p. 33). Vogwill, McHugh, O’Boy and Yu (2008) found that the model is very sensitive to native vegetation density because of the very broad distribution of native vegetation on the mound. Xu et. al (2004) report “there is also some uncertainty in the estimated leaf area index for native woodland” (p. 27) on Gnangara Mound. If the native vegetation density has been incorrectly described then this too could be a significant source of error in prescribing the relative portions of water use in the whole system water balance.

Dr. Ramsis Salama former Senior Principal Research Scientist and Project Leader CSIRO Land and Water, Australia is highly critical of PRAMS (Salama 2008). Salama (2008) states that “according to Vogwill (2004) a large number of problems and difficulties have been encountered in the climate modelling including lack of data to construct “representative” sequences from existing data, uncertain inter-relationships between climatic stations, and current inability to produce “manufactured” data due to the nature and detail of data requirements” (p. 1) Salama (2008) further contends in most cases the large numbers of parameters needed for modelling are unknown and must be estimated as there is no data for the recharge response units. For example soil characteristics are poorly defined, LAI are not known for the different vegetation types and recharge characteristics are “a big mystery” (p. 1) (Salama 2008). Salama (2008) is also critical that “because the models calibrations are based on trial and error and in most cases the sensitivity of any of the parameters is dependent on so many variables that in the end there will be no relationship between what is true and what is creation” (p. 1). Salama (2008) concludes that the “PRAMS model is not suitable to
understand or predict impact to the level required for fixing allocation limits or to investigate the dominant factors that are influencing declines” (p. 1).

There is a further important potential source of error in the PRAMS model. It is dependent on the base year used for calibration. The net total impact of pines includes an increase of water tables depth due to the original clearing of native vegetation, which would have a rebound period. A base year of 1979 is used in PRAMS modelling, such as that used by Department of Environment (2005). The usage of 1979 as a base year for comparisons in looking at water level impacts will be influenced by the impact of a large clearing surge in water table caused by prior clearing for establishment of pine. Figure 64 quite clearly shows there was significant clearing that was carried out prior to planting pines before 1979.

The impact of clearing for pines was assessed by constructing a cross section through the Pinjar area and graphing the water table level results for 1979, 1988 and 2002 (Figure 66). Figure 68 shows that the water table increased from 1979 to 1988 then receded for a significant portion of this cross section. The net impact of pine management including clearing for establishment therefore needs to be taken into account. Significant errors because water tables rose upwards of 4 metres directly after clearing at some monitor sites could be made if 1979 is use as a base comparison year because there may be a decline from a higher base caused by clearing for pines in this area. Prescribing all this loss to other factors may be incorrect. Indeed the water table rise caused by clearing of native vegetation prior to pine establishment may make calibration of PRAMS extremely difficult as there is an insufficient set of data prior to 1979 when major water table measurements commenced regularly.
Figure 65. Planting years in Pinjar and Yanchep plantations
Figure 66. Cross sections and water table levels over time
Figure 67. Cross section A water table levels in 1979, 1988, 2002 and depth to water table in 2002 and surface elevation above sea level (water levels as provided by Water and Rivers commission)

Water recharge percentage of *P. pinaster* Aiton using hypothesised linear relationship (Figure 64) to LAI and PRAMS recharge to LAI relationship (Table 6) where calculated to compare the different theorised recharge to LAI relationships.

Table 7 and Figure 68 show a relative difference of 23 GL recharge in 2008 between an equivalent area of Banksia to that of the *P. pinaster* Aiton if a linear relationship of LAI to recharge is assumed. Whereas using the PRAMS recharge relationship it is only 11GL in 2008. Water recharge amounts of Gnangara mound *P. pinaster* Aiton and Banksia using hypothesised linear relationship to LAI are significantly greater than the PRAMS recharge to LAI relationship (Figure 68).
Table 7 Water recharge percentage of *P. pinaster* Aiton using hypothesised linear relationship (Figure 65) to LAI and PRAMS recharge to LAI relationship (Table 6).

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<tr>
<td>Average LAI m²/m²</td>
<td>1.23</td>
<td>1.99</td>
<td>1.58</td>
<td>1.78</td>
<td>1.57</td>
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<td>Recharge GL</td>
<td>46.3</td>
<td>26.4</td>
<td>37.2</td>
<td>31.9</td>
<td>37.4</td>
<td>50.3</td>
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<td>Percentage recharge</td>
<td>26.6</td>
<td>15.2</td>
<td>21.3</td>
<td>18.3</td>
<td>21.5</td>
<td>28.8</td>
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<td>Recharge GL</td>
<td>21.5</td>
<td>15.2</td>
<td>16.8</td>
<td>20.7</td>
<td>18.5</td>
<td>29.5</td>
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<tr>
<td>Percentage recharge</td>
<td>12.3</td>
<td>8.7</td>
<td>9.6</td>
<td>11.9</td>
<td>10.6</td>
<td>16.9</td>
</tr>
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Figure 68. Water recharge amounts of Gnangara mound *P. pinaster* Aiton and Banksia using hypothesised linear relationship to LAI and PRAMS recharge to LAI relationship

**iv) Using LAI as a substitute for water recharge**

Given some uncertainty in the LAI to water recharge relationship its use directly in the model could potentially have introduced unquantifiable errors, which would add additional uncertainty to the model. It was therefore decided not to add in a water recharge relationship.
directly into the model to be constructed to test different harvesting regimes. Fortunately, LAI has a strong inverse relation to water recharge. Consequently, LAI minimization within a model however would have the same effect as maximizing the water recharge.

If required any water relationship to LAI can then be added on to the results of scenarios without adding additional sources of potential error. Provided the same LAI to water recharge relationship is used for all the scenarios and a comparison area of *Banksia sp.* then the best scenario for water can be still found. For example, if a scenario has a much lower LAI because of different silvicultural choices, but still maintains an ability to meet the contractual timber volume demands, then this would be a better choice when trying to achieve a greater water recharge outcome than another scenario with a higher LAI. There will be however, be some significant remaining uncertainty of the exact quantity of the water recharge outcome. The consequence of this will be that it will only be possible to compare scenario outcomes and rank them from best to worst in regards to water outcome rather than be definitive in exact water recharge amounts achieved.

It was decided to use both the linear hypothesised LAI to recharge relationship and the PRAMS LAI to water recharge relationship on the model result with a LAI minimisation scenario. A sensitivity analysis of the water outcome could then be undertaken by varying the LAI to water recharge relationship factors. Each scenario and their rankings against each other can be compared for both LAI to water recharge relationships.

<table>
<thead>
<tr>
<th>Lower LAI with volumes met</th>
<th>= Better water outcome within constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higher LAI with volumes met</td>
<td>= Poorer water outcome within constraints</td>
</tr>
</tbody>
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