Future streamflows from the northern jarrah forest: Learnings from the Wungong Catchment Trial

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2012

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Acknowledgements

This paper was prepared for the Water Corporation by Amanda Reed and Keith Barrett of the Water Corporation and James Croton of Water and Environmental Consultants.

The authors acknowledge with gratitude the valuable contribution made by hydrographers from the 1960s to the present day in the collection of essential gauged catchment rainfall, streamflow and water quality information. A special thank you to Kelvin Baldock, Rebecca James and the Department of Water hydrographers operating gauged catchments associated with the Wungong Catchment Trial.

Many scientists, engineers and foresters have been involved in studying the hydrology, forest attributes and environment of the forested water catchments over many decades. They provided the building blocks for the current sound knowledge and their work is gratefully acknowledged.

Particular thanks go to Frank Batini, Jack Bradshaw, Craig Macfarlane and Geoff Mauger for their special contributions towards the information presented in this paper.

ISBN 1 74043 797 7
July 2012

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Background

In the late 1960s to mid-1970s there was a change in the rainfall regime in the south-west of Western Australia. While there were dry years prior to 1975, these were interspersed with some very wet years (ten over 1500 mm, of which five were over 1700 mm, in the 1901-1975 record).

Since 1975 these wet winters have been absent and rain per rain-day has been much reduced (Sadler 2004). Rainfall at Jarrahdale has reduced by 17% since 1975 and streamflow in the water supply catchments since this time has more than halved.

The forest has been able to continue transpiring relatively unconstrained by drawing on soil-water and groundwater reserves. The water-yielding higher rainfall areas of the water catchments are predominately vegetated by regrowth forest, with higher water-use capacity than old growth forest (Macfarlane *et al* 2010).

While there had been declines in groundwater levels throughout the northern jarrah forest since the mid-1970s, groundwater was still connected to the streams in the early 1990s; this provided the summer base-flow, which is important to the streamzone environment. However, groundwater was continuing to decline through vegetation use and the lack of very wet years to 'top up' the system.

By the early 2000s many perennial streams on the Darling Plateau ceased to flow for the first time and many are now dry for up to five months each year.

Streamflow since 2000 has halved again, and the 2006 to 2012 average inflow is now only 19% of the pre-1975 average, as shown at www.watercorporation.com.au/D/dams_streamflow.cfm.

Maintenance of streamflow is important to aquatic ecosystems (Davies and Storey 2012) and to the health of the near-stream riparian vegetation, which has a high environmental value (Dundas *et al* 2012, and Batini 2011). If these flows are to be maintained into the future, it will be important to return the soil moisture and groundwater store to the levels of the 1990s. These increases in soil moisture and groundwater levels will in turn result in improved streamflow.

The Wungong Catchment Trial has been a catalyst for enhanced monitoring, research and hydrological-process modelling that has built on previous research. The hydrology of the forested water catchments under a drying climate is now well understood and this paper outlines this knowledge with the view to exploring alternative management scenarios for the water supply catchments.

Wungong Catchment Trial

The Wungong Catchment Trial began in 2005, with a purpose of improving soil moisture and groundwater levels (and thereby streamflow) by reducing transpiration in the catchment through the use of silvicultural practices.

Based on our understanding of jarrah forest catchment hydrology at that time, reducing the basal area of the catchment to 15 m^2/ha every 15 years was thought to generate sufficient recovery of groundwater levels and provide the anticipated streamflow increases (Water Corporation 2005). This basal area is consistent with the approved silviculture described in the Conservation

Commission's Forest Management Plan 2004-2013. It corresponds to a Leaf Area Index[1] of about 1.0 to 1.2.

However, since 2005 continued reductions in rainfall, particularly during 2006 and 2010, have contributed to further reductions in streamflow. Hydrological modelling undertaken by Croton (2010) as part of the Wungong Catchment Trial showed that, under this rainfall regime, groundwater levels have declined to such a degree that the original proposal will no longer recover groundwater levels sufficiently to create the required increases in streamflows.

As a result of these findings, the outcomes of the Trial were amended. Instead of aiming for a 25% increase in streamflow (as originally proposed), the Wungong Catchment Trial now aims to recover soil moisture and groundwater back to the level of the 1990s, which will result in a long-term recovery of catchment hydrology and streamflows.

This is a significant change to the Trial and is reflected in the Department of Environment and Conservation's draft silviculture guideline for Treatment Area 4 (a 2000 ha area within Wungong catchment). The draft guideline was released by the Water Corporation for public comment in June 2012[2].

Hydrologic monitoring

Stream gauging with associated continuous rainfall measurement (pluviometers) was initiated in Western Australia in the early 1960s to better understand water resources availability and the rainfall-runoff process. Well instrumented small catchments were established as part of a number of cooperative research programs instigated to assess the impact of clearing, forest harvesting, thinning and bauxite mining on the quantity and quality of streamflow. Great advances in information gathering were made through the 1970s and 1980s. However, funding cuts during the 1990s saw the scaling back of the gauging network.

In 2005, following approval and funding for the Wungong Catchment Trial, a number of stream gauging stations were re-established within and around the Wungong catchment. A new gauging station was established at Chandler Road to monitor the first area to be treated. The water quality monitoring program was upgraded and pumping samplers were installed at key stations.

Groundwater bores, established by Alcoa in the early 1990s and mothballed in 1998, were identified as being of value to the Wungong Catchment Trial and their monitoring was re-established in 2005.

The locations of key gauged catchments in and near the Wungong catchment are shown in Figure 1. A summary of the gauging network (stream gauging stations with associated pluviometer stations) of special interest to the Wungong Catchment Trial is provided in Appendix 1.

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[1] Or LAI, a measure of vegetation density by defining its single side leaf area cover per unit ground area; LAI is used in transpiration calculations in catchment modelling.

[2] *Silvicultural treatment of native forest to enhance streamflow and groundwater reserves in the Wungong catchment (Treatment Area 4)*, pending approval at time of publication.

Through this monitoring, and the research and hydrologic process modelling that utilise these data, there is now a sound and evolving understanding of the hydrology of the northern jarrah forest under a drying climate.

The Wungong Catchment Trial is supporting a comprehensive range of research, particularly in aquatic biodiversity, fauna, flora, and tree health. The results of these projects are well documented and widely published and can be accessed at www.watercorporation.com.au/W/wungong_trial_research_and_monitoring.cfm.

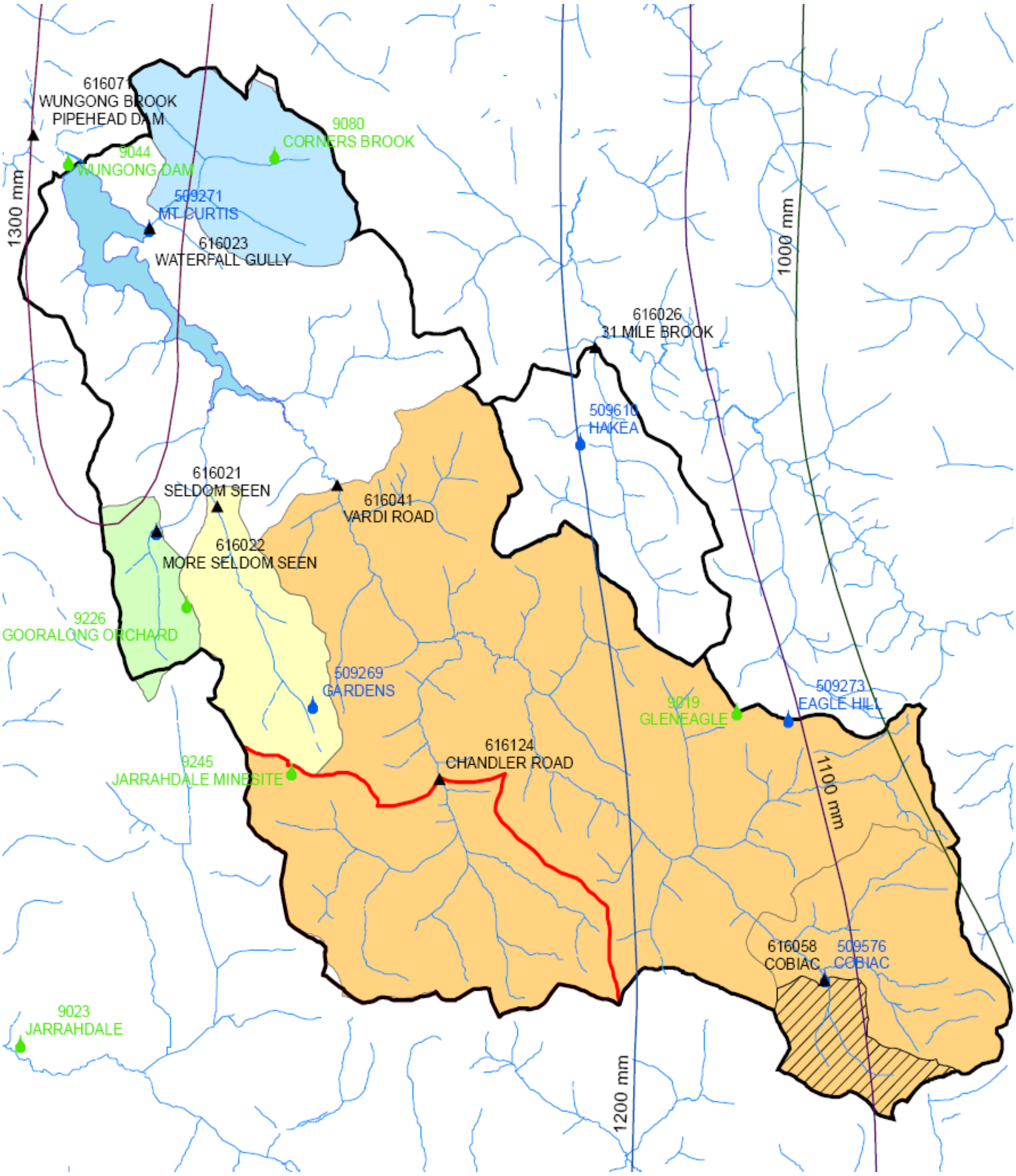

Figure 1 Location of key gauged catchments within and around the Wungong catchment.

Treated catchments

To date, there are two gauged sub-catchments within the Wungong catchment that have been treated using the prescriptions originally proposed by Water Corporation (2005). They are Chandler Road and Cobiac, and their results have been quite different due to specific differences regarding each catchment's history and hydrology, the location of treatment with regards to reserve areas, and the overall success of treatment in reducing canopy cover. The location of each catchment is presented in Figure 1.

Chandler Road

The Chandler Road sub-catchment is part of the larger Vardi Road catchment. It is 1750 ha in area, and approximately 25% has been bauxite mined and rehabilitated. A large proportion of the catchment is allocated as reserves, 31% in total, combining streamzones and a fauna habitat zone. These reserves are all located in lower slope areas, which is the area critical for streamflow generation.

Thinning activities were undertaken in 2006 in 55% of the catchment, which included over 98% of the mine rehabilitation areas. Details of the silvicultural activities are documented in Appendix 2.

While not receiving the highest rainfall within the Wungong catchment, Chandler Road does receive higher rainfall than Cobiac, with an annual average of 991 mm compared with 892 mm for the 2004 to 2011 period. The 1926-1979 annual averages are 1220 mm and 1110 mm respectively (Hayes and Garnaut 1981). However, despite this higher rainfall there was no immediately obvious hydrologic response to thinning observed at the gauging station.

With only one active bore within the catchment (located within a mine-rehabilitation area) the groundwater system within Chandler Road is an unknown entity. At the location of this bore the groundwater is very deep (in excess of 20 m), and although the mining rehabilitation was clearfelled at this site the groundwater response has been slow, with only a 1.5 m rise since 2006. This slow response is presumably due to the depth to the water table. While an interesting observation in and of itself, it is impossible to draw catchment-wide conclusions from this result.

However, from our understanding of catchment hydrology we can assume that any improvements in soil moisture and groundwater levels generated by the treatment have been lost through transpiration of the vegetation in the large lower-slope reserve system.

Cobiac

Cobiac is 364 ha in size and is also part of the larger Vardi Road catchment. There has been only a minimal amount of mining and mine rehabilitation in the Cobiac catchment, located on the mid and upper slopes on the western side. Forest reserves within the catchment are confined to streamzone reserves, and an untreated control transect on the eastern side of the catchment.

Cobiac received an average rainfall of 892 mm annually since gauging at the site was re-established in 2004. Thinning activities were undertaken in early 2008 in 66% of the catchment area. A map of the Cobiac forest coupe showing treatment and reserve locations is shown in Figure 2. The area harvested with follow up notching is all within the gauged Cobiac sub-catchment. Further details of the silvicultural treatments undertaken are given in Appendix 3.

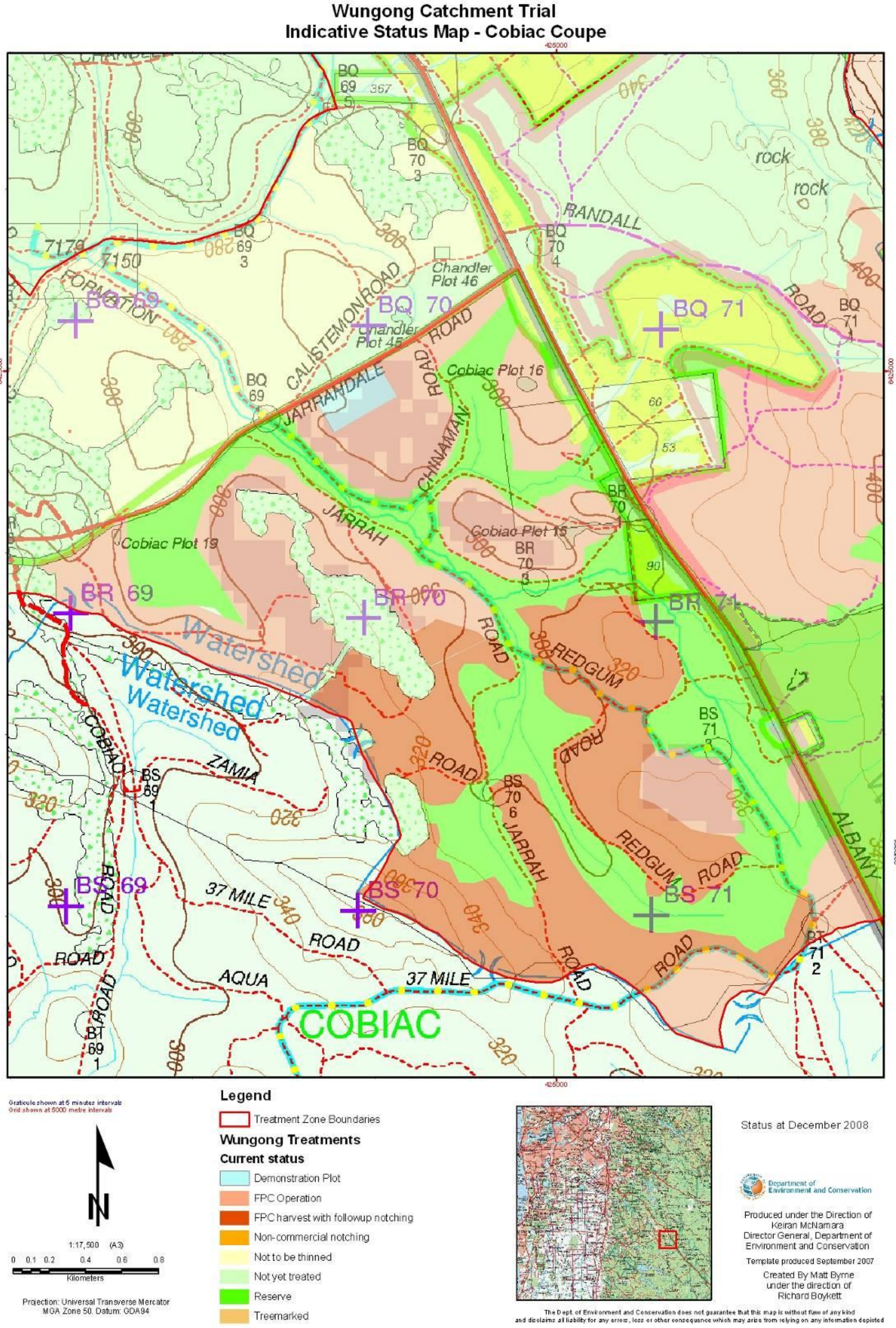

Figure 2 Cobiac forest coupe that contains the Cobiac catchment, showing treated areas and reserves, from Reed (2008).

The success of treatment in Cobiac is demonstrated by improvements in streamflow observed at its gauging station. This is illustrated by the correlation between 31 Mile Brook (as the control catchment) and Cobiac stations, shown in Figure 3. Post-treatment readings above the regression line indicate that more streamflow occurred at the Cobiac gauging station than would be expected had treatment not occurred. The point marking the 2008 result is positioned on the regression line, indicating that this result is consistent with the pre-treatment data rather than with post-treatment data. This result is not unexpected, as prior research findings have indicated that the first year following treatment tends to show little to no streamflow improvements from thinning (Bari and Ruprecht 2003). However, the results for 2009 and 2011 indicate that there has been a measurable improvement in streamflow as a result of the treatment undertaken within Cobiac. The poor result from 2010 is indicative of the historical low rainfall of that year, with only 471 mm of rainfall recorded.

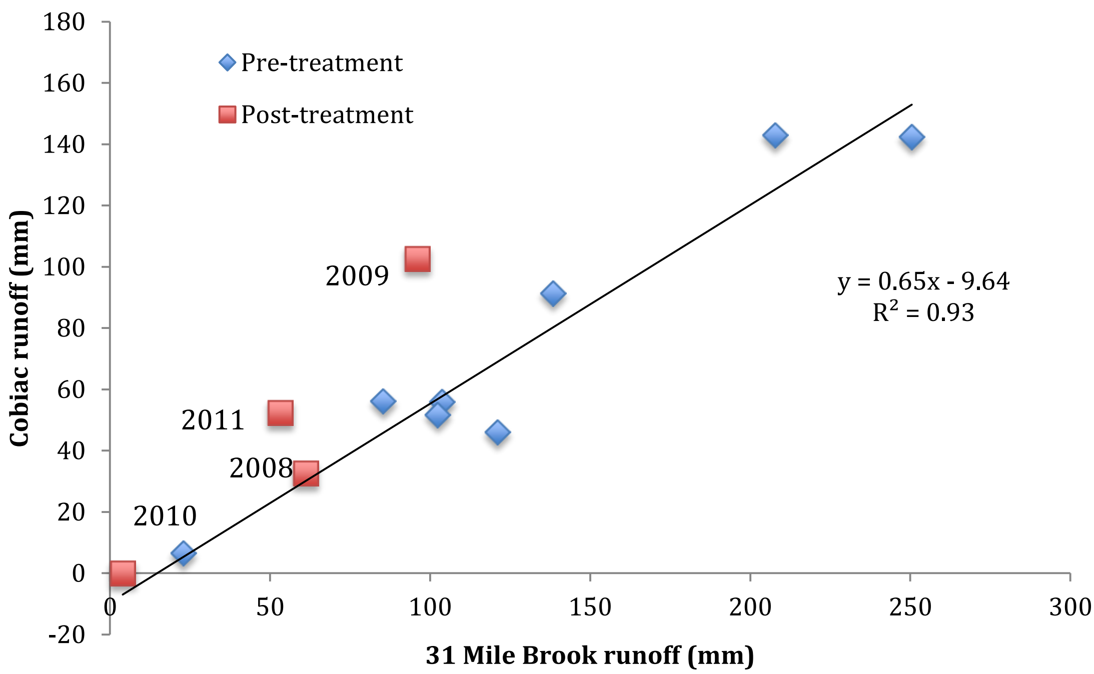

Figure 3 Runoff correlation between 31 Mile Brook (control) and Cobiac.

The groundwater monitoring network and trends prior to treatment have been summarised by Reed (2008). With three years of post-treatment data, comparison between groundwater levels within a treated area and a bore located in the control transect (both mid-slope bores) is shown in Figure 4. This indicates that while groundwater levels in the control transect are continuing to decline, the levels within treated areas are improving.

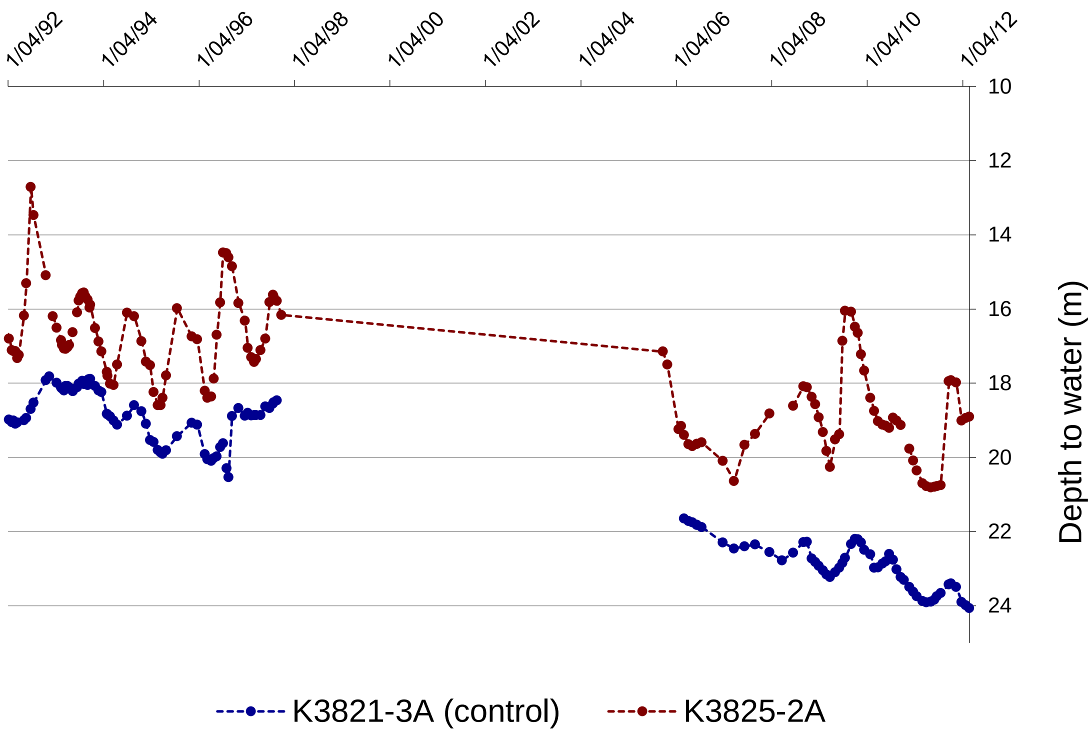

Figure 4 Comparison between two bores located mid-slope. The control bore located in an untreated area is shown by the blue line, the bore located within the treated area is shown by the red line.

The groundwater levels within the catchment have declined since the 1990s, however there are improvements being seen throughout the catchment. Figure 5 shows the groundwater level history near the Cobiac gauging station.

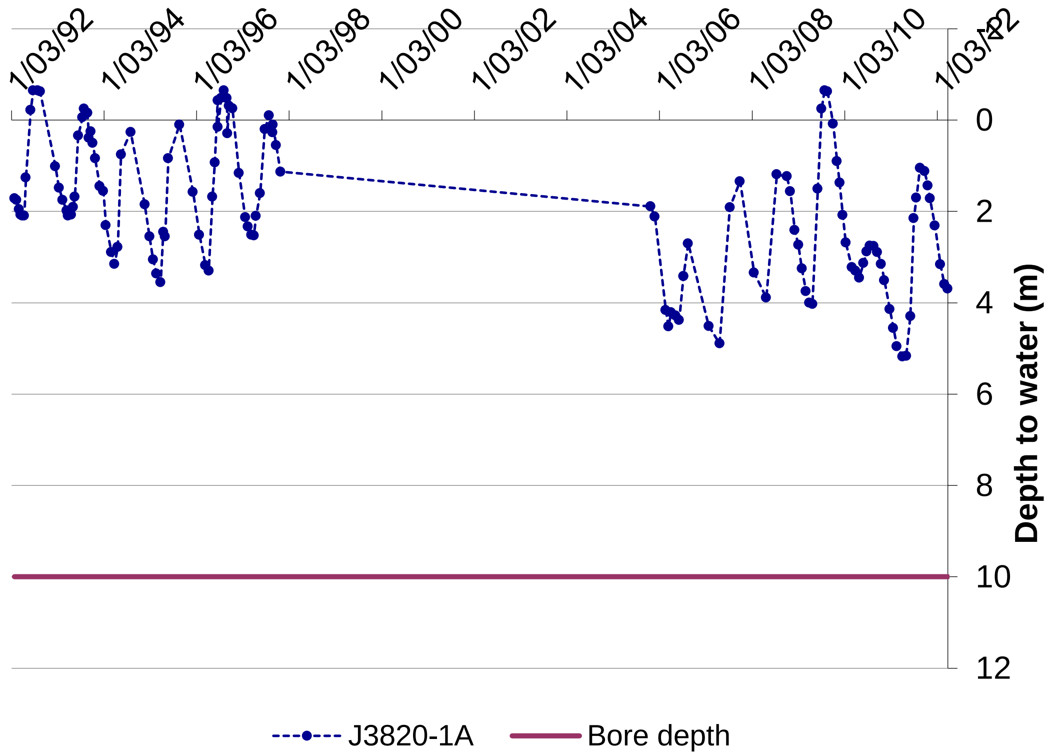

Figure 5 Observed depth readings from a bore located near Cobiac gauging station.

At this bore, the groundwater made significant recovery in 2009 following successful treatment within the catchment. However, this treatment was not sufficient to counteract the extremely poor winter of 2010. Although the streamflow from Cobiac in 2011 was greater than that expected had treatment not taken place (Figure 3), groundwater levels are still recovering and have not reached pre-treatment depths.

Catchment modelling

As part of the Wungong Catchment Trial, catchment modelling of three key research-scale catchments within and around the Wungong catchment was undertaken – Chandler Road, Cobiac and 31 Mile Brook (located within the Canning catchment). This modelling was completed by Water and Environmental Consultants using their WEC-C model, which is detailed in Appendix 4. The purpose of modelling Chandler Road and Cobiac was to assist in our understanding of the success, or otherwise, of treatments undertaken in these areas. This work has been previously presented by Croton (2010).

The 31 Mile Brook model builds on work completed as part of wider research projects in the northern jarrah forest. The WEC-C model of 31 Mile Brook catchment has been extensively used as part of these projects, which have focussed on forest treatment for groundwater recharge and streamflow generation. The 31 Mile Brook catchment is considered to be more representative of the higher rainfall areas of the water supply catchments in terms of rainfall, topography, groundwater levels, forest cover, and reserve locations than either Chandler Road or Cobiac. As such, the 31 Mile Brook modelling has been the focus of our efforts to improve our knowledge.

Background

Figure 6 shows the match of the 31 Mile Brook model to observed streamflow and flow-days on an annual basis. While the general match to the observed data is very good, of particular importance is the ability of the model to follow the downward trend in both streamflow volume and flow-days. These indicate that the model is able to simulate the general drying trend that has been observed across the forested catchments, and gives confidence in the results of the various future scenarios that have been modelled.

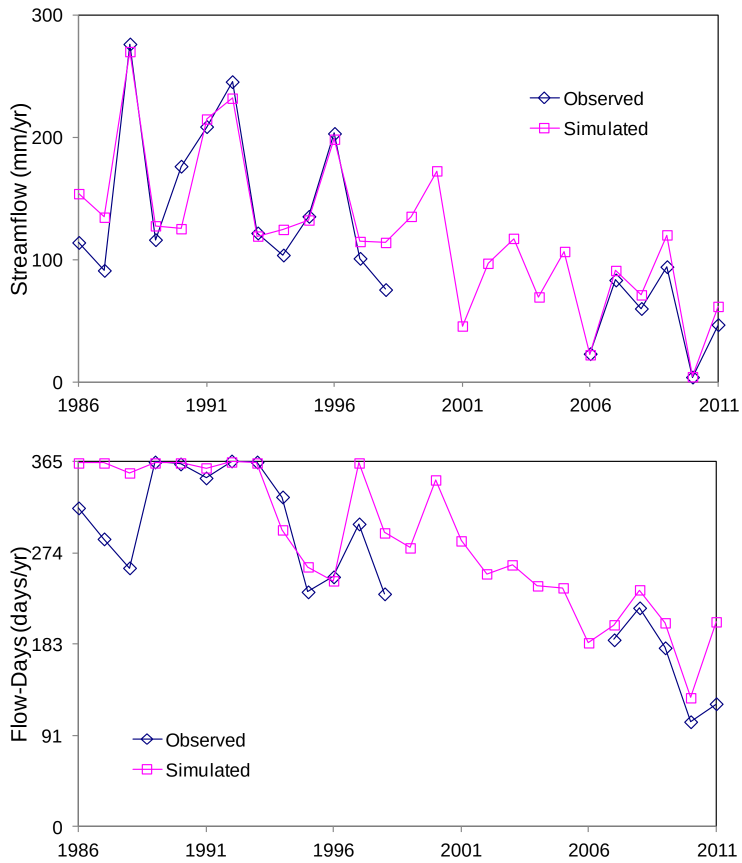

Figure 6 Comparison of observed and modelled annual streamflow volume and flow days.

The 31 Mile Brook model has well illustrated the reductions in soil-water storage and the groundwater system since the rainfall decline in the 1970s (Figures 7 and 8). Figure 7 shows how the total soil-water storage, that is both saturated and unsaturated storages, has steadily declined and is now 1200 mm less than it was in 1986. Figure 8 shows simulated depth-to-water maps for the groundwater system; it can be seen that the groundwater levels have declined across the catchment and the groundwater system has gone from one in the 1970s with extensive sections of the valley floor with heads above the soil surface (pink and purple on the maps), to one with limited groundwater contact with the soil surface in 2010. These reductions in the groundwater system and disconnection of groundwater from the streamzone explain how the recent small declines in rainfall averages have resulted in significant streamflow declines. For example, for 31 Mile Brook from 1991 to 2000 the average rainfall was 1123 mm, and average simulated streamflow was 153 mm. The period 2001 to 2010 had a 15% reduction in rainfall from the 1991-2000 average, but the average simulated streamflow reduced to half (78 mm, or a 49% reduction).

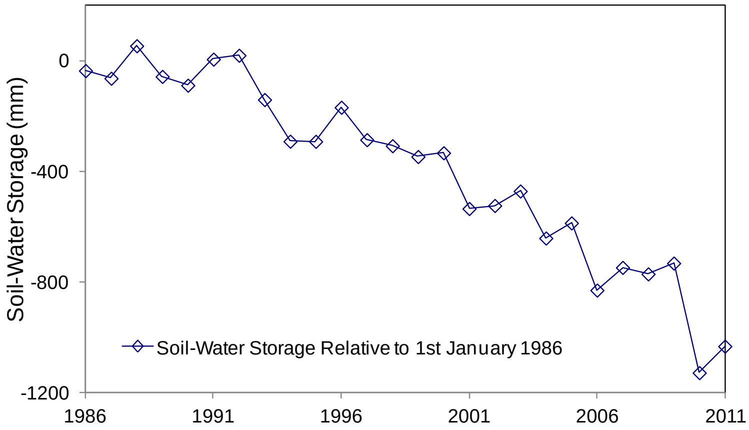

Figure 7 Simulated soil-water storage changes relative to 1 January 1986.

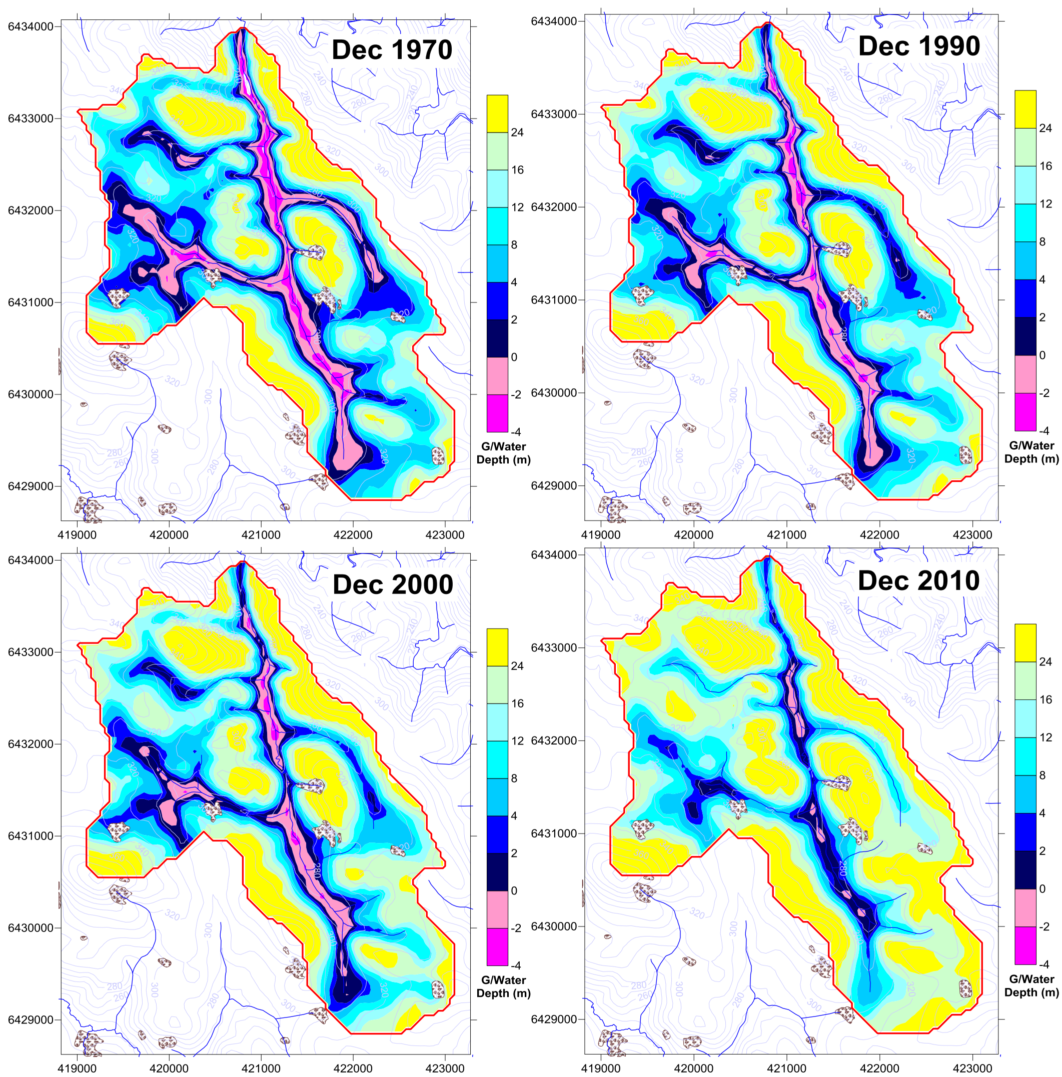

Figure 8 Simulated depth to groundwater maps of 31 Mile Brook catchment from 1970 to 2010.

Due to the deep rooting of the jarrah tree, the groundwater system has continued to fall for decades with little apparent adverse impact on the forest. In the summer of 2011 there were early signs of stress; following the historic low rainfall of 2010, pockets of collapse were observed throughout the northern jarrah forest (Water Corporation 2011).

Simulating forest growth following treatment

The transpiration of vegetation on a catchment is calculated in the model through the use of LAI (Leaf Area Index), which is derived from imagery provided by the LANDSAT satellite. While this imagery provides a historic record of catchment vegetation, LAI growth curves need to be developed for future scenarios. In this case the growth curves needed to reflect the silvicultural activities that would be taking place in the catchment model over the scenario period. The LAI growth curves used in the modelling are discussed in detail in Appendix 5.

Thinning treatments to LAI values of 0.4, 0.6, 0.8, and 1.0 have been modelled with a range of treatment frequencies to understand the management regime required to recover the groundwater system and streamflow (Croton *et al* 2012).

Rainfall scenarios

The what-if 31 Mile Brook model uses rainfall information to the end of 2010 to set the initial conditions, and future scenarios start from 1 January 2011 using defined 'drier' and 'wetter' rainfall sequences. The 'drier' sequence repeats the 2001 to 2010 rainfall record (annual average of 958 mm) five times, while the 'wetter' sequence repeats the rainfall record from 2000 to 2009 (annual average of 1026 mm) five times. The 'drier' sequence is considered to be the most likely rainfall scenario into the near future, and the 'wetter' sequence provides a level of sensitivity analysis to the results while still remaining a realistic scenario.

The justification for the 'drier' sequence being the most likely is based on the statement by CSIRO (2009) that "Rainfall is estimated to decrease by more than 10% by 2030 relative to the historic period..." where the historic period refers to the average of the period 1975-2007. The rainfall record for the 10 years 2001 to 2010 has been selected for the current modelling, as it is a close representation of these predictions to 2030. The 2001-2010 average (958 mm) recorded at the Gardens pluviometer (see Figure 1) used in the simulations is 11% less than the 1975-2007 average (1082 mm).

Modelling results

The initial scenario required for comparison is the no treatment scenario. In this case, the forest is 'frozen' at that measured by satellite imagery in 2010, and the 2001-2010 rainfall sequence is repeated to 2060. The depth to groundwater maps for the catchment through the decades is shown in Figure 9, and is a direct follow-on from the maps shown in Figure 8. These maps indicate that the continuation of the climate observed over the last decade will result in the contraction of the groundwater system to such a degree that groundwater will become completely disconnected from the streamzone. The resulting streamflows in this case are 40 mm/year in the decade to 2020, reducing to 28 mm/year by the decade beginning 2041 and this decadal flow continues to the end of the simulation period in 2060. This is compared with the average of 236 mm/year during the 1970s, and 74 mm/year in the period 2001-2010.

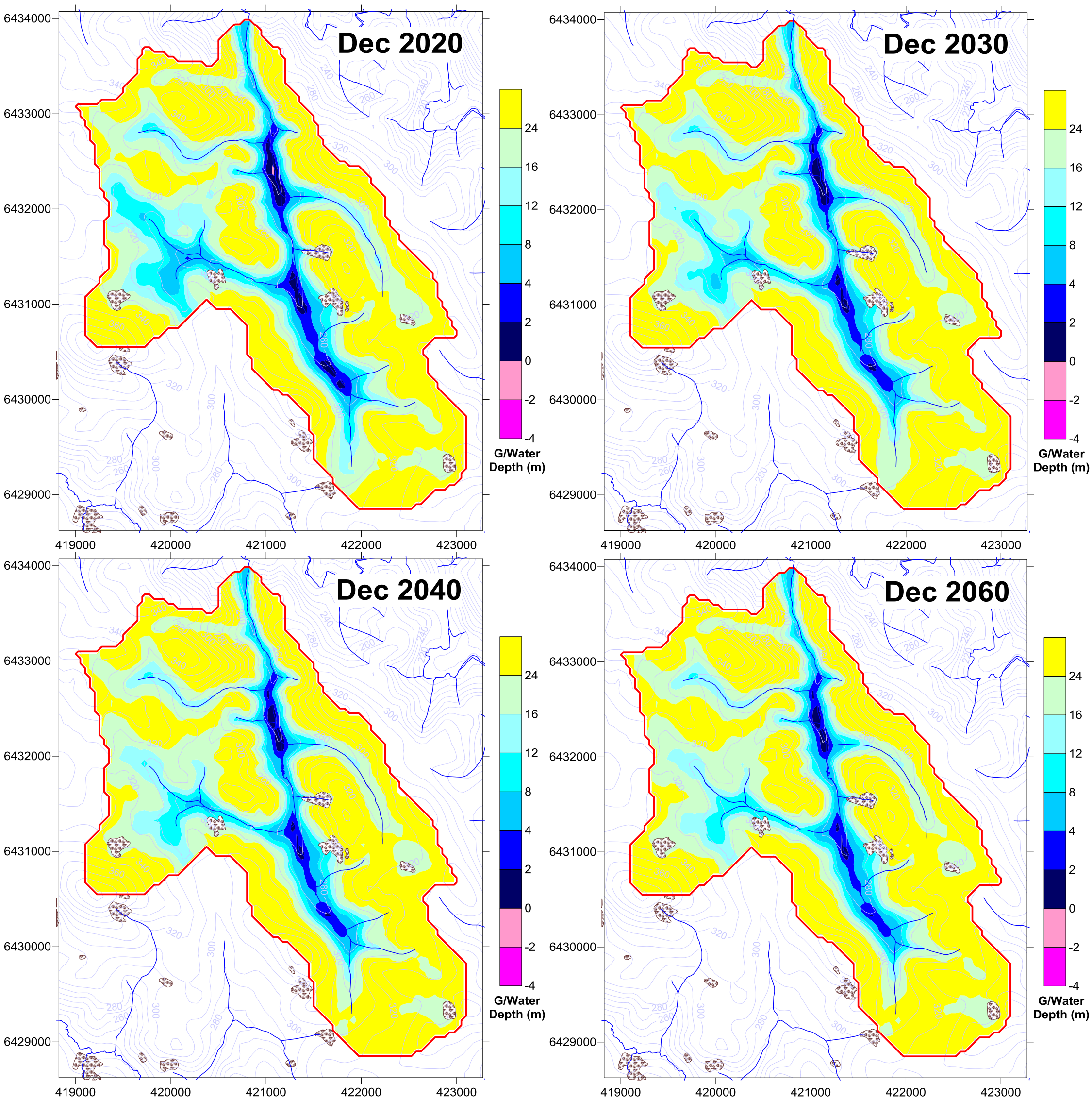

Figure 9 Simulated depth to groundwater catchment maps for the untreated future scenario.

Some 57 scenarios were modelled for the two rainfall scenarios and are detailed in Croton *et al* (2012); this wide range of scenarios was modelled in order to fully understand the variation in response due to treatment. From this range can be selected the level of intervention to meet a particular objective, for instance to recover groundwater levels (and therefore streamflows) to the levels observed during the 1990s.

Figure 10 shows the simulated soil-water storage where the forest, other than the stream reserves, is thinned to the various target LAIs with this treatment repeated every nine years; treatments include regular control of regrowth and coppice between overstorey treatments. The resulting recovery of streamflow, both volume and flow-days, are provided at Figures 11 and 12.

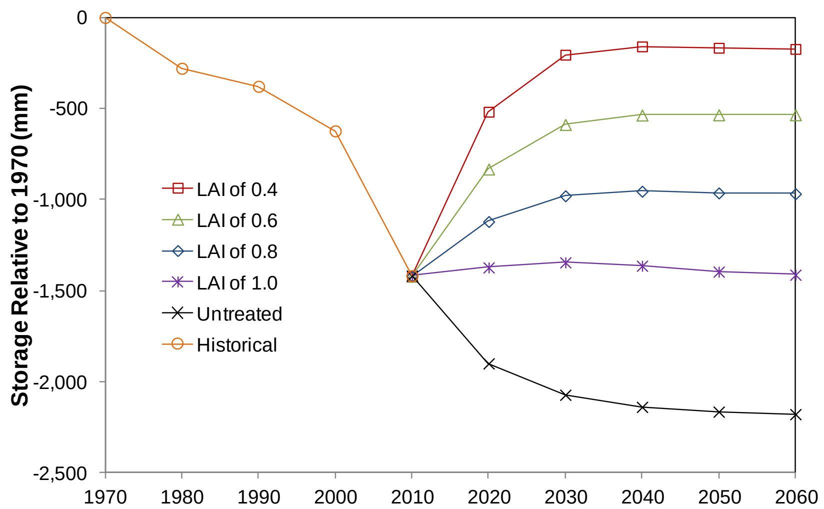

Figure 10 Soil-water storage difference relative to 1 January 1970 for the full-treatment cases to LAIs of 0.4, 0.6, 0.8 and 1.0 with retreatments every nine years for the rainfall scenario 2001 to 2010 repeated. Also included are simulated historical flows.

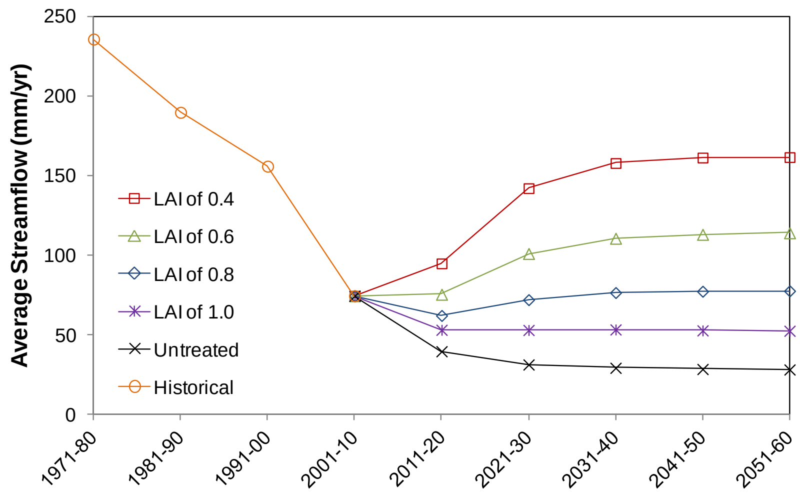

Figure 11 Decadal average streamflows for the full-treatment cases to LAIs of 0.4, 0.6, 0.8 and 1.0 with retreatments every nine years for the rainfall scenario 2001 to 2010 repeated. Also included are simulated historical flows.

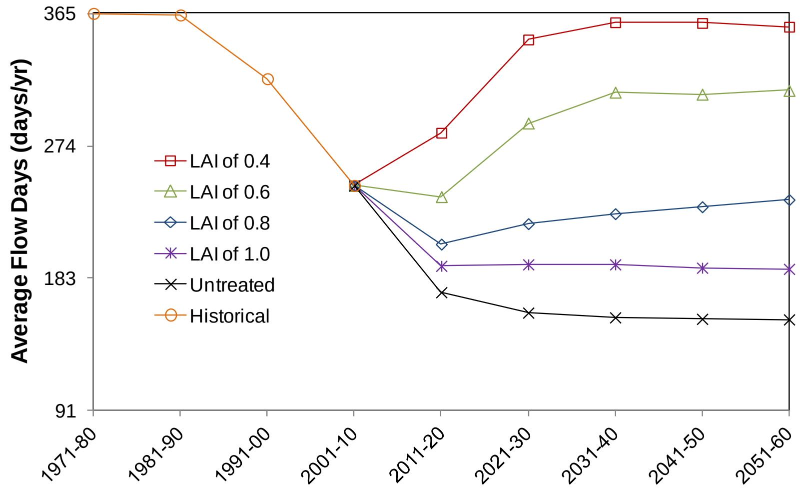

Figure 12 Decadal average flow-days for the full-treatment cases to LAIs of 0.4, 0.6, 0.8 and 1.0 with retreatments every nine years for the rainfall scenario 2001 to 2010 repeated. Also included are simulated historical flow-days.

This modelling indicates that under the 2001 to 2010 rainfall scenario, returning 31 Mile Brook to a perennial stream and to the flows of the 1990s would require thinning to an LAI of 0.4. However, Figure 10 indicates that treating to a more acceptable LAI of 0.6 recovers the soil-water store, and by implication the groundwater system, to that of about year 2000, with the stream flowing for the greater part of the year and with streamflow volume at about 70% of the 1990s. This level of intervention probably best satisfies the combined environmental needs of the stream, riparian and upslope forest fauna and flora.

For this selected scenario the forest has to be treated over the majority of the catchment area (all, excluding the streamzone reserve). The forest needs to be reduced to an LAI of 0.6 (between 8-10 m^2/ha basal area), and this treatment needs to be repeated every nine years and include regular control of regrowth and coppice between overstorey treatments. As an alternative future to that shown in Figure 9, the resulting depth to groundwater maps for the catchment as a result of this treatment are provided in Figure 13.

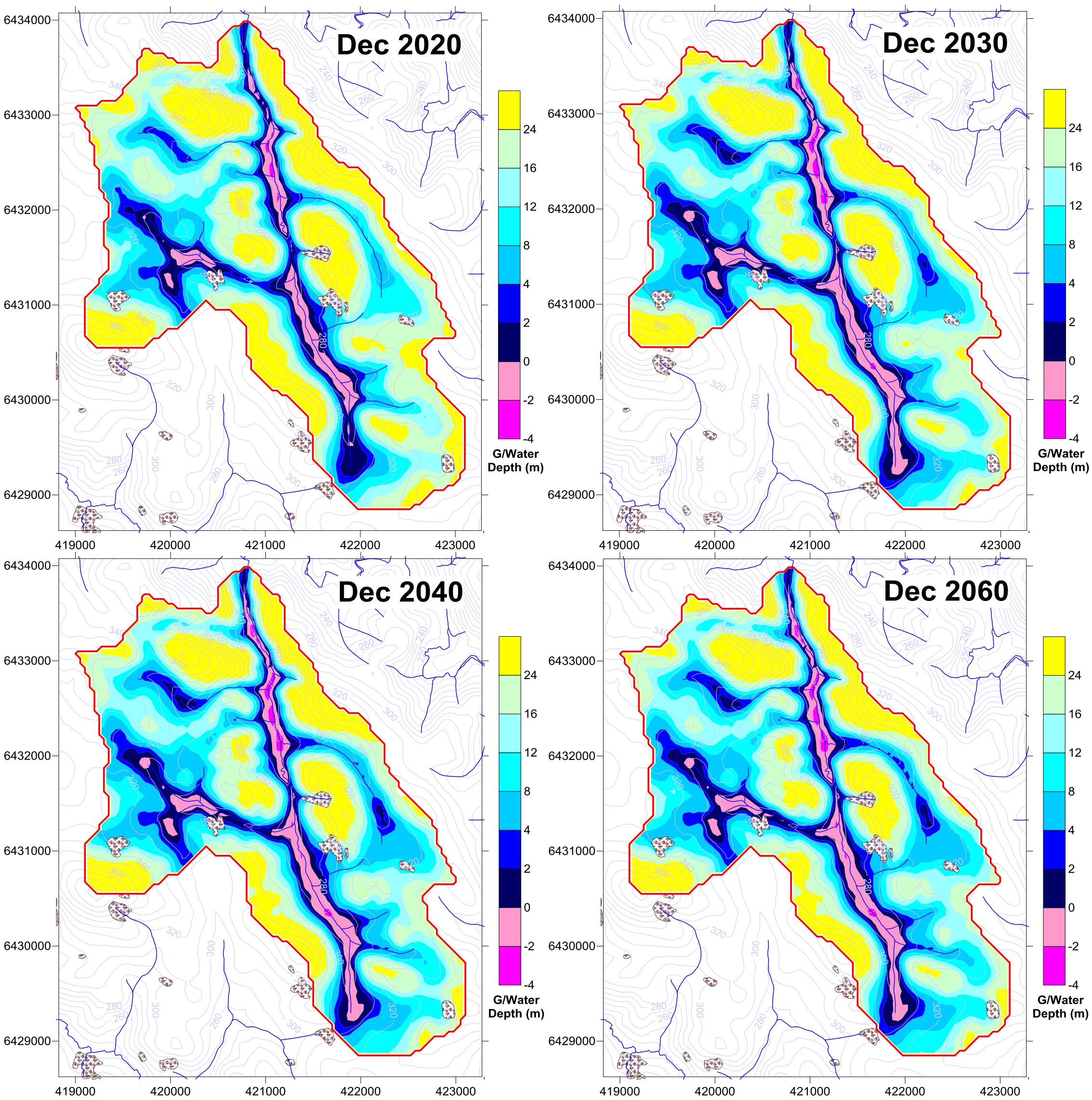

Figure 13 Simulated depth to groundwater maps for the proposed treatment scenario.

Under this scenario, which is also based on the 2001-2010 rainfall sequence, the contraction of the groundwater system in the early 2000s (2010 results in Figure 8) has been reversed by 2020. The latest modelling results (Croton *et al* 2012) indicate that the reconnection of the groundwater system results in streamflow increases over the untreated scenario of 36 mm/year in the first decade following treatment, and 70 mm/year over the second decade. Prior modelling resulted in slightly more conservative figures of 34 mm/year for the first decade and 69 mm/year for the second decade. These earlier values were used in the Wungong Catchment Trial Treatment Area 4 submission (Water Corporation 2012), and for consistency are used in later sections of this report. The minor differences are due to the latest simulations using slightly improved input information (LAI mapping).

Upscaling

Through the hydrological analysis associated with the Wungong Catchment Trial, 31 Mile Brook streamflow has been previously recognised as having a very good correlation with that of Vardi Road catchment; Vardi Rd is the main sub-catchment of the Wungong Reservoir catchment. This correlation is demonstrated in Figure 14.

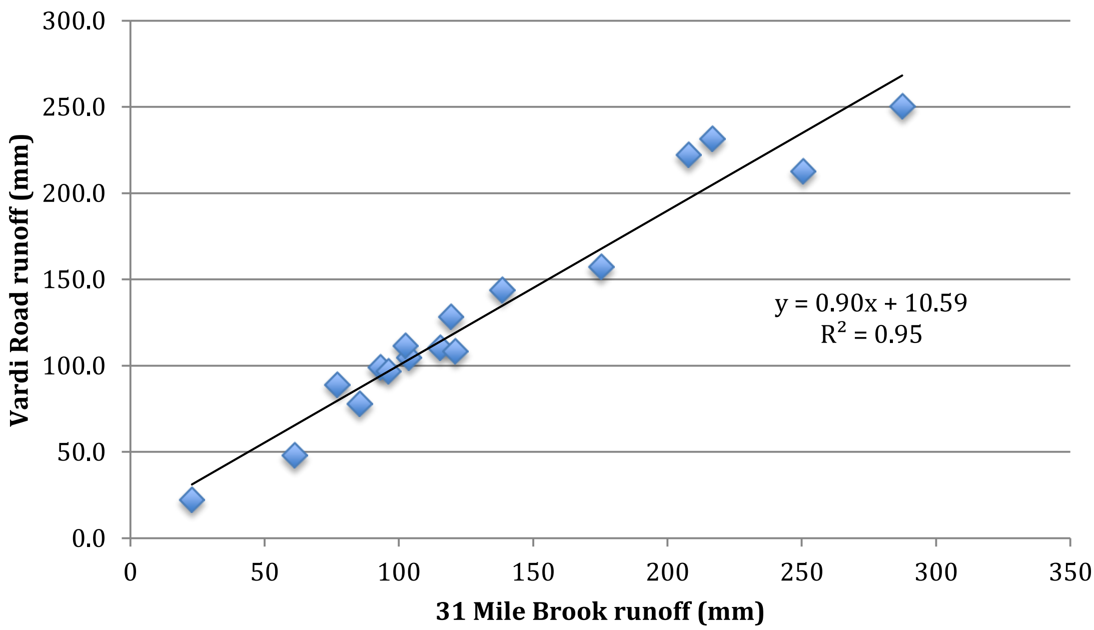

Figure 14 Correlation of Vardi Road annual flow to 31 Mile Brook. Annual figures are based on a 'water year', the 12 months from 1 April to 31 March.

Given this result, correlations of the major surface water catchments that make up the Integrated Water Supply System (IWSS) were undertaken. The IWSS is the system that supplies the Perth metropolitan area, some South West towns, the Goldfields, and towns and farms along the Goldfields pipeline with a combination of groundwater, desalinated seawater, and surface water from forested catchments located on the Darling Plateau.

The IWSS correlations used all available measured data and were completed for both the individual catchments and the total inflow to the supply catchments. The result of the correlation with the IWSS as a whole is shown in Figure 15. The correlations of the individual catchments were undertaken on both an annual basis (using a water year from 1 May to 30 April) and a monthly basis. All correlations resulted in R^2 (the coefficient of correlation[3]) similar to that shown in Figure 15, and are provided in Appendix 6.

[3] The coefficient of correlation is used in statistical models (such as that shown in Figures 14 and 15), to 'measure' how well one outcome (on the vertical axis, *y*) may be predicted by another (on the horizontal axis, *x*), and ranges in value from 0 to 1 – where 1 means that the outcome '*y*' is completely predicted by '*x*', and 0 means that '*y*' is not at all predicted by the events described by '*x*'.

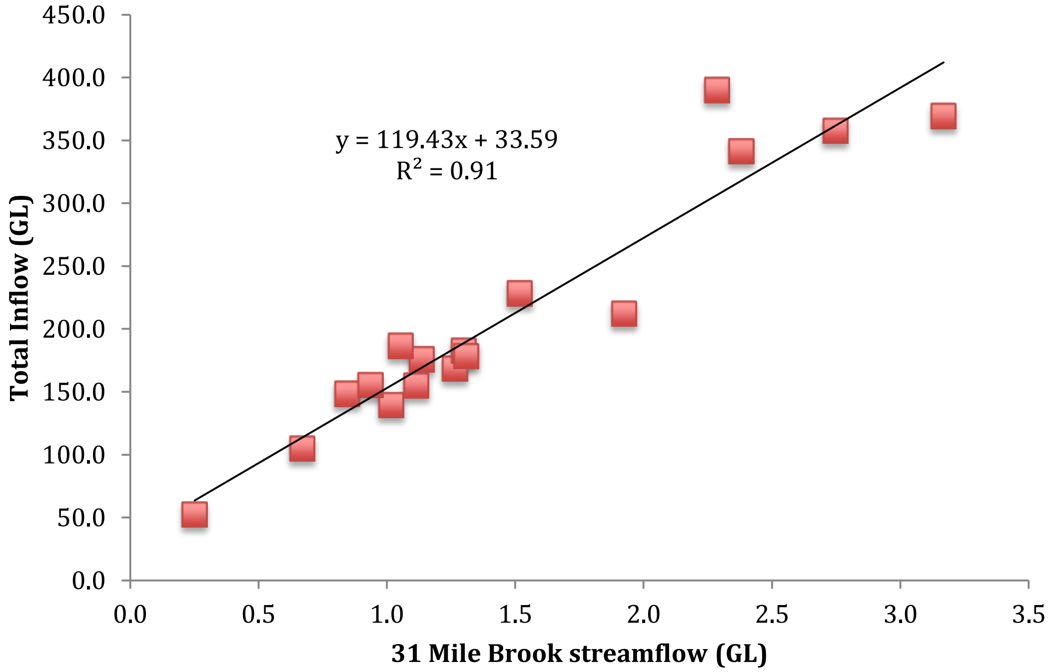

Figure 15 Correlation of IWSS total values to 31 Mile Brook. The annual figures are based on a water year from 1 May to 30 April.

These results lend confidence in the validity of using 31 Mile Brook as a surrogate for other catchments. However, upscaling the 31 Mile Brook results requires careful consideration as to where such results could be expected from similar silvicultural activities in other catchments. Initially these results should be confined to areas with similar or greater average rainfall and similar topography, as these areas are likely to have similar (or better) groundwater systems. This is the basis of the amended Wungong Catchment Trial (Water Corporation 2012). As more understanding is gained and more catchment models are developed for the areas of interest, our reliance on upscaling the results from 31 Mile Brook will reduce.

Potential treatment areas

The water supply catchments have many social, environmental, forest and water values. Historically the provision of water for the environment and domestic/irrigation supply was a priority land use.

The major surface water catchments for the IWSS are shown on Figure 16 together with the 1926-1979 average annual rainfall isohyets (Hayes and Garnaut 1981).

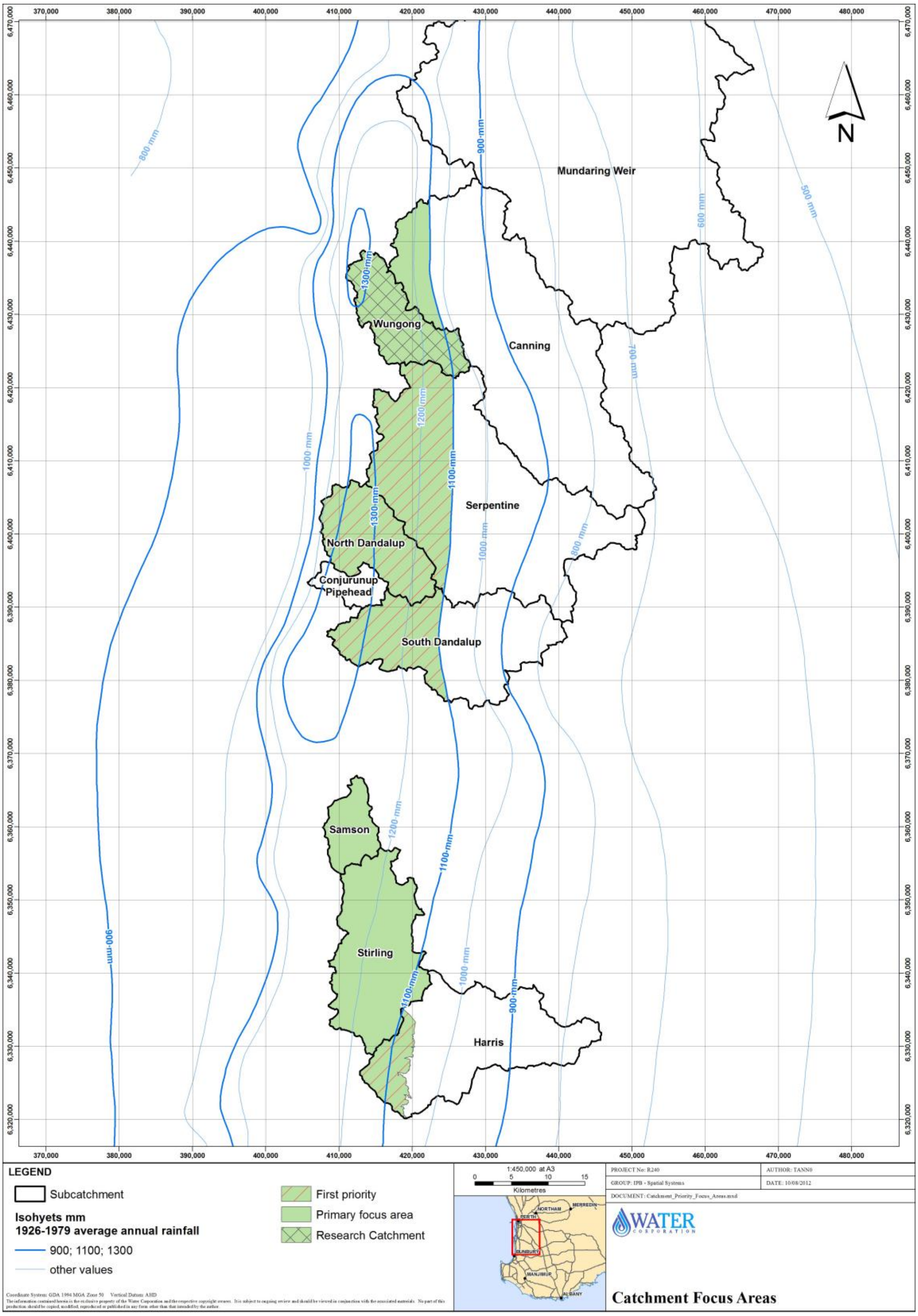

Figure 16 Major surface water catchments of the IWSS, 1926-1979 rainfall isohyets, and potential focus areas.

The ability to recover streamflow without risk to stream water quality guides the selection of the potential treatment area envelope (the primary focus area shown in Figure 16).

The controlling factor in stream salinisation potential is the quantity of accumulated salts in the soil profile. This has a strong inverse relationship to the average annual rainfall for the past century or more, so the 1926-1979 average annual isohyets are used as the indicator of salt risk (Stokes 1980). Rainfall zones defined by the 1926-1979 rainfall isohyets have been used since the 1980s to delineate areas with similar risk to stream water salinity if the forest is severely thinned or cleared. For hydrologic analysis and modelling the actual daily data from the network of rain gauges are used.

Streams in the high rainfall zone (greater than 1100 mm/annum) remain fresh whether their catchments are permanently cleared or are left forested. Those within the intermediate rainfall zone (900-1100 mm/annum) may become marginal or brackish upon being cleared, while those within the low rainfall zone (less than 900 mm/annum) usually become brackish or saline after clearing (Department of Environment and Conservation 1984). With the current lower rainfall regime, groundwater levels in the intermediate rainfall zone have fallen substantially so temporary clearing or moderate thinning is now unlikely to result in a measurable increase in stream salinity; it is also unlikely to result in temporary increases in streamflow volume (Croton *et al* 2011).

Considering this information, the potential treatment area envelope has concentrated on the high rainfall zone with only a few, small, specially selected areas in the higher rainfall section of the intermediate rainfall zone – such as the Cobiac area in Wungong catchment which straddles the high and intermediate rainfall zones but where drilling shows low soil salt storages, and the area in Harris catchment to the west of the reservoir with 1926-1979 rainfall above 1050 mm.

Mundaring catchment is in the intermediate and low rainfall zones and is too high a salinity risk to consider for treatment.

Conjurunup, a traditionally high yielding catchment, has not been included within the potential treatment envelope at this stage because a significant proportion of the catchment is mining rehabilitation which is yet to be handed back to the State for management. Treatment of this catchment would provide environmental and water supply benefits, so it should be added to the potential areas for treatment after it is handed back to be managed as State forest.

First priority would be assigned to the Serpentine, North Dandalup, South Dandalup and Wungong catchments as they provide water direct to Perth without requiring pumping, and to the Harris catchment due to the importance of this source to the Great Southern Towns Water Supply System (which provides water to Collie and the Upper Great Southern).

Theoretical streamflow recovery

The potential treatment envelope has an area of some 108 000 ha. After excluding all formal and informal reserves there are about 77 500 ha of State forest that could potentially be considered for treatment. Experience from the Wungong Catchment Trial indicates that after ground inspection and hydrological modelling of potential streamflow response, there would be variations to the area that is both available and suitable for treatment. Based on the Wungong Catchment Trial experience, it has been assumed that about 60% of the area within the envelope in each catchment could be treated to assess the runoff recovery potential.

Bauxite mining has and is occurring in many of the water supply catchments within the potential treatment envelope and rehabilitation of the mine pits has an impact on forest hydrology. It is desirable that bauxite mine rehabilitation does not adversely impact riparian vegetation and streamflows through additional reductions to groundwater (beyond what is already experienced through the drying climate), and attention to this topic is provided by the Mining and Management Program Liaison Group (MMPLG), which is chaired by the WA Department of State Development. For the analysis in this report it is assumed that the mine rehabilitated areas would be treated appropriately and provide the same yield recovery as treated native forest.

Table: Treated Areas and Water Yield greater than no treatment case

Catchment	Total Area (hectares)	Treatable Area (hectares)	Proportion of catchment (%)	Theoretical Additional Runoff (GL) (annual average)			
				One cycle of treatment		Ongoing Cycles of Treatment	
				1st ten years 34 mm	2nd ten years 34 mm	1st ten years 34 mm	2nd ten years* 69 mm
Wungong	13000	6900	53%	2.3	2.3	2.3	4.8
Serpentine	66400	14300	22%	4.9	4.9	4.9	9.9
North Dandalup	15300	9180	60%	3.1	3.1	3.1	6.3
South Dandalup	31100	7730	25%	2.6	2.6	2.6	5.3
Harris	32100	5000	16%	1.7	1.7	1.7	3.5
Canning	78900	4050	5%	1.4	1.4	1.4	2.8
Stirling	25100	14450	58%	4.9	4.9	4.9	10.0
Samson	6500	3900	60%	1.3	1.3	1.3	2.7
TOTAL	**268400**	**65510**	**24%**	**22.3**	**22.3**	**22.3**	**45.2**

* Also the average for the subsequent decades in perpetuity, assuming ongoing, periodic, treatment cycles.

The information provided in the table above is a theoretical estimate for planning purposes.

The additional runoff values are based on the results of the 31 Mile Brook modelling (Croton *et al* 2012) and would vary depending on future climate. These data indicate that treating 65 500 ha on a periodic basis could increase dam inflow by a total of 22 GL per year on average for the first ten years and possibly 45 GL per year on average thereafter, compared to the do nothing case. The treatment would involve thinning to 0.6 LAI every nine years, with regular management of the regrowth and coppice, until the groundwater store recovers to late 1990 levels. The frequency and level of periodic intervention required would then progressively reduce as the forest structure evolved to that of a larger tree forest. An appropriate burning regime would be important to exclude damaging wildfires, which have negative environmental and water quality outcomes.

The modelling indicates that if there was only one cycle of thinning to 0.6 LAI, with follow up control of regrowth and coppice, the theoretical increase over the do nothing case is estimated at 22 GL per year averaged over twenty years.

Catchment management planning

The future health of water-dependent aquatic ecosystems, riparian vegetation and associated fauna is dependent on the forest on the uplands sharing some of the water being received as rain. Sharing the available water by applying a silviculture prescription for ecosystem health and water would directly benefit these water-dependent environments. The forest on the uplands would also benefit from reduced drought stress (Batini 2011).

An important consideration for management of the forested water supply catchments is the integration of rehabilitated mine areas into any plans for treatment of catchments to improve groundwater systems and streamflow. Revegetation on rehabilitated mine areas is characterised by dense, young vegetation that has high water demand. There are some 10 000 ha of existing rehabilitation, with presently 760 ha added each year. Much of this rehabilitation is located within the higher water generating sections of water supply catchments and integration within a whole of catchment management framework would be desirable.

Integrated catchment management planning would include, as a first step, the collation of forest inventory data, forest condition and management history, and the location of high value environmental assets that are dependent on soil-moisture, groundwater, pond water and flowing streams.

Future scenarios could then be developed for the entire catchment or sub-catchments. Silvicultural prescriptions could be developed that are suited to the various current forest structures and desired outcomes. Modelling could then simulate the hydrologic processes using this mosaic of forest treatments and related growth predictions, and thereby predict the volume and duration of streamflow and generate maps of groundwater levels. In turn this would allow the yield recovery and environmental outcomes from the range of possible management regimes to be compared.

Conclusion

The Wungong Catchment Trial has been a catalyst for comprehensive gauged catchment rainfall and streamflow monitoring, research and hydrological processes modelling. As a result of this effort we now have a sound understanding of the hydrology of the northern jarrah forest under a drying climate.

Modelling has demonstrated the contraction of the groundwater systems of the catchments, and has indicated that under the expected continuing drying trend, groundwater will continue to decline to such a level that there is likely to be wide scale disconnection of the groundwater from the streamzone, resulting in ongoing streamflow declines. While the use of silviculture to reverse groundwater level decline has been recognised as a management method for many decades, the soil moisture store and groundwater levels have now reduced to such a degree that in order to effect a recovery, forest treatment needs to be more intensive than previously anticipated.

The treatment required to bring groundwater levels back to those of the 1990s, and therefore recover streamflows, is a regular reduction of the LAI of the forest available for treatment to 0.6, to be undertaken about every nine years. Ongoing control of regrowth and coppice is also required. While LAI reductions to 0.4, and/or more regular treatments would provide better groundwater recovery, a treatment to LAI of 0.6 every nine years is likely as intense a treatment as could be implemented in the field without significantly affecting other forest values. As this treatment has been developed via modelling with all the incumbent assumptions of possible future rainfall and vegetation response, any implementation, particularly with regards to timing of follow-up treatments, would need to be based on post-treatment LAI measurements and further modelling rather than as a prescription ‘set in stone’ at the outset.

Since there is variability in the hydrological response of catchments to forest management activities, hydrological processes-based modelling needs to be undertaken in the development of any comprehensive catchment management plans. These plans should include all at risk riparian ecosystems, water needs, and allow for appropriate forest management to be planned, modelled and approved prior to implementation.

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Appendix 1

Summary of gauged catchments associated with the Wungong Catchment Trial

Gauging station name	Station number	Catchment area (km2)	Historic rainfall* (mm)	Runoff** (mm)	Record period	Pluviometer station(s)
Wungong Brook Catchment						
Wungong Brook, Vardi Road	616041	80.84	1170	150	May 1981 -	509269 509273 509576
Wungong Brook, Cobiac	616058	3.64	1110		May 1992 – June 1998, May 2005 -	509576
Wungong Chandler Road	616124		1220		May 2005 -	509269
Seldom Seen Creek, Travellers Arms	616021	7.21	1250	236	May 1966 -	509269
More Seldom Seen Creek, Ceriani Farm	616022	3.41	1275	211	April 1966 -	509270
Waterfall Gully, Mount Curtis (control)	616023	8.62	1275	275	April 1966 -	509271
Correlation and Regional Context						
31 Mile Brook, 31 Mile Road	616026	10.96	1180	151	July 1985 - April 1999, April 2006 -	509610
39 Mile Brook Jack Rocks	614031	55.36	1120	101	May 1981 - April 1999, April 2006 -	509232 509324
North Dandalup North Rd	614036	79.74	1240	96	March 1983 - March 1999, May 2006 -	509189 509548 509349
Canning River Glen Eagle	616065	520.00	850	25	June 1950 - May 1999, May 2008 -	509273 509410
Canning River, Millars Road	616039	140.59	800	12	June 1985 - April 1999, May 2008 -	509422 509423
Big Brook O'Neil Rd	614037	148.99	1050	34	April 1983 -	509221
Serpentine River, River Road	614035	242.90	900	30	May 1982 - April 1999	509405 509322 509424
Harvey River, Dingo Road	613002	147.21	1250	238	March 1970 -	509119 509223 509224 509116 509117
Little Dandalup Trib, Bates,	614062	2.22	1300#		July 1988 -	509579
Wildfire Impact (January 2005 wildfire)						
Little Darkin, Hairpin Bend	616010	37.82	900	23	May1969 - May 1999, April 2005 -	509159 509155
Pickering Brook, Slavery Lane	616009	29.44	1050	63	May 1969 - May 1999, April 2005 -	509280 509631

* Historic catchment rainfall average taken from "Streamflow Records of WA to 1982" (Public Works Department 1984).
** Average annual runoff for 1983 to 1998 is provided for simple comparison of gauged catchments listed.

Additionally, the Serpentine River Road and Conjurunup 614122 stations are being operated as investigation sites to provide supplementary knowledge, and two additional stations were established before 2011 winter to monitor the TA4 area.

Monthly streamflow and rainfall data are available on the Department of Water website:
http://kumina.water.wa.gov.au/waterinformation/wrdata/wrdata.cfm

Appendix 2

The Chandler Road research catchment trial

Silvicultural operations

The trial area of about 1750 ha is located within Chandler forest Block at the south-western end of the Wungong catchment. The 1926-1979 average annual rainfall is 1220 mm (Hayes and Garnaut 1981) and the Mattiske-Havel vegetation complexes are mapped as: Dwellingup 1 and 2 (on slopes and ridges), Yarragil 2 (in broad valleys) and Swamp (Water Corporation 2005).

Area statements have been derived from remotely sensed imagery collected by Spec Terra Services at a resolution of 0.5 m, four pixels per square metre. These data were collected for 100 separate “blocks”, 56 for native forest, 28 for rehabilitated areas and 16 in the untreated stream and fauna habitat reserves.

A considerable area (445 ha or 25%) of the Chandler research catchment has been mined and rehabilitated by Alcoa World Alumina, primarily with exotic eucalypt species. The hydrology of the pits has changed markedly as all pits were deep-ripped prior to planting and are also internally draining, with large sumps to prevent over-flow.

A very large area (552 ha or 31%) was then selected by the Department of Environment and Conservation (DEC) as either steam reserves or fauna habitat zone. There was minimal consultation with Water Corporation on the location of such a large area on all the lower slopes of this research catchment.

In Spring 2006 the catchment was prescribed burnt to remove excess fuel in advance of thinning. Then, in early 2007, areas of native forest and bauxite rehabilitation were tree-marked by wages staff of the DEC in accordance with tree-marking guidelines 1, 2 and 3 approved for the Wungong Catchment Trial. Trees were retained as either “habitat trees” or as “growing stock”. All other trees that were not marked for retention were then notched by staff from the DEC.

During summer 2009 about 22 ha of exotic plantation were clear-felled by contractors to the Forest Products Commission (FPC) and a further 6ha were thinned to a basal area of 8 m^2/ha. The products were sold to WAPRES at Bunbury as “mixed chip”. Forest Products also commercially logged 95 ha of native forest within the catchment and south of Jarrahdale road in 2009.

Of the total of 1750 ha, 968 ha or 55% were commercially logged or notched. This was comprised of 530 ha of native forest notched by DEC, 315 ha of rehabilitated pits notched by DEC and a further 123 ha logged by FPC. The remaining 778 ha (45%) were left untreated as either stream reserve, fauna habitat zone, rehabilitated areas that were too young to thin or for other reasons. Data were then collected on basal area density, crown cover and an index of leaf area.

Results

Monitoring data provided by DEC show that the original basal area prior to notching treatment was 26 m^2/ha, that the retained basal area averaged 16 m^2/ha (a reduction of 38%) and that the target range of 13-19 m^2/ha was achieved on all nine sample sites. More supervision is required to minimise the number of cull trees (on average 2 m^2/ha) that were “missed” by notching crews. Notching success averaged 90% and the level of herbicide damage to retained trees (flash-back) was negligible.

Crown cover estimates obtained between 2005 and 2009 from remotely sensed imagery show that the average canopy cover in forest before treatment was 63% and after treatment 50%, a reduction of 21% (Figure A1). Crown cover for untreated areas ranged between 65 and 69%.

Stream reserves were slightly more open, within a narrow range, from 56 to 60%. Since only 55% of the catchment was treated by logging or notching, the overall reduction in crown cover for the whole catchment is only 11.5%.

Estimates of Leaf Area Index (LAI) were also obtained by the Water Corporation from data supplied by consultant G Mauger (Geographic Information Analysis). Parts of the stream reserve and some of the untreated areas still have LAI's that exceed 2. Treated areas have a much lower LAI, all are below 1.6 and many areas are below an LAI of 1. Mauger has also supplied average LAI values for January data for all of the Chandler catchment during the period 2004-2011. These LAI values average 1.72 (three years, pre-treatment) and 1.45 (five years, post-treatment), an overall reduction of 15.5%.

Tree health
The 2010 winter rainfall was the lowest ever recorded in Perth and the forest areas. This was followed by a long, dry, hot summer. By March 2011, major collapse of vegetation was obvious, particularly in the higher-rainfall, western jarrah forest, and deaths then continued until June/July. Deaths occurred on all tenures – State forest, National Park and Conservation Park.

Deaths were observed in all major upland species – jarrah, marri, allocasuarina and banksia. A number of the dead trees were large, exceeding 90cm dbhob and therefore probably over 200 years old. Most sites were associated with shallow soils, but deaths were also observed on good-quality jarrah sites, as well as on water-gaining sites where some bullich and blackbutt had died. The understorey species on most sites were healthy.

The low winter rainfall followed by a dry summer, the pattern of deaths and recovery in the overstorey, the healthy understorey and the timing of the collapse all point to drought stress as the primary driver.

Within the Chandler Road trial area, some tree deaths were observed within native forest on good deep soils, on soil shallow to rock and in water-gaining sites. None of these sites had been thinned and this was confirmed by field survey. Unsurprisingly, the tree crowns in the thinned areas were denser and healthier, with no recent drought deaths observed.

Summary
Too small a percentage of the catchment was treated – 55%.
On the treated areas, the reduction in crown cover was too low – 21%.
A very large part of the catchment has pits that are now internally draining – 25%.
The overall reduction in transpiration of 11.5-15.5%, was too low to impact streamflow.
Areas that had been thinned were healthier, with fewer deaths in summer 2011.

F E Batini

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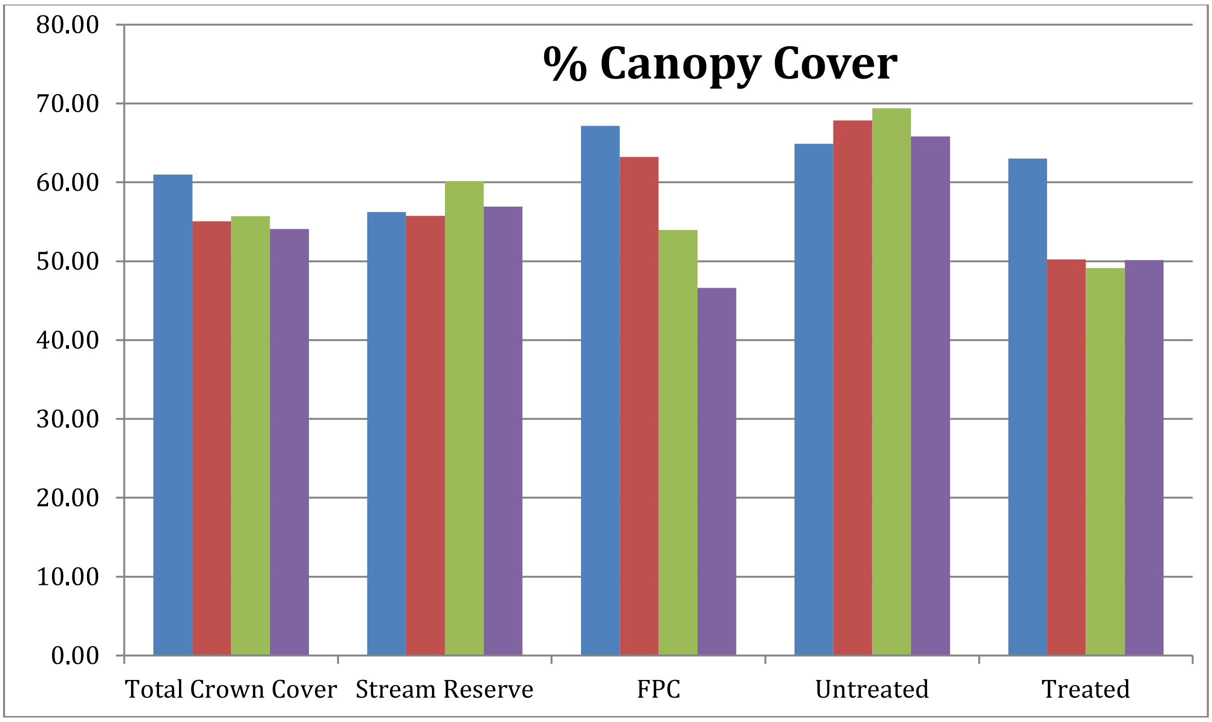

Figure A1
Canopy cover estimates for Chandler Road catchment taken in November, for the years 2005, 2008, 2009 and 2010 (Spec Terra Services Pty Ltd).

Appendix 3

The Cobiac research catchment trial

Silvicultural operations

The trial area of about 360 ha is located within Cobiac forest Block at the south-eastern end of the Wungong catchment. The 1926-1979 average annual rainfall is 1190 mm (Hayes and Garnaut 1981) and the Mattiske-Havel vegetation complexes are mapped as: Dwellingup 2 (on slopes and ridges), Yarragil 2 (in broad valleys) and Swamp (Water Corporation 2005).

In early 2008, a 240 ha area was tree-marked for felling by Forest Products Commission (FPC) staff to either a thinning or a shelterwood prescription, in accordance with tree-marking guidelines approved in the Forest Management Plan 2004-2013. Trees were retained as either "habitat trees" or as "growing stock". Following the commercial operation, all other trees that were not marked for retention were then notched in autumn by contractors from Western Forest Management, supervised by staff from the Department of Environment and Conservation (DEC). Non-commercial notching was required, as the smaller-sized logs could not be sold due to current Policies relating to use of native timber for bio-energy.

The designated stream reserve was left un-thinned, as was a "control" strip 200 m in width from stream zone to ridge top for experimental purposes, as well as three small areas totalling 15 ha that had been mined for bauxite by Alcoa World Alumina and then rehabilitated. The areas not treated totalled 120 ha or one-third the area of the catchment. Data were then collected on basal area density, stems per hectare, diameter class distribution, crown cover and an index of leaf area, both before and after these operations.

Results

About one-third of the catchment on lower slopes is protected as stream reserves or has been affected by Phytophthora disease. These more open areas were left untreated and have an average basal area of 11 m^2.

The data show that the basal area in treated sites was reduced from 34 to 18 m^2/ha, a reduction of 47%. Of this 16 m^2, only 6 m^2 were removed commercially with the balance being notched. Of the retained basal area, 7 m^2 were classified as "habitat trees", 6.5 m^2 as "future growing stock" and 4.5 m^2 as "culls/notching misses". The number of stems per hectare (sph) were reduced by two-thirds, from about 410 to 140 sph. As notching targeted the smaller size classes (87% of notched stems were less than 30 cm dbhob), the average size of the retained trees increased after silvicultural treatment.

Larger trees have less sapwood area for a given basal area and therefore transpire less than an equivalent basal area of smaller trees. Estimates of sapwood area were made using the diameter class distributions before and after thinning using a spreadsheet and sapwood data provided by Dr C Macfarlane of CSIRO. The calculated estimate of sapwood area before thinning was 2.9 m^2/ha and after thinning as 1.3, a difference of 1.6, or 55%.

Crown cover estimates were obtained from remotely sensed imagery collected by Spec Terra Services at a resolution of 0.5 m, that is four pixels per square metre. These data were collected for 13 separate "blocks", nine for native forest, three for rehabilitated areas and the stream zone. These show that the average canopy cover for native forest before treatment was 50% (range 48-52%), the cover for rehabilitated areas was 44% and that the streamzone was more open at 33%. Following treatment, native forest cover in November 2008 averaged 27% (range 21-40%), a reduction of about 46% (Figure A2).

Data for canopy area and percentage cover are also available for November 2009 (following an average winter rainfall) and for November 2010, which followed the driest winter ever recorded Figure A3). The pattern of growth varied markedly between the untreated and treated areas. In both the stream zone and the bauxite rehabilitation the crown cover increased substantially from 2005 to 2009, by nine and fourteen percent respectively; but then fell after the poor 2010 winter, both by seven percent. Tree deaths and loss of crown were visible on both sites by late summer 2011.

In contrast, the thinned areas took some time to recover, with the 2008 and 2009 data being similar at 27%. Crowns then expanded by nine percent between November 2009 and 2010. This is probably in response to the 2009 winter rainfall, since jarrah crown growth usually occurs in late spring-early summer, between November 2009 and January 2010. Tree crowns were still healthy and no deaths were observed by late summer 2011.

The estimated reduction in basal area (47%), sapwood area (55%), stems per hectare (66%) and crown cover (46%) make sense. As the smaller trees were targeted for thinning, it is expected that tree numbers and sapwood area would decrease more than basal area or crown cover. However, these reductions apply to only 220 ha of this 340 ha catchment. Thus the overall reduction in potential transpiration for the whole catchment, as estimated from sapwood area or crown cover, lies between 30 and 37%, not 46 to 55%.

Estimates of Leaf Area Index (LAI) were obtained by the Water Corporation from data supplied by consultant G Mauger (Geographic Information Analysis). These data show that LAI values in adjacent untreated areas can range from 2 to 2.5 whereas in treated areas the range was from 0.4 to 1.4 with an average of 0.8 (Figure A4). Mauger has also supplied average LAI values for January data in the Cobiac catchment for the period 2004-2011. These LAI values average 1.50 (four years, pre treatment) and 0.95 (four years, post treatment), a reduction of 37%.

Tree health

The 2010 winter rainfall was the lowest ever recorded in Perth and the forest areas. This was followed by a long, dry, hot summer. By March 2011, major collapse of vegetation was obvious, particularly in the higher-rainfall, western jarrah forest, and deaths then continued until June/July. Deaths occurred on all tenures – State forest, National Park and Conservation Park.

Deaths were observed in all major upland species – jarrah, marri, allocasuarina and banksia. A number of the dead trees were large, exceeding 90 cm dbhob and therefore probably over 200 years old. Most sites were associated with shallow soils, but deaths were also observed on good-quality jarrah sites, as well as on water-gaining sites where some bullich and blackbutt had died. The understorey species on most sites were healthy.

The low winter rainfall followed by a dry summer, the pattern of deaths and recovery in the overstorey, the healthy understorey and the timing of the collapse all point to drought stress as the primary driver.

Within the Cobiac trial area, loss of crown and tree deaths were observed in the bauxite rehabilitated areas, the stream reserve and the un-thinned strip, where about half the crowns were thin and unhealthy (Figure A5). These were confirmed by field survey. Unsurprisingly, the tree crowns in the thinned areas were denser and healthier, with no recent drought deaths observed.

Summary
Two-thirds of the catchment was treated.
On the treated areas, the reduction in crown cover was measured as 46%.
A very small part of the catchment (four percent) has pits that are now internally draining.
The overall reduction in transpiration of 30-37% raised the groundwater tables and increased streamflow.
Areas that had been thinned were healthier, with fewer deaths in summer 2011.

F E Batini

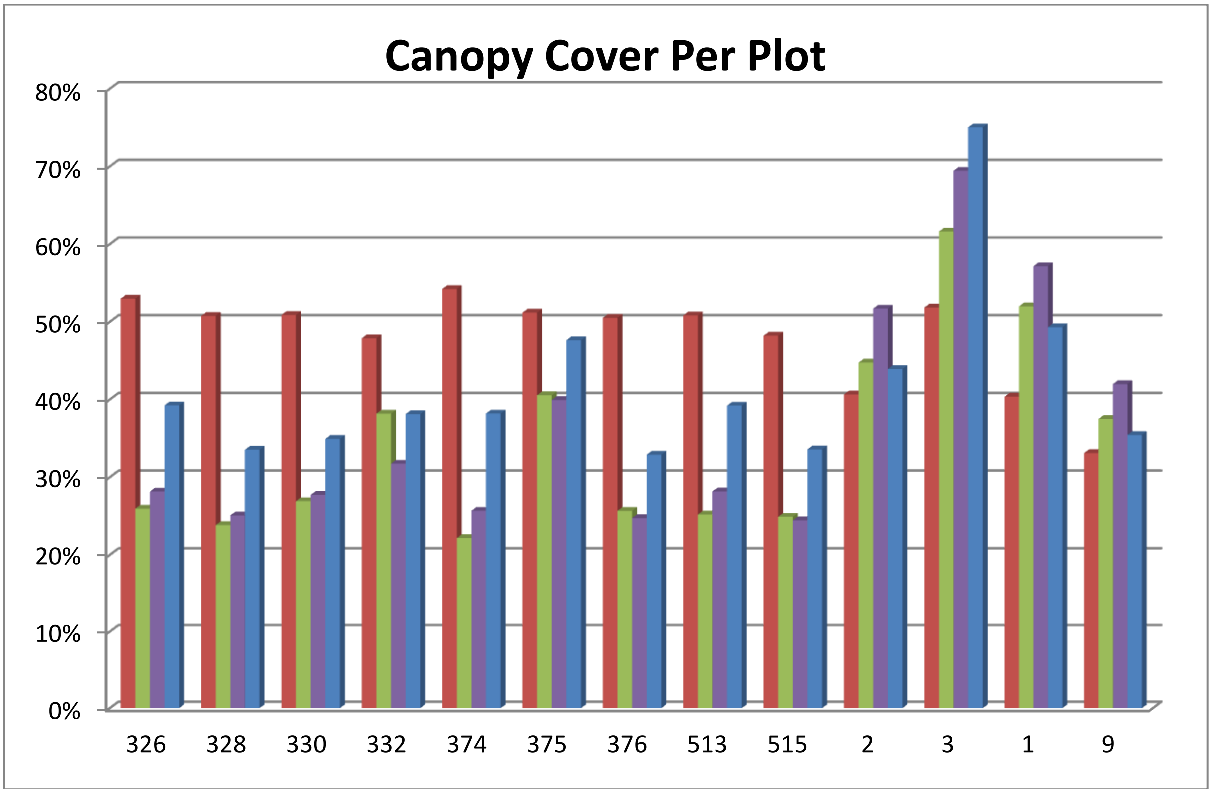

Figure A2
Canopy cover estimates (percent) for Cobiac taken in November, for years 2005, 2008, 2009 and 2010 (Spec Terra Services Pty Ltd).

Identifiers are as follows;	9	Stream reserve
	1, 2 and 3	Rehabilitated bauxite pits
	All others	Areas treated by thinning

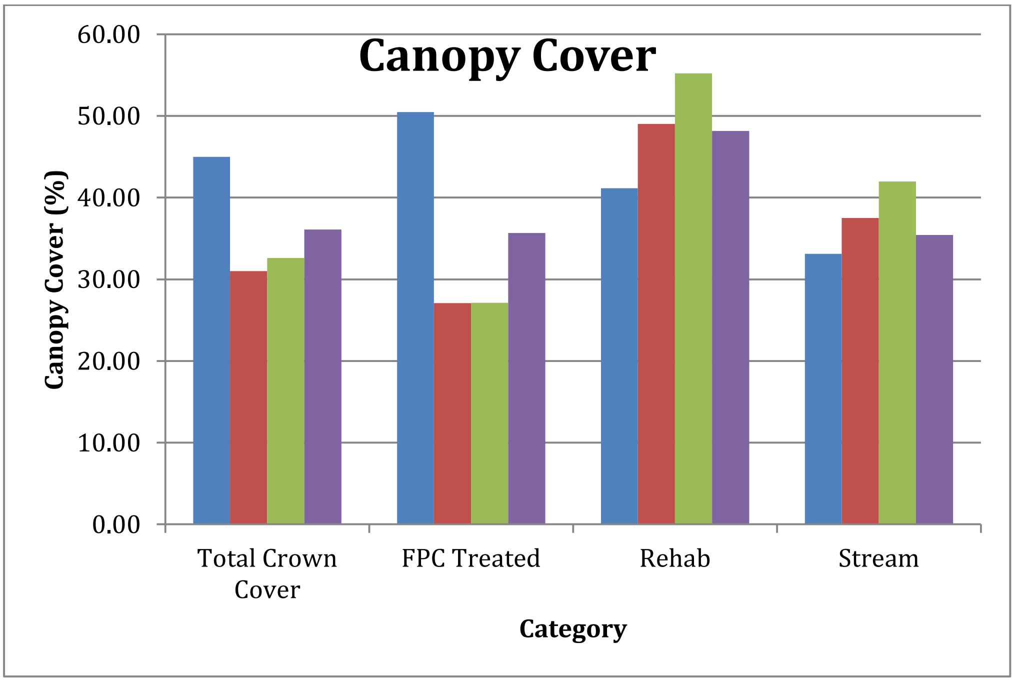

Figure A3
Canopy cover estimates for Cobiac catchment taken in November, for the years 2005, 2008, 2009 and 2010 (Spec Terra Services Pty Ltd).

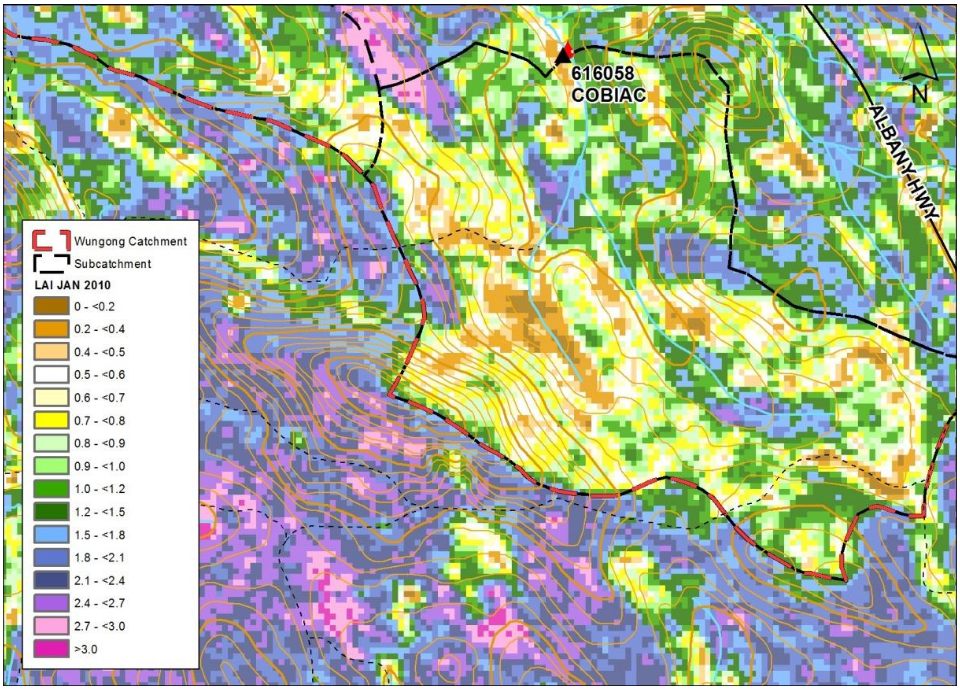

Figure A4
Estimates of leaf Area Index (LAI) in January 2010.
Thinned areas have low LAI, mostly <1.0, whereas un-thinned areas have LAI that exceed 2.0

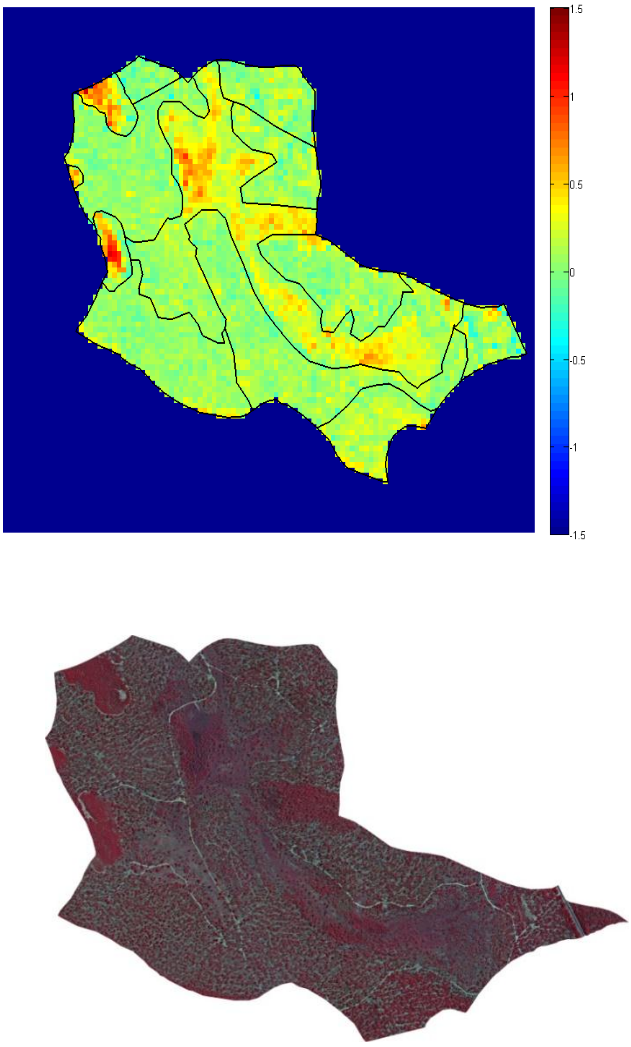

Figure A5
Top: Estimates of changes in Leaf Area Index(LAI), January 2010 to March 2011
(red and yellow = decline; green and blue = improvement) provided by Dr C Macfarlane, CSIRO

Bottom: canopy density post thinning, false colour image, provided by Spec Terra remote sensing services.

Note: the denser areas were not thinned and show a greater decline in LAI.

Appendix 4

WEC-C: A fully distributed, deterministic catchment model

The Water & Environmental Consultants - Catchment (WEC-C) model is a distributed, deterministic model of numerical form, simulating both water and solute movement within a catchment by solving the governing equations for flow and transport. WEC-C employs a rectangular grid of uniform cell size in the lateral plane combined with a system of soil layers in the vertical, to represent the soil profile of a catchment (see Figure A6). The WEC-C model uses operator splitting to link the vertical and lateral models and move water and solutes around this model domain. The explicit form of WEC-C allows a direct linkage between the vertical and lateral models and creates a highly efficient model which can be used to study detailed hydrological processes such as groundwater levels and discharge areas within the catchment as well as streamflow outputs, both volume and solutes.

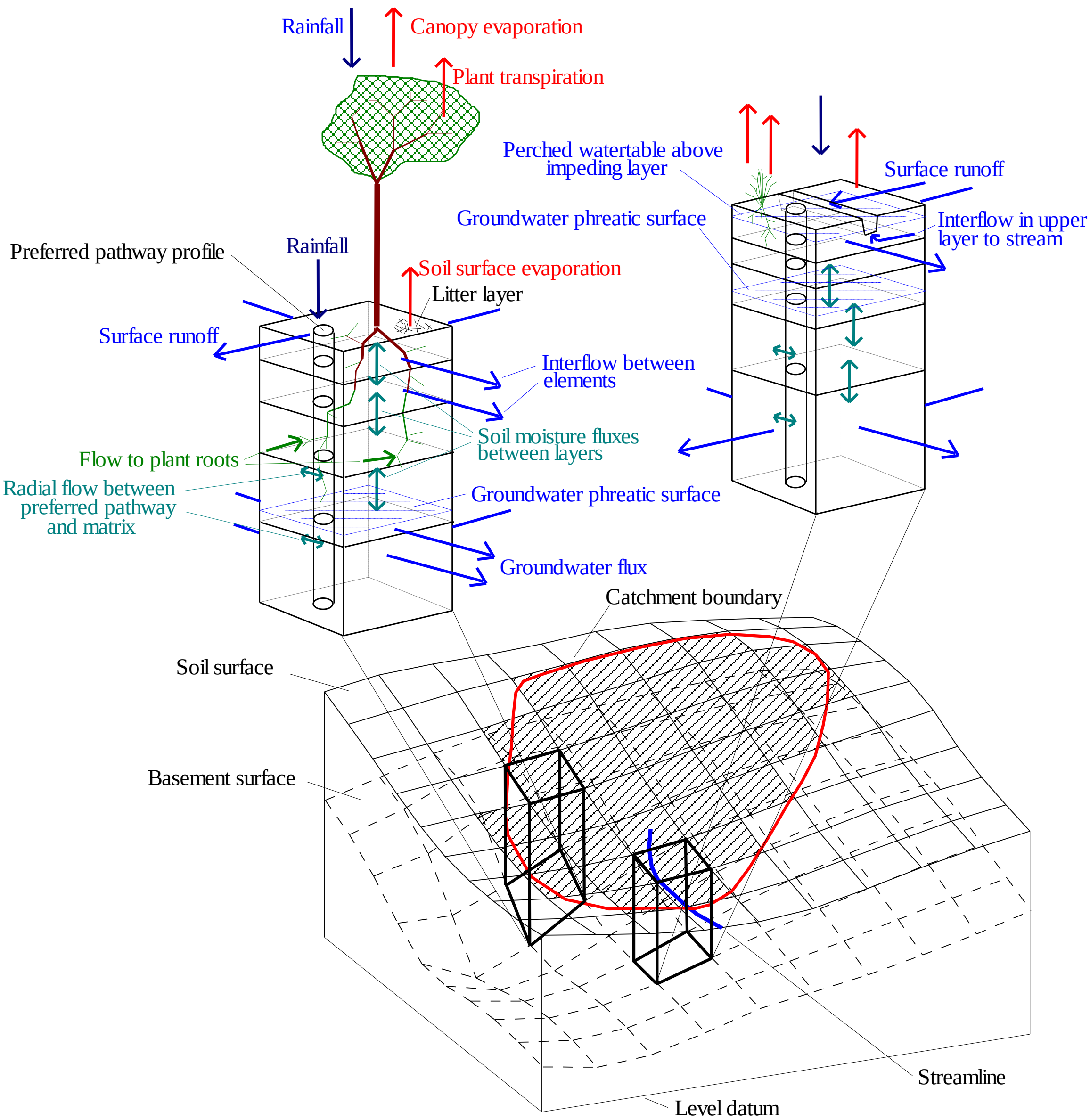

Figure A6 Schematic of model layout and processes modelled.

The WEC-C model is complete in that it simulates sub-surface lateral flows by an explicit finite-difference model in each soil layer, has vertical fluxes between layers by a dual-continua moisture-model; and incorporates all the other hydrological processes of stream channel and overland flow, rainfall interception by the vegetation canopy, evaporation from the soil surface, plant transpiration and flow to roots, etc. (see Figure). A component found to be particularly important for the south-west of Western Australia is the dual-continua model within WEC-C, which is a system of preferred pathways of high permeability within a soil matrix of lesser permeability. Preferred pathways are the reason why soil salt-storages have developed in south-west soils, and any modelling without them simply fails to include the correct hydrological processes.

An essential component of distributed modelling is the efficient management of spatial input and output data. For most mapping tasks the WEC-C model employs the CATMAGIC system, developed by Geoff Mauger formerly of the Water & Rivers Commission of WA, as its model GIS. CATMAGIC (www.catmagic.com.au) is a stand-alone system which has been specifically developed for the management, analysis and visualisation of hydrological data on a rectangular grid. It can easily exchange data with packages such as SURFER and ArcGIS. The net result is effective data-management using systems which are independent of WEC-C and supported by others. This allows WEC-C model applications to be pursued without concern for the support of the data-management software.

While the WEC-C model has been in its present form since the late 1990s, an important component of WEC-C proposed for development is the incorporation of parallel-processing. To date, virtually all hydrology models have been developed as a single-thread model: a computer undertakes the model calculations one after the other in a linear sequence. In parallel processing this linear form is replaced with one where calculations for different parts of the model domain are concurrent, thereby greatly reducing the time taken to run a model. While the concept of parallel-processing is straightforward and has existed for decades at the level of Cray computers used in high-level research, its incorporation into every-day hydrological modelling has had to wait for the development of suitable software compilers and multi-core CPUs and CUDA processing on GPUs. The explicit form of WEC-C is particularly suited to conversion to a parallel-processing model; once developed, a parallelised version of WEC-C should remove all limitations of catchment size. A present development target is the construction of a workable parallelised WEC-C model for the Serpentine Reservoir catchment by the end of 2012.

The WEC-C model is customised for the simulation of vegetation-cover dynamics and includes all the components of evapo-transpiration (ET) as well as an efficient methodology through CATMAGIC for the input of various vegetation treatment-scenario maps. A detailed understanding and quantification of WEC-C parameters, particularly for vegetation, has been developed through the model's application to a wide variety of catchments in the south-west of WA. Without such a history of application it would be difficult to undertake what-if simulations where the vegetation cover is being significantly altered. As well, the hydrology of the forested catchments of the south-west of WA is undergoing continuous change due to the present below-average rainfalls causing steady depletion of the soil-water storage. This hydrological non-stationarity means that the hydrological processes that were in operation during the historical monitoring of these catchments differ from those that will be in operation in the future, and so for predictive modelling to be realistic and successful this non-stationarity must be included in the model-verification process. Employing the standard methodology of dividing the past record into calibration and verification periods will thus add little to the proof of a model as a reliable predictor for future what-if scenarios. Instead, the approach adopted in the parameterisation of WEC-C where a generic WEC-C parameter set has been developed by the application of the model to a wide variety of catchments appears to be the only scientifically acceptable approach in the present situation.

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Appendix 5

Post-thinning LAI

Previous thinning trials in the jarrah forest show that initial streamflow response can be negated within a few years due to a rapid increase in LAI after thinning. Much of this increase is due to the development of regrowth and coppice and to a lesser degree due to increased leaf density on the retained trees. Coppice and regrowth control is therefore the critical means by which thinning response can be extended. LAI input to the water yield model is based on a separate prediction of LAI increase over time for the retained trees and for coppice and regrowth. Since this has not been measured directly in previous trials these predictions are based on information from several sources.

The initial basal area/LAI relationship (LAI = 0.0442 BAOB + 0.125) is based on pre-thinning data from mixed aged forest in 31 Mile Brook. Pre-thinning basal area of 10 m^2/ha is equivalent to an LAI of 0.57.

Following thinning the basal area is assumed to increase at the rate of 0.3 m^2/ha/annum (Stoneman *et al* 1989).

For the first two years after thinning the LAI of the retained trees is increased at the rate of 0.179 to account for the rapid increase in crown density following thinning and is based on the thinning response from earlier heavily thinned trial areas (Ritson & Bari 1997).

The annual increase in LAI of the retained trees from that point onwards is based on a linear trajectory to a maximum LAI of 1.6 at 30 years (an increase of 0.0125/annum). This is based on the maximum LAI that was reached in the Inglehope thinning plots 30 years after thinning. This is a higher ratio of LAI to basal area than the pre-thinning condition (Stoneman *et al* 1996).

The LAI increase of regrowth and coppice is extremely variable under normal conditions. The thinning program proposed assumes that the LAI of the regrowth and coppice will be controlled so that it contributes an average of 0.05 to the stand LAI during the post-thinning period. This is based on the assumption that the regrowth and coppice will be allowed to increase to an LAI of 0.1, then reducing it to zero; repeating the process as necessary. Because of the variability of development the timing of treatment varies from stand to stand but is represented as a constant 0.05 LAI for this purpose.

Under this projected increase in LAI, the post thinning LAI will average 1.0 at about age 10 when the basal area is expected to be 13 m^2/ha and the LAI is 1.2.

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Appendix 6

R^2 values from correlations of the annual and monthly inflows from IWSS catchments with 31 Mile Brook

Catchment	Annual R^2 value	Monthly R^2 value
Bickley	0.76	0.78
Canning	0.85	0.88
Churchman	0.92	0.88
Conjurunup	0.76	0.84
North Dandalup	0.80	0.83
South Dandalup	0.74	0.79
Serpentine	0.84	0.86
Serpentine Pipe Head	0.84	0.86
Victoria	0.80	0.82
Wungong	0.93	0.92
Helena	0.77*	0.62**
Lower Helena	0.76	0.81
Stirling	0.88	0.84
Samson	0.87	0.79

* Annual correlation for Helena (also known as the Mundaring catchment) excluding the values for the year 1996, when extensive summer rainfall occurred in the Mundaring catchment, but no other water supply catchments. Including 1996 into the calculation reduces the R^2 to 0.48.

** Monthly correlation for Helena, including the monthly values for 1996.