Northern Jarrah Forest Water-Balance Study to Inform the Review of Silviculture Guidelines

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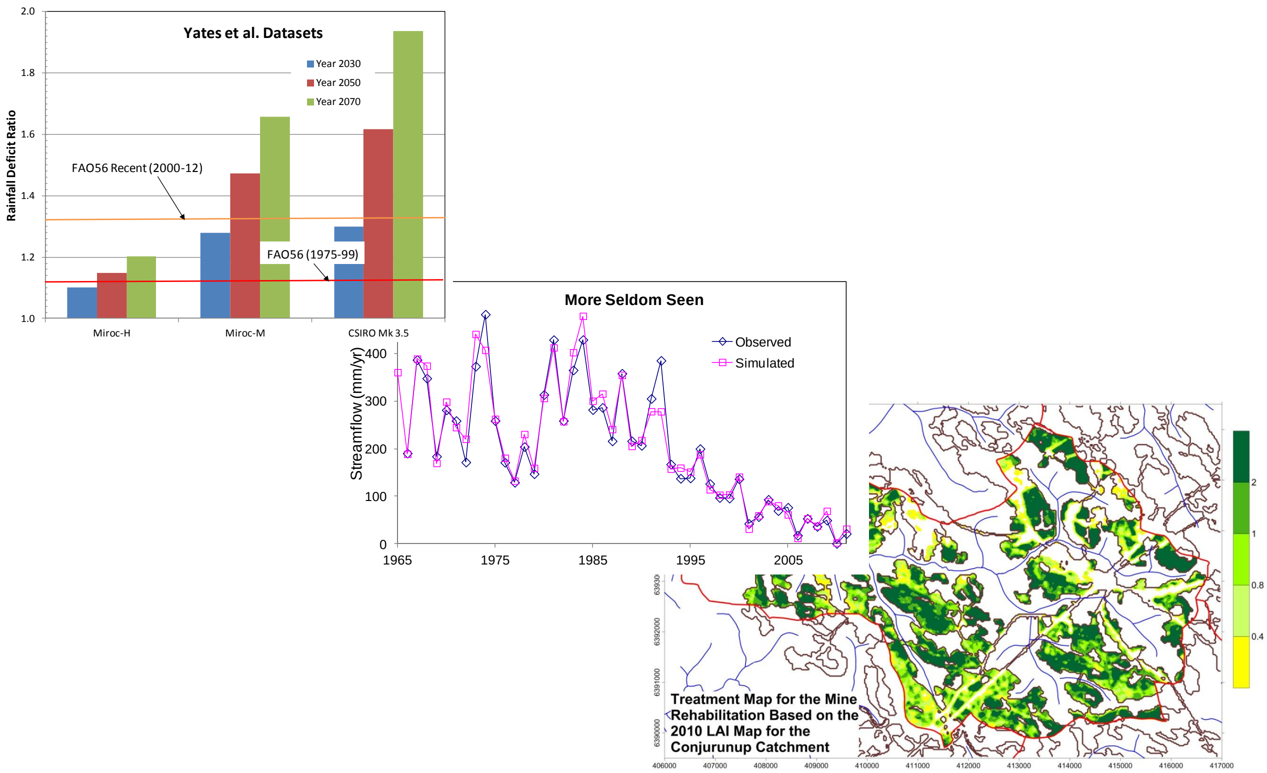

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Cover: *Examples of data and analysis used in the study*

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Custodian: Director, Forest and Ecosystem Management

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1 Executive summary

This report was prepared at the request of the Department of Parks and Wildlife (DPaW) to inform the review of silviculture guidelines, particularly guidance in relation to 'silviculture for water production' and 'silviculture for ecosystem health' for the south-west forests. Silviculture guidelines and their subsidiary documents include target stand-density (basal area, stocking, and spacing) for areas of State forest and for those timber reserves subject to timber harvesting and associated treatments. The process of reviewing silviculture guidelines includes considering possible adjustments to the target stand-densities specified in the current guidelines as a result of observed and projected climate change. The present study is restricted to the northern jarrah forest as this area is already extensively modelled hydrologically; a follow-up study for the balance of the south-west forest areas of WA is possible. The aim of the present study was to provide target estimates of forest density, expressed as a leaf area index (LAI) and basal area, required for a stable water balance.

The study covered a wide range of topics related to hydrology in the northern jarrah forest; how forest hydrology is linked to forest density, what is the hydrological future prognosis, and what silviculture treatments would be required to achieve various hydrological outcomes. One of the first findings is that climate already affects the vegetation density of the northern jarrah forest, and there is evidence that forest LAIs are responding up and down to variations in climate. Another finding is that for the three climate scenarios obtained from CSIRO & BoM (2007) via Yates *et al.* (2010), the moderate and worst case scenarios of Miroc-M and CSIRO Mk 3.5 scenarios were very similar to recent climate when both rainfall and potential evaporation are considered together. It was concluded therefore that the climate of the recent past (2000 to 2012 inclusive) was probably at least an equal predictor of the likely near future, that is to 2030. A further finding on climate is that the seasonal-rainfall behaviour for the northern jarrah forest is changing in line with climate predictions; the onset of winter rains is now more damped than was observed in the period 1961 to 1990.

When the present hydrology of the northern jarrah forest is assessed, it is a system where soil-water storages, groundwater levels and streamflows have declined from historical levels, and left to its own devices they are likely to decline further. At the same time, the level of intervention required to return these parameters to the historical levels that occurred during the period 1961 to 1990 would probably be too extreme in terms of LAI reduction to be considered. However, if more modest targets are set, similar to the hydrology of the 1980s and 1990s, then it may be practical to achieve useful gains. Figure 1(a) shows the LAIs required to generate rainfall-zone specific streamflows of 100 mm/yr for the HRZ, 10 mm/yr for the IRZ, and 1.0 mm/yr for the LRZ, and Figure 1(b) shows the basal areas required to achieve the same streamflows. The HRZ/IRZ (1,100 mm/yr rainfall for 1961 to 1990) and IRZ/LRZ (900 mm/yr rainfall for 1961 to 1990) boundaries are shown as isohyets in Figure 1.

While groundwater depths, soil-water storages, and levels of vegetation water-stress are all important to the ecosystem health of the northern jarrah forest, the importance of streamflow maintenance for the High Rainfall Zone (HRZ - >1,100 mm/yr rainfall for 1961 to 1990) can be directly quantified: while the HRZ is only one-fifth of the area of the water-supply catchments operated by the Water Corporation in the northern jarrah forest, it has been estimated that 60% of the stream inflow to these water-supply reservoirs comes from the HRZ. As an example of what could be achieved in the HRZ, the study assessed the practicality of treatments within this area and their capacity to maintain streamflow at a level at least comparable to historical, *viz* of order 100 mm/yr. It was seen that if this level of streamflow was maintained, then the other hydrological parameters would also be maintained at levels comparable to historical; groundwater would be kept close to, or at, the surface in the streamzone, soil-water storages would be within historical ranges, and plant water-stress would remain at low levels. In the assessment process the concept of rainfall deficit was introduced. Annual rainfall deficit is annual potential-evaporation minus annual rainfall. When rainfall deficit was converted by modelling into a carrying capacity of vegetation expressed as an LAI, and into likely streamflow for a given LAI, it became obvious that within the HRZ there were only limited sections for which treatment may be a practical proposition. In particular, it was determined that the northern section of the HRZ fell outside this category; this explained why there had been limited success with the Wungong Catchment Trial.

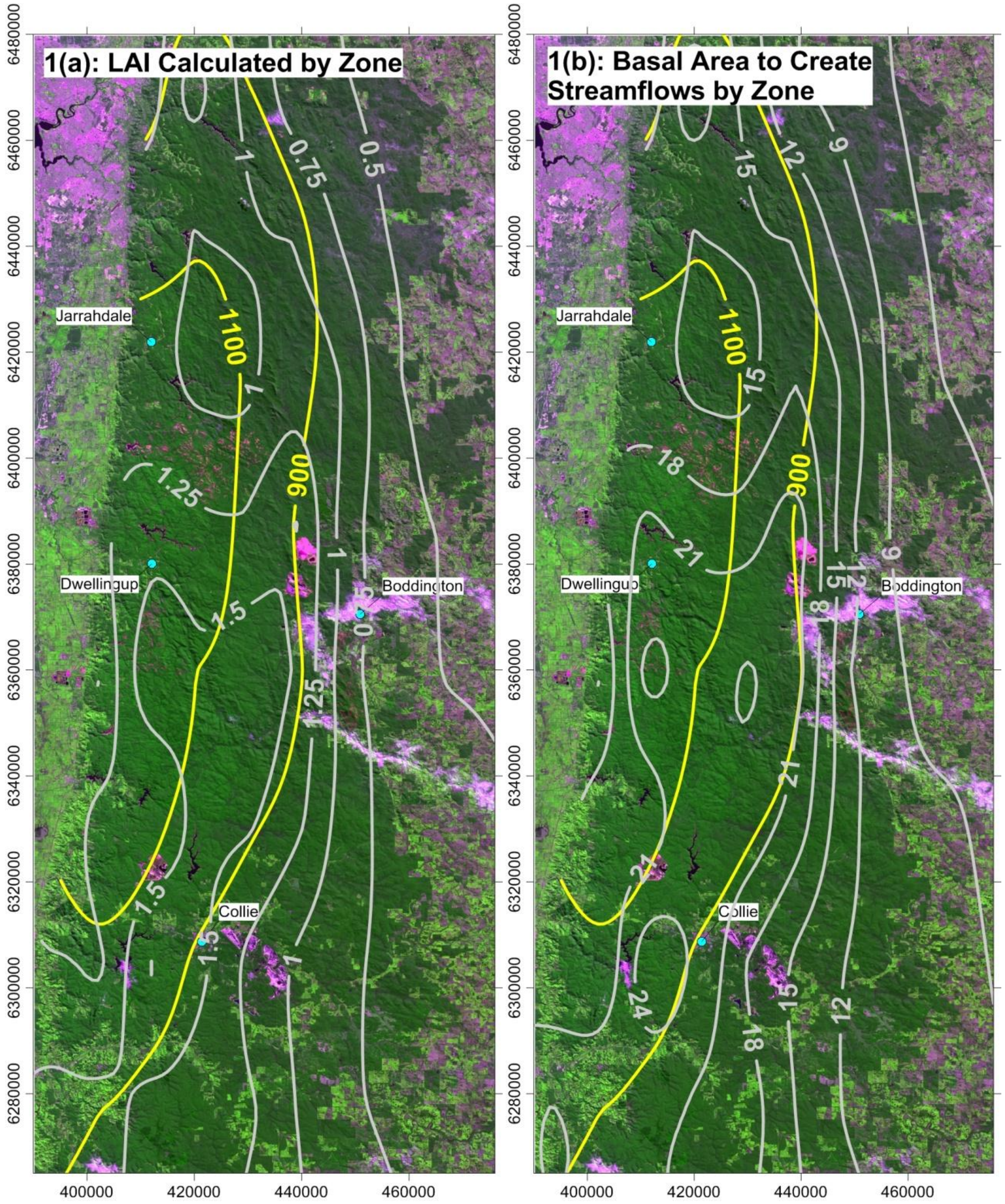


Figure 1 (a) LAIs to generate rainfall-zone specific streamflows of 100 mm/yr for the HRZ, 10 mm/yr for the IRZ, and 1.0 mm/yr for the LRZ, (b) basal area to generate the same rainfall-zone streamflows. The rainfall for 1961 to 1990 is shown as yellow isohyets.

In assessing the practicality of forest treatments within the HRZ, possible post-treatment growth responses needed to be considered. Regrowth scenarios developed by Jack Bradshaw (Jack Bradshaw, pers. comm.) for the Wungong Catchment Trial showed promise; but they do assume follow-up silvicultural treatments, including coppice control, without which the recovery in LAI would be more rapid and probably render the treatments ineffective after too short a time.

The narrowing of the possible treatment area to just within the mid-section of the HRZ, introduced a complication. This area has been, and is continuing to be, mined for bauxite. However, the existence of bauxite mining in the possible treatment area also creates an opportunity. If the final rehabilitation target is changed from that of achieving a tall forest consistent with the surrounding jarrah forest, to that of maintaining LAIs consistent with the target LAIs required for streamflow generation, then a hydrological outcome can be obtained. For options regarding the actual treatment of mine rehabilitation, Croton *et al.* (2012.b) provided a comprehensive review of possible mine rehabilitation options and their implications on catchment hydrology; the reader is referred to this document as a good starting point for discussion.

As an initial demonstration of how both forest and mine areas may be managed, the Conjurunup and North Dandalup catchments were discussed. In particular, the smallness of the Conjurunup catchment combined with it presently being in a state which would allow relatively cost-effective management, recommends it for further consideration. It also has a number of existing research catchments within it, and they could yield additional information on treatment responses as well as be sites of future treatments studies. From an operational viewpoint, a number of demonstration alternatives to the Conjurunup catchment exist, particularly the Waroona and Samson Brook dam catchments further south which have the highest target-LAIs for the HRZ. This means these catchments could be maintained at a higher LAI for the same streamflow per unit area as Conjurunup, or could achieve a higher streamflow per unit area if maintained at the same LAI as Conjurunup. The Waroona and Samson Brook dam catchments are two of the seven dam catchments operated by the Water Corporation for supply of water to the Harvey Water Irrigation Area (HWIA). The HWIA has differing needs to the overall Integrated Water Supply System (IWSS) operated by the Water Corporation in that it is dependent on releases from seven dams in the northern jarrah forest as its primary supply and presently can't resort to options such as sea-water desalinisation.

In closing it needs to be emphasised that care is required before any on-ground activities are considered. For treatment scenarios like those discussed by Croton *et al*. (2012.b) to be successful, they must be correctly targeted to the hydrology of the catchment. The WEC-C modelling in the final stages of the Wungong Catchment Trial, of which Croton *et al*. (2012.b) is an example, showed how to undertake such treatment design. Conversely, the modelling and analysis at the outset of the Wungong Catchment Trial using simple parametric models and other basic analysis tools showed the weaknesses of such approaches, including failure to identify the inadvisability of placing the trial at Wungong instead of further south. The knowledge and experience gained during the Wungong Catchment Trial should be retained and used to drive future processes in the catchment-management area.

2 Terms of reference

Water & Environmental Consultants will provide a report to the Director of Forest and Ecosystem Management that informs the review of silviculture guidelines, particularly those relating to ‘silviculture for water production’ and ‘silviculture for ecosystem health’ for the south-west forests. Silviculture guidelines and their subsidiary documents include target stand-density (basal area, stocking, and spacing) for areas of State forest and those timber reserves subject to timber harvesting and associated treatments. The review of silviculture guidelines will also consider adjustments to the target stand-densities specified in the current guidelines as a result of observed and projected climate change.

The aim of the study is to provide estimates of the leaf area index (LAI) that would be required to maintain a water balance*:

- Over time, both historically (from 1950) using historical weather information, to the current period, and forward in time (to 2030, 2050 and 2070) using accepted climate-change severity scenarios; and
- Over space, taking account of major factors that influence the water balance across the region including rainfall, evaporation and soil.

* Maintenance of a water balance may need to consider a range of settings such as maintenance of historic levels of groundwater recharge and streamflow, to no further reductions in groundwater levels and soil-water storage.

3 Introduction

There is now a considerable body of evidence that the present below-average rainfall period is having a significant effect upon the hydrology of the south-west of WA. In terms of the northern jarrah forest, these hydrological changes have been made more real to the general community via the Water Corporation of WA and its documentation of the changes in historical stream-inflows to Perth's water-supply reservoirs which are located in the northern jarrah forest (Figures 2 and 3). The average stream-inflow for 1912 to 1974 for the catchments directly associated with Perth (red outlines in Figure 2) was 342 GL/yr, the average for 1975 to 1999 was half this at 173 GL/yr, and the average for 2000 to 2012 was half this again at 88 GL/yr.

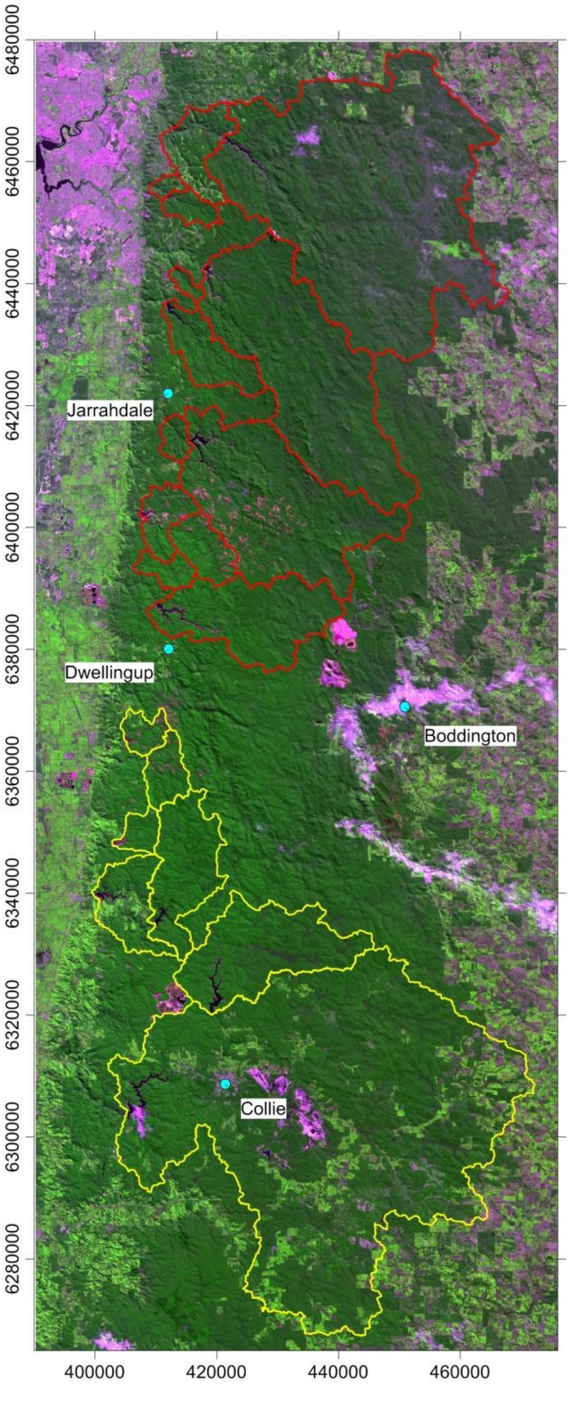


Figure 2 Northern jarrah forest water-supply catchments (red and yellow outlines) within the Integrated Water Supply System (IWSS). Background is a Landsat 8 false-colour image for June 2013.

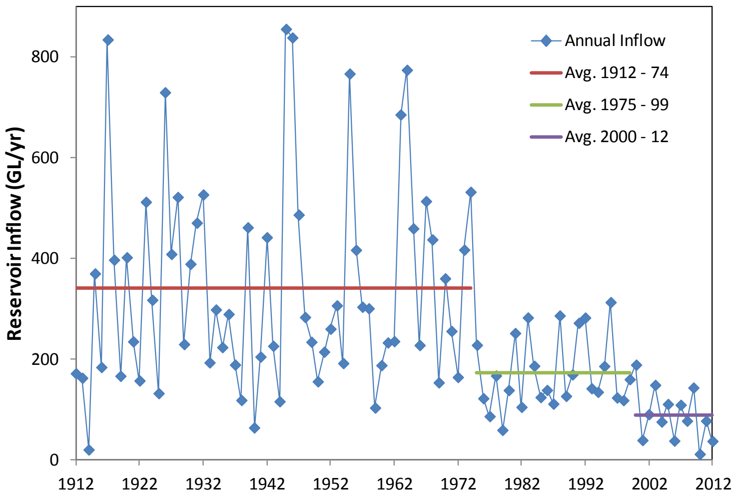


Figure 3 Total historical inflows to the water-supply reservoirs shown with a red outline in Figure 2 (see author's notes 1 and 2).

While the implications from Figure 3 for reservoir inflow declines are significant enough, a number of studies have identified the non-stationarity of catchment hydrological-processes in the northern jarrah forest and how further streamflow declines may occur due to a further "drying out" of the soil-water stores of the catchments (Kinal & Stoneman - 2012, Hughes *et al*. - 2012, and Croton & Silberstein - 2009).

There has also been extensive discussion of the form of the rainfall trends driving the changes in hydrology in the northern jarrah forest. Figure 4 shows a plot of historical annual-rainfalls (see author's note 2) for the Big Brook pluviometer for the period 1889 to present; these are synthetic annual rainfalls obtained from the SILO Data Drill system. (The Big Brook pluviometer is being used here to show "typical" rainfall patterns in the northern jarrah forest, later sections of the report will deal with the issues of rainfall distribution, etc.). Figure 4 shows there have been four distinct periods of rainfall behaviour for the Big Brook site. Firstly, there was a period of below-average rainfall which persisted up to the dry year of 1914. This was followed by a period of average and above average rainfall from 1915 till 1974. The year 1975 marks the beginning of a below-average period where, while the mean for this period is below the record average, there are still frequent moderate-rainfall years which rise above the mean. The fourth, and last, period is from 2001 to date where only one year (2003) rose above the long-term mean, with the rest below it.

Author's note 1: Inflows for the red outline catchments in Figure 2 are those estimated by the Water Corporation; they have been provided to the study by Charles Jeevaraj of the Water Corporation as monthly data.

Author's note 2: This report uses the standard calendar year, 1st January to 31st December, for annual reporting of data. A water year of 1st May to 30th April is normally used in south-west W.A. for reporting reservoir inflows and the hydrology of larger catchments. While this water year would have been better for Figure 2, it wasn't used as the calendar year was used in the balance of the report; the calendar year better considers the effects of summer rainfall on the antecedent conditions of a catchment and the effect of this rainfall on streamflow and groundwater levels in the coming winter.

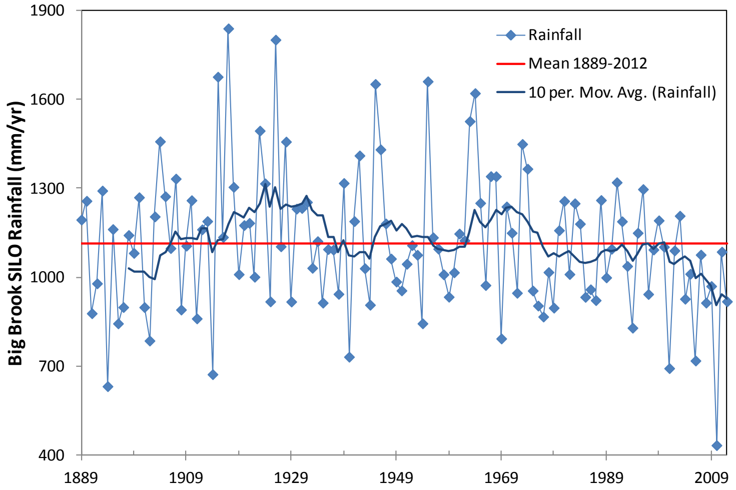


Figure 4 Synthetic annual rainfalls from 1889 for the Big Brook pluviometer obtained using the SILO Data Drill system (http://www.longpaddock.qld.gov.au/silo/)

A close inspection of Figure 4 also reveals two components to the rainfall behaviour of the recent period compared to the balance of the dataset. Firstly, there is the over-representation of low-rainfall years, there are three years with a rainfall below 800 mm/yr in the 12 years since 2001, but only five in the other 112 years of record. Secondly, there is the general absence of high-rainfall years with this trend extending back to 1975; there has been only one year with a rainfall above 1,300 mm/yr since 1975 (1,321 mm in 1991, or once in 37 years), while there are some 20 years above 1,300 mm/yr in the balance of the record (once every 4.5 years). Because the hydrological processes of the northern jarrah forest are non-linear, or at least threshold driven, due to their dominance by forest evapo-transpiration, with the high-rainfall years producing disproportionally more groundwater recharge and streamflow, it is likely that the general lack of high-rainfall years since 1975 is a significant driver, and probably equal to below-average rainfall years, in producing the presently observed hydrological declines in streamflow and groundwater levels.

To illustrate the effects of the present below-average rainfalls on groundwater systems in the northern jarrah forest, depth-to-water (DTW) data for the 11 presently monitored piezometers in the Gordon control catchment are shown in Figure 5; Gordon is part of the Cameron Experimental Catchments in the Intermediate Rainfall Zone (IRZ – 900 to 1,100 mm/annum) of the northern jarrah forest. What is most striking about Figure 5 is the steady decline in all 11 graphs. By the end of 2012, the groundwater is at least 14 metres below the soil surface across the whole Gordon catchment. Two additional points are also apparent in the Figure 5 hydrographs. Firstly, the seasonal fluctuations have either greatly reduced in amplitude since 1996, or have ceased completely and the hydrographs have become relatively smooth lines. This lack of seasonality is an indication that groundwater recharge is decreasing or even ceasing altogether; recharge is essentially a winter and spring process due to the Mediterranean climate of the northern jarrah forest with most rainfall occurring between May and October, so a normal indicator of its presence is a seasonal fluctuation in groundwater levels. The second item apparent from Figure 5 is the overall straightness of the hydrographs during the post-1996 decline period. It would be expected that were the declines related primarily to lateral-flow in the regolith, then the basic equations of groundwater hydraulics would make these declines concave in form, that is the slope of the hydrograph would lessen as the groundwater declined. Instead, all groundwater hydrographs are essentially straight post-1996; in essence, what is considered to be normal groundwater hydrology is greatly curtailed in the Gordon catchment.

The aim of the present study is to determine whether changes in vegetation cover can be used to maintain a water balance and curtail the present climate-related downward trends in hydrology. In terms of previous studies for the northern jarrah forest with similar objectives, the Wungong Catchment Trial (Water Corporation - 2005) was a major on-ground trial within the Wungong water-supply reservoir catchment north-east of Jarrahdale. As well, CSIRO (2009 & 2011) outlined a series of studies with similar objectives, though they were targeted at the south-west in general, rather than at the northern jarrah forest in particular. Reed *et al*. (2012) studied the effects of various forest-treatment options on groundwater levels, soil-water storages and streamflows and they linked the results to possible additional inflows to Perth's water-supply reservoirs via forest treatment. Croton *et al*. (2012.a) assessed the effects of various treatment options using the 31 Mile Brook catchment as an example; they concluded that large positive changes in groundwater levels, soil-water storages, and streamflows were possible by forest treatment, but the treatments needed to be intense and frequent to be effective. Prior to the above studies related to the Wungong catchment, there were a number of small-catchment forest-treatment studies in the Conjurunup catchment group, e.g. Ruprecht, *et al*. (1991) and Robinson *et al*. (1997). The streamflow responses on the Conjurunup experimental-catchments were considerable and were a major factor in deciding to proceed to a larger scale trial.

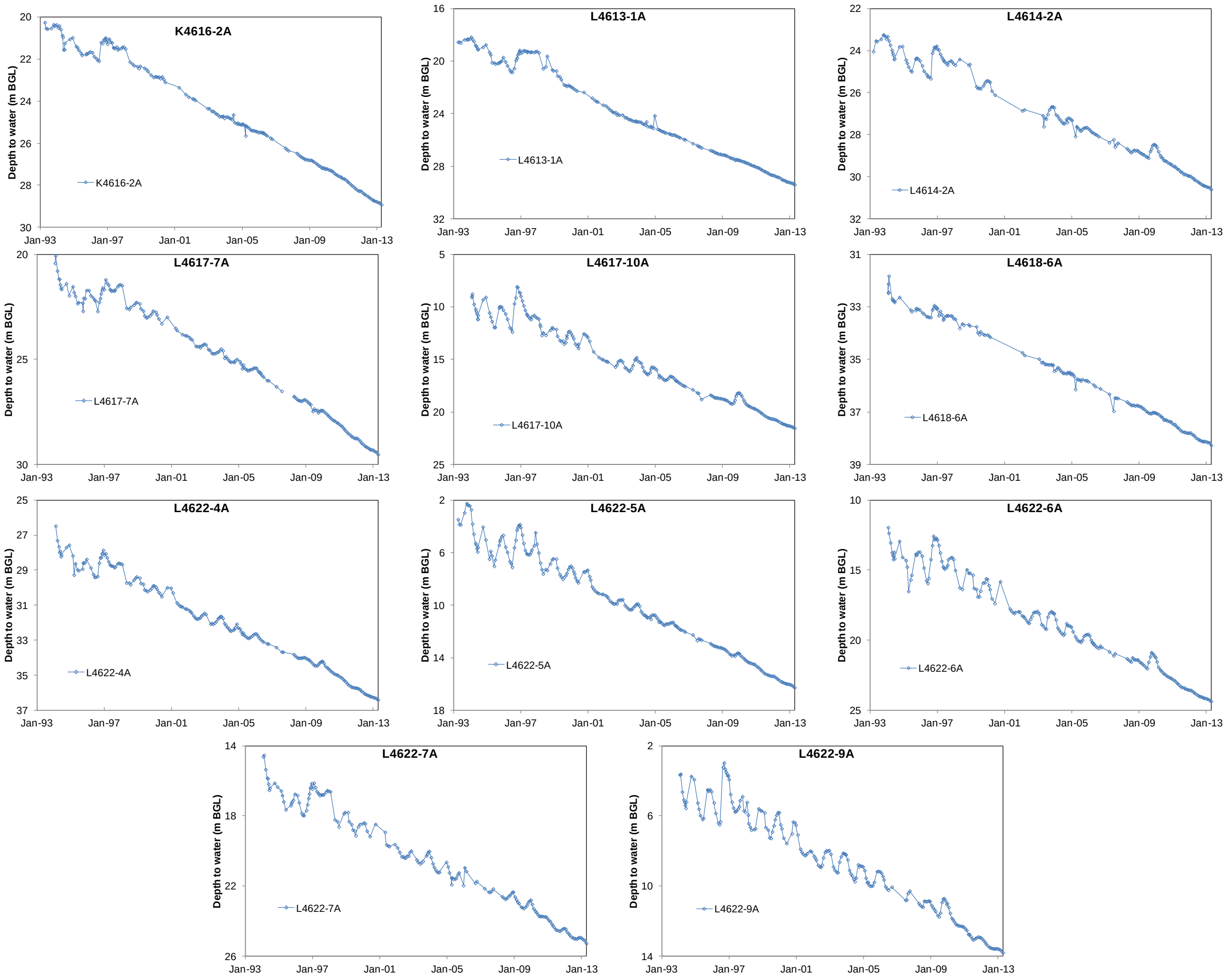


Figure 5 The groundwater-level hydrographs for the 11 monitored piezometers in the Gordon control catchment. (Based on data provided by Alcoa of Australia)

4 Study Outline

4.1 Study Overview and Its Components

To show how the study components link together, Figure 6 is a flow diagram of the study processes. The study commences with a definition of the study area and study methodology (top left-hand corner), and model selection and verification (middle top). It moves to defining historical vegetation-cover of the study area via Landsat (far left, second row), and the collation of historical climate-datasets across the study area (second row). These data are then used in historical modelling (left, third row). A second study-stream exists on the right hand side where the future-climate scenarios to be used in the study are selected (right, top row) and then modelled (right, third row). Finally the whole is brought together as a comparison between historical and likely future hydrology, and an example management application is provided (fourth row). In Figure 6 the report sections that relate to each component have been listed in red.

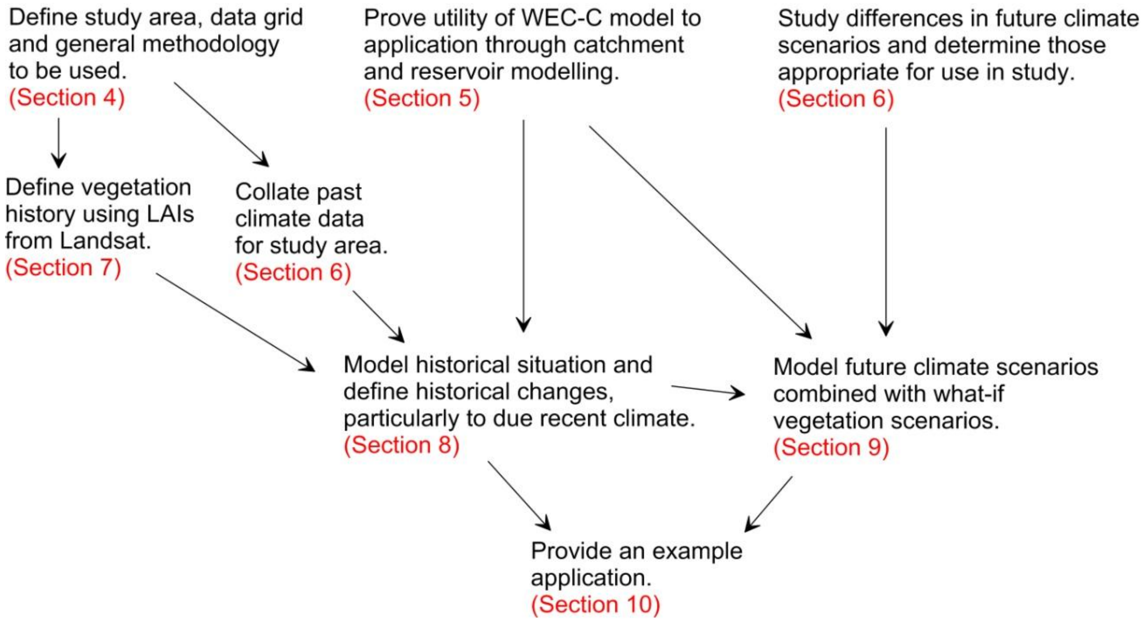
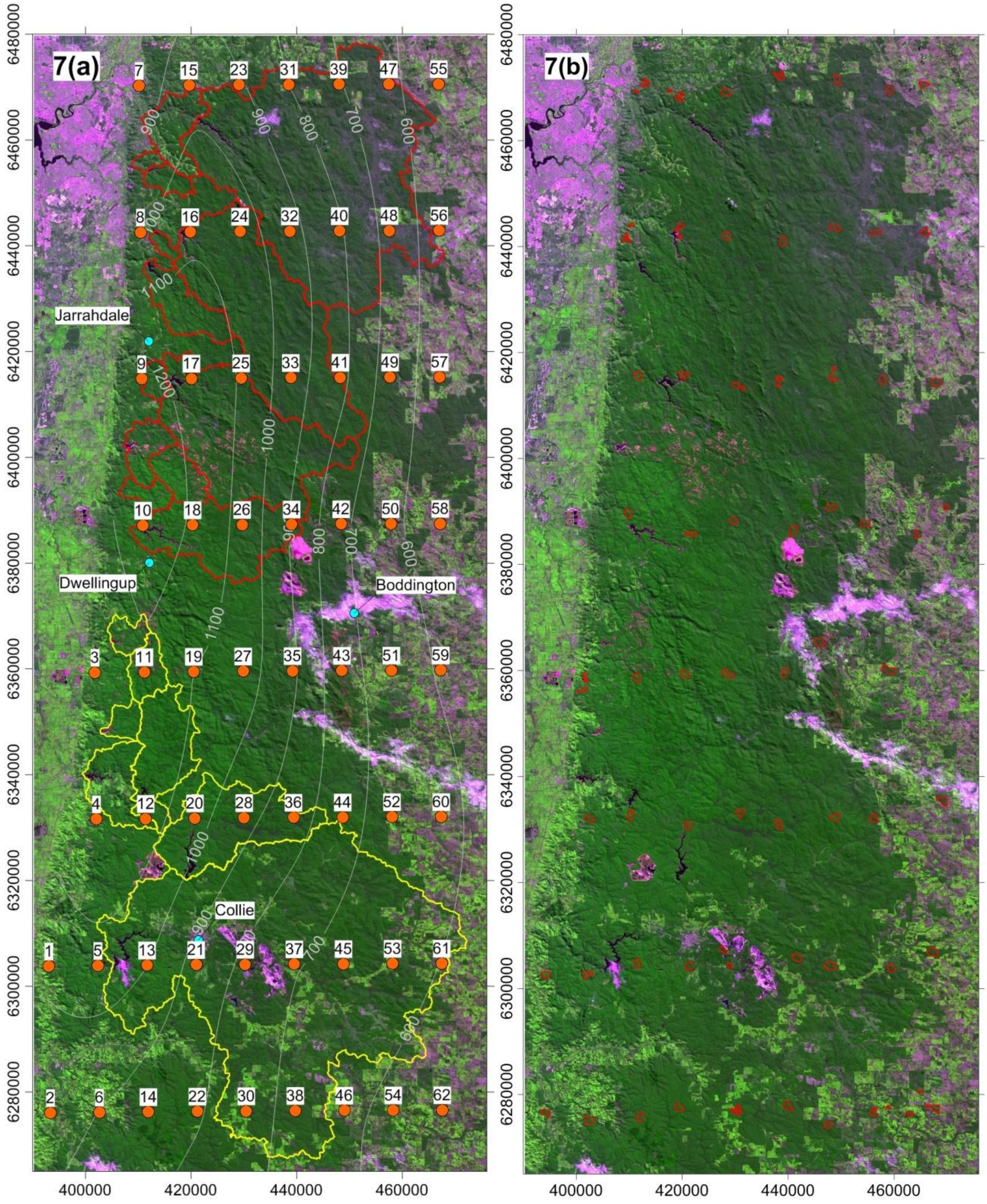


Figure 6 Flow diagram of the study processes.

4.2 Study Area and Study Methodology

Figures 2 and 7 show the outline of the study area. Its limits are driven in part by geographic considerations, the desire to include the entire Collie catchment in the south and the entire Helena catchment in the north, in part by data considerations, and in part by ensuring the whole of what is normally referred to as the northern jarrah forest is included. The topographic spatial extents are: 390000 to 476000 E by 6265000 to 6480000 N GDA94.

After a number of options were considered for the study, the process decided upon was to use the Water & Environmental Consultants - Catchment (WEC-C) model (see Appendix) to produce a series of hillslope strip-models on a regular grid across the study area. The WEC-C model has already been extensively applied to catchments within the north jarrah forest and a robust parameter set developed (Section 5). The distributed, deterministic form of the WEC-C model allows the parameterisation from the catchment models to be directly applied to the strip models without modification for scale-dependency, etc. The strip models were based on an actual hillslope transect in the 31 Mile Brook catchment, with the average slope of the strip adjusted to match the 7% which is the overall average for the study area. The strip was 600 m long cell centroid to cell centroid, and with a grid-cell size of 50 m, making it 13 cells long. The model was as per the catchment models already applied in the northern jarrah forest, which have seven layers with an assumed total soil-depth of 25 m. The models are dual continua, that is there is a soil matrix containing higher permeability preferred-pathways for vertical flow in each layer.



Figures 7 (a): The grid of 62 reference sites at which the strip model was applied. Also shown are the rainfall isohyets for the period 1961 to 1990 based on SILO data. (b): The LAI sample areas. Note that reference site 59 has no sample area.

The grid of 62 reference sites at which the strip model was applied are shown in Figure 7(a). Also shown on Figure 7(a) are the rainfall isohyets for the period 1961 to 1990. For each of the reference sites in Figure 7(a) rainfall and potential evaporation data was obtained from three sources.

- DPaW provided the data used by Yates *et al*. (2010) and provided by CSIRO & BoM (2007). This was in the form of averages for rainfall and potential evaporation by calendar month for the historical period 1961 to 90, and rainfall and potential evaporation by calendar month for three future climate scenarios for 2030, 2050 and 2070.
- CSIRO provided daily series for 1960 to 2040 for 15 climate models with each having three variations in temperature increase by 2030 (0.7, 1.0 and 1.3 degrees). Historical data is for 1960 to 2007, and synthetic data for 2008 on. CSIRO assigned the year 2030 as the identifier for the future-prediction period.
- SILO Data Drill system (http://www.longpaddock.qld.gov.au/silo/) datasets for daily historical data from 1889 to 2012. Two measures of potential evaporation were used for SILO data, FAO56 and Morton's Wet. Morton's Wet is understood to be the calculated potential-evaporation for both CSIRO and Yates *et al*. and so the historical data from these two sources should match the SILO Morton's Wet potential evaporation, and FAO56 is the potential evaporation normally used in WEC-C modelling.

Vegetation density was sampled for 61 of the 62 reference sites, using Leaf Area Index (LAI) derived from Landsat 5 TM data for the period 1988 to 2011 and Landsat MSS data for the period 1973 to 1987 (site 59 was not sampled due the lack of remnant vegetation there). The method of translation from Landsat to LAI was based on a modified Normalised Difference Vegetation Index (NDVI) that had been developed by Mauger *et al*. (2013). The sample areas for the 61 reference sites are shown on Figure 7(b). The sample areas were subjectively selected to be a representation of intact upland forest in that locality. It can be seen that for a number of representative sites, the sample area consisted of multiple polygons, this was necessary to reach the desired area-minimum of 150 ha per sample.

5 Suitability of the WEC-C Model to the Study

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 (see Appendix). The model was described by Croton & Barry (2001) and there have been numerous applications of the model to catchments within the northern jarrah forest. The reasons for using the WEC-C model in present study are:

1. A proven parameter set through its many applications in the northern jarrah forest.
2. An ability to model a representative strip using the same layout as a catchment model, thereby avoiding any issues with scale dependency, etc.
3. A flexible structure that allows rapid inclusion of management options, including detailed changes in vegetation cover and the excavation associated with bauxite mining.
4. A structure that allows ready preparation, running and output processing of thousands of strip models. This permits the simulation of a wide range of different climate scenarios with different vegetation scenarios across the whole of the northern jarrah forest. It will also allow future studies to readily extend the present study.
5. Being a deterministic model, the outputs are real-world variables that have a physical meaning, e.g. streamflow, and depth to groundwater for the valley-floor.

5.1 Transpiration Parameters

WEC-C modelling in the northern jarrah forest has been undertaken as part of a number of campaigns, with the two most recent being that for the Wungong Catchment Trial (Water Corporation - 2005), and a follow-up internal study by Water & Environmental Consultants as a precursor to the present study. The essential difference between the Wungong modelling applications and the most recent ones is the parameterisation of the vegetation transpiration relations. The algorithm of the WEC-C transpiration model is given by Equation 1.

$$T_u = \begin{cases} A\ln(E_n) + B, & E_n > T_{lin} \\ \dfrac{E_n[A\ln(T_{lin}) + B]}{T_{lin}}, & \text{otherwise.} \end{cases} \qquad \text{Eq.1}$$

Where:

A & B user input variables in the transpiration relation.

E_n net daily evaporation, normally defined by FAO56 from SILO Data Drill (mm/day).

T_{lin} user input variable to ensure the relation passes through zero (mm/day).

T_u transpiration per unit leaf area (mm/day).

In the Wungong study, the parameter values used in the modelling for normal forest were: $A = 0.785$, $B = 0.5$ and $T_{lin} = 1.5$. For post-treatment forest, the A parameter was increased by 50% to 1.18 to account for increased potential transpiration due to reduced between-leaf competition within the thinned canopy. While this functional form worked well and resulted in good model fits, it did require the input of treatment areas. In pursuit of a simpler solution, at least in terms of not having to define treatment areas, an investigation was made into whether a relation could be developed whereby A was not a fixed value for normal forest and an adjusted value for treated forest, but rather a functional relationship to vegetation density, that is to LAI. Using the existing catchment-averages as a starting point, a relation was quickly determined that achieved model fits which were essentially equivalent to those of the previous models. As well in the previous modelling, the treated value of $A = 1.18$ was applied to newly rehabilitated bauxite minepits; this seemed to account for the juvenile vigour of the young rehabilitation. Results for the Seldom Seen and More Seldom Seen catchments implied this elevation lasted for about a decade if it was considered as a simple step-function. The latest modelling has implied that even when the new functional form is used, the elevation of the *A* term is still required for the first decade of revegetation. In support of this model parameter difference, a sapwood-area per unit basal-area difference between forest and even-age juvenile mine-revegetation was noted by Macfarlane & Silberstein (2011). The developed relations between the transpiration *A* term and LAI are given in Figure 8.

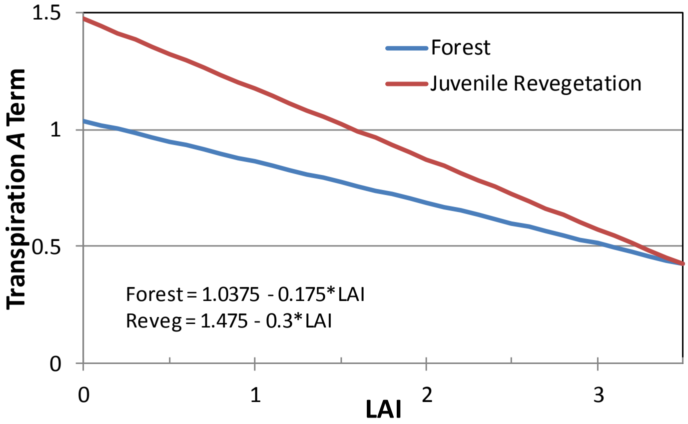


Figure 8 Developed relations between the transpiration A term and LAI.

The relations given in Figure 8 have been developed through model application to the set of catchments described below. There is no doubt that this transpiration functional form is preliminary, and if additional effort were applied then a different, or at least refined, functional form to that given may result. The extensive work of Beven, e.g. Beven (1995), on parameter uncertainty and selection subjectivity should always be kept in mind when such modelling is undertaken. However, given our present state of knowledge, and the success of catchment applications, the above relation between the transpiration *A* term and LAI appears to be a workable hypothesis.

An uncertainty in terms of model parameterisation that presently exists is what transpiration *A* term to LAI relation should be applied to mine-rehabilitation post-treatment. For forest post-treatment the modelling below has shown the transpiration *A* term remains on the forest relation in Figure 8. For mine rehabilitation, there has been modelling for catchments from initial rehabilitation establishment to 30 plus years of age, but the only modelling where there has been treatment of mine rehabilitation is for thinning of very limited areas of rehabilitation in the Vardi Rd catchment. The Warren and Bennetts catchments within the Conjurunup catchment group have had their rehabilitation treated, so they would be useful in quantifying post-treatment responses. While these catchments have had issues with monitoring-weir leakage, these can be overcome by appropriate analysis. The balance of this report assumes that mine-rehabilitation post-treatment remains on the forest relation in Figure 8; it is noted that the post-treatment vegetation-growth data of Grigg & Grant (2009) brings into question this assumption, but given the youth of the revegetation studied, 10 to 13 years, and the complexity of extrapolation from small-plot to catchment-scale, it is considered advisable to model the Warren and Bennetts catchments before making a catchment-scale determination.

5.2 Catchment Applications

The following is a list of catchments in the northern jarrah forest where WEC-C modelling with the latest functional form of the transpiration *A* term has been applied. All catchments were part of the Wungong Catchment Trial.

1. 31 Mile Brook. Forest treatment to part of the catchments in later years.
2. Cobiac. Forest treatment across the majority of the catchment.
3. More Seldom Seen. Extensive mining and rehabilitation throughout monitoring period.
4. Seldom Seen. Extensive mining and rehabilitation throughout monitoring period.
5. Vardi Rd. Larger-scale catchment subjected to both forest treatment and bauxite mining.

Results in terms of annual streamflows, observed to simulated, are given in Figure 9. Overall it can be seen that the fits are good with R^2 values in the range 0.86 to 0.97. In terms of regression slopes, Seldom Seen at 0.91 is the worst fit, however, this low slope is due to the mismatching of a number of the earlier years when the accuracy of LAI maps would be at their lowest. For now it is sufficient to see that overall, the WEC-C model using the same generic parameter set, including the new transpiration *A* term to LAI relation, has successfully matched simulated streamflow to observed in a wide variety of catchment situations. For accuracy in fitting to the other parameters of groundwater levels, stream flow-days, etc., the reader is referred to the list in the Appendix of modelling reports for the Wungong Catchment Trial. While these are for the modelling without the latest functional form for the transpiration *A* term, the results are for all practical purposes identical to those for the present model.

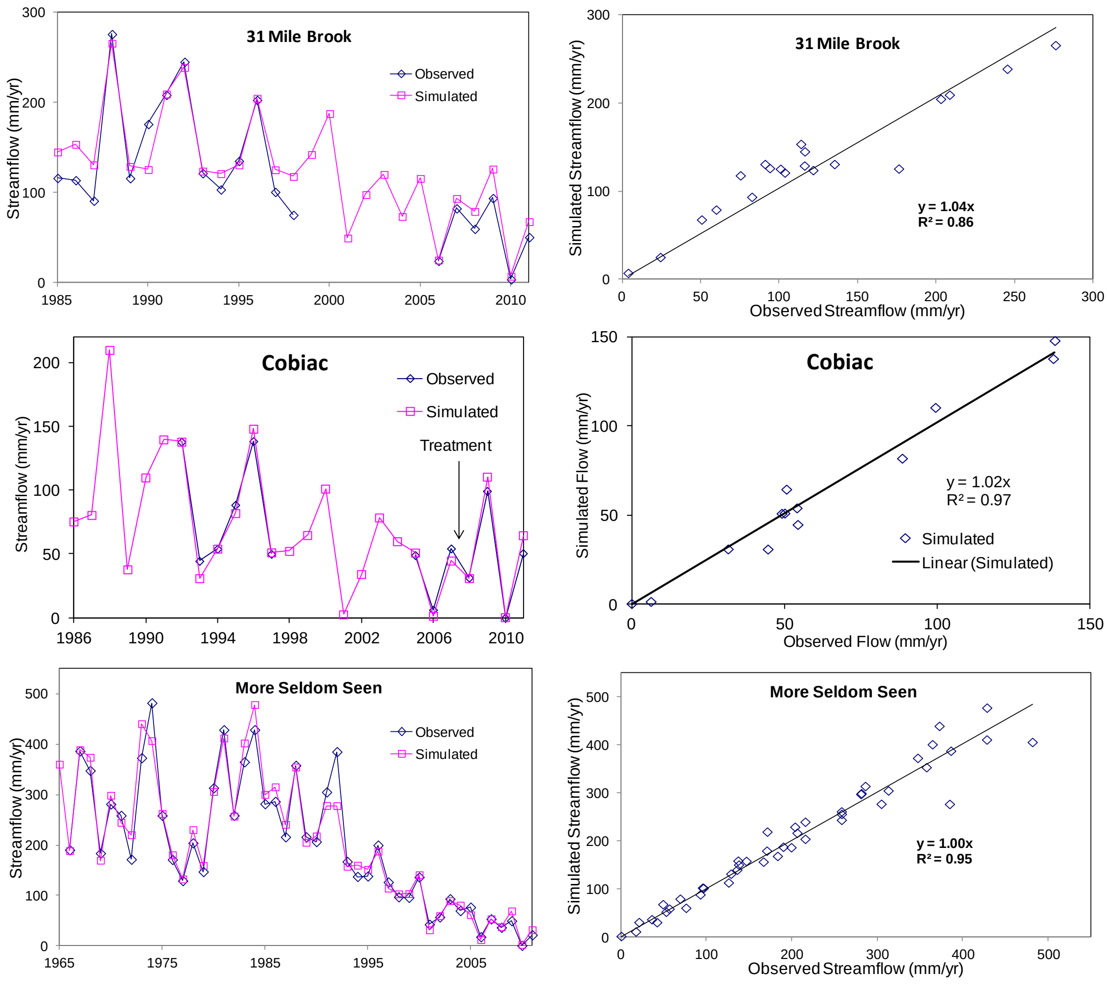


Figure 9 cont'd.

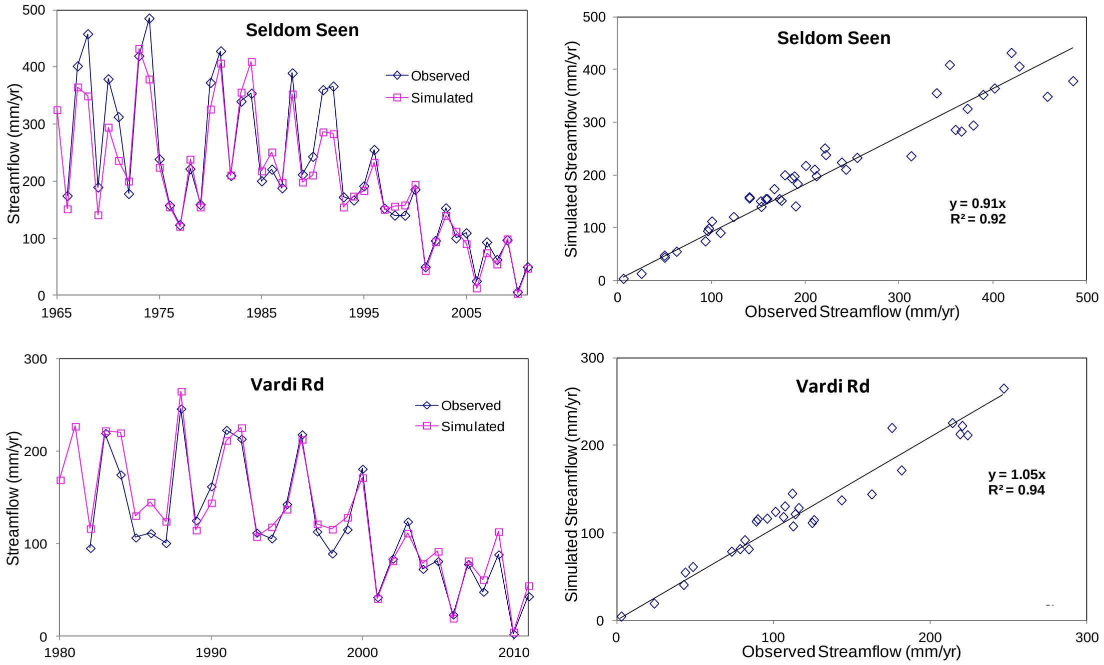


Figure 9 Annual streamflows, observed to simulated.

5.3 Reservoir Application

This item is somewhat at odds with the normal reporting process in that an output from the modelling of the study has been placed in an early section of the report. However, it is important to establish at the outset the utility of the modelling and the parameter sets used. In this exercise the reservoir inflows given in Figure 3, which are for the catchments outlined in red in Figure 2, are being simulated via the strip-models developed as part of this study. The historical LAIs used for each strip are those from the sample areas given in Figure 7(b). Figure 10 shows the resultant inflows for the period 1912 to 2012, and Figure 11 shows the results for the low-rainfall period from 1975.

From Figure 10, it can be seen that overall the strip-modelling exercise tends to significantly overestimate high-inflows, that is flows above 300 GL/yr, and it also generally overestimates inflows for the first decades of the 20th century. In viewing Figure 10, it needs to be remembered firstly that the Water Corporation inflows are also estimates, with the level of uncertainty increasing the further back in time one goes. Secondly, for this exercise the Landsat LAIs being used to drive the strip-models start in 1980, so prior to this the 1980s values are being assumed. It is likely that the LAIs in the early high-rainfall periods would have been higher than those assumed, and so the models are producing excessive flows probably because of this.

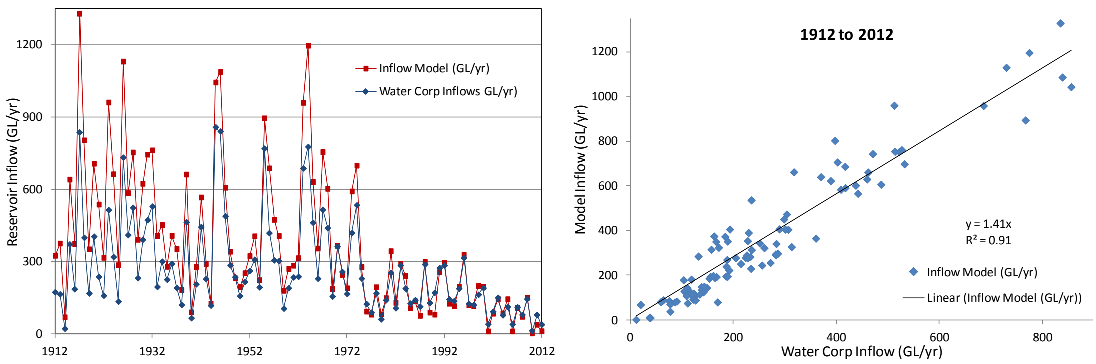


Figure 10 Annual reservoir inflows, Water Corporation estimated inflows to WEC-C strip-model simulated inflows, for the period 1912 to 2012.

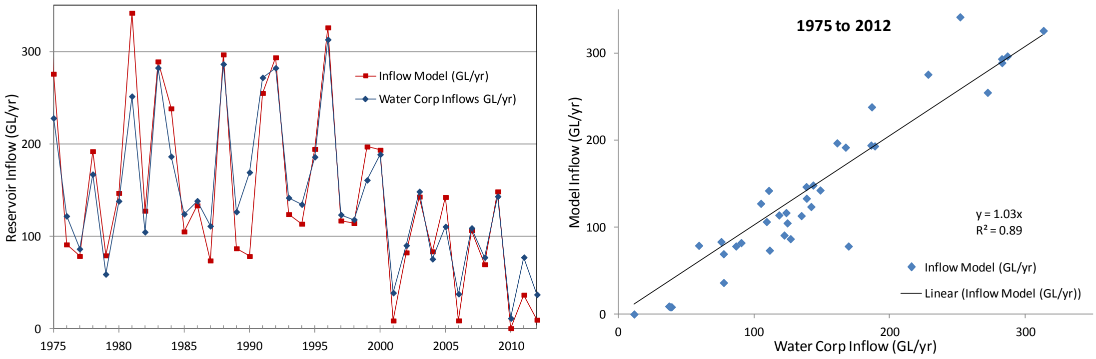


Figure 11 Annual reservoir inflows, Water Corporation estimated inflows to WEC-C strip-model simulated inflows, for the period 1975 to 2012.

From Figure 11, it can be seen that the strip-models are in much closer agreement with the Water Corporation estimated inflows in the low-flow period from 1975. Probably the only disappointment for this period is the underestimation of low flows at the simulation end, particularly for the last two years. The models seem to go further into soil-water deficit than may have been the case during low-rainfall years, though the recoveries for 2002 to 2005 and again for 2007 to 2009 seem to imply that the effect is temporary.

The conclusion that can be drawn from the strip-modelling exercise at the reservoir scale is that while it has limitations, it is showing that the general parameter set is operating to an acceptable level across the range of rainfall regimes, from 1,200 mm/annum in the west to the 600 mm/annum in the east, and this operation is at its best for the low-rainfall period from 1975.

6 Climate Data Used in the Study

As already mentioned, rainfall and potential evaporation data were obtained from three sources:

- DPaW provided the data used by Yates *et al*. (2010). This was averages for rainfall and potential evaporation by calendar month for the historical period 1961 to 90, and rainfall and potential evaporation by calendar month for three future climate scenarios for 2030, 2050 and 2070.
- CSIRO provided daily series for 1960 to 2040 for 15 climate models with each having three variations in temperature increase by 2030 (0.7, 1.0 and 1.3 degrees). Historical data is for 1960 to 2007, and synthetic data for 2008 on. CSIRO assigned the year 2030 as the identifier for the future-prediction period.
- SILO Data Drill system (http://www.longpaddock.qld.gov.au/silo/) datasets for daily historical data from 1889 to 2012. Two measures of potential evaporation were used for SILO data, FAO56 and Morton's Wet. Morton's Wet is understood to be the calculated potential evaporation for both CSIRO and Yates *et al*. and so the historical data from these two sources should match the SILO Morton's Wet potential evaporation; and FAO56 is the potential evaporation normally used in WEC-C modelling.

As a first step, the historical data for each of the three sources were compared. This was followed by a comparison of the future-predicted series for the different climate-change scenarios.

6.1 Historical Climate Data

The Yates *et al*. (2010) data used the period 1961 to 1990 as the standard historical period, and this convention was also adopted when processing the CSIRO and SILO data. The data for all 62 sites (Figure 7(a)) was averaged to create overall estimates of rainfall and potential evaporation for the three series. These three series have been plotted by calendar month in Figure 12 and by annual averages in Table 1. For the SILO potential evaporation, both Morton's Wet and FAO56 are shown.

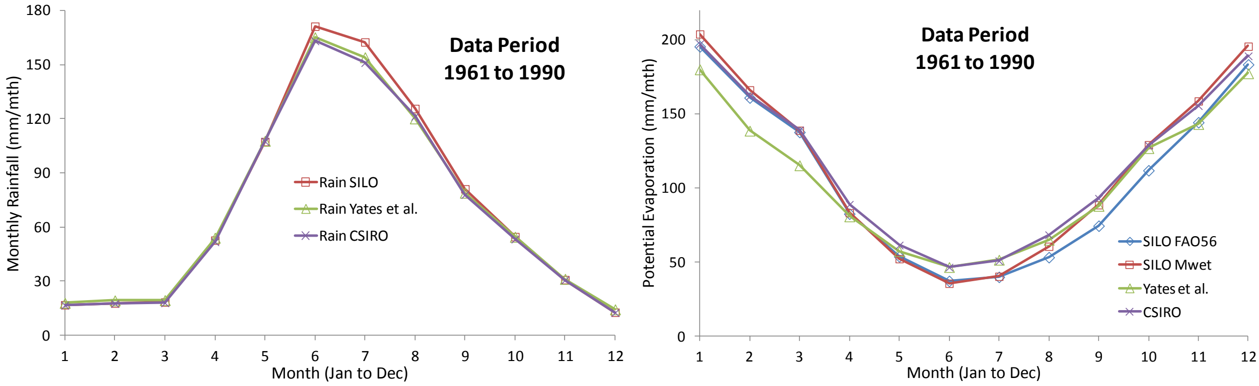


Figure 12 Comparison of rainfall and potential evaporation for the three series for the period 1961 to 1990.

Given their historical context, perhaps the most surprising thing about Figure 12 and Table 1 is that there is any variation at all between the three series. They are based on the same 62 geographic locations and all three datasets have similar origins. The data for Yates *et al.* (2010) was obtained from CSIRO & BoM (2007), the CSIRO series were from CSIRO (2009), and the SILO data was obtained from the SILO Data Drill system (http://www.longpaddock.qld.gov.au/silo/) which uses the methodology described by Jeffrey *et al.* (2001) and is aligned in its operation with the Bureau of Meteorology.

For rainfall, SILO is significantly higher for the June to August period and this is reflected in the annual average being the highest for this data set. However, the main differences are in potential evaporation; at 1,382 mm/yr the CSIRO data set is much higher than either the Yates *et al.* at

1,271 mm/yr or the SILO (FAO56) at 1276 mm/yr, though it is much closer to the SILO (Morton's Wet) at 1,354 mm/yr. The four potential-evaporation datasets also vary through the year. All except Yates *et al.* start the year as a group, then in April they all converge only to separate again as different groupings through the winter months, followed by a further switching of groupings in spring. There was considerable Email discussion as to the reasons for these variations, with the primary reason quoted relating to the reprocessing that SILO data undergoes on a regular basis. Yates *et al.* was produced in 2007 and CSIRO in 2008, while SILO is regularly updated with the last update being in 2012. The conclusion was that because it is the most recent analysis, SILO is probably the best present estimate of the climate of the period 1961 to 1990. It was decided to adopt SILO rainfall and FAO56 potential evaporation as the baseline datasets for this period for the study. Plots of their average site-values for the period 1961 to 1990 are given in Figure 13. The basic trends can be readily seen in these plots: rainfall declines west to east and evaporation decreases north to south.

Table 1 Annual averages for the three series for the period 1961 to 1990 for the 62 study sites.

Dataset	**Rainfall** (mm/yr)	**Potential Evaporation** (mm/yr)
CSIRO	821	1,382
Yates *et al*.	836	1,271
SILO (FAO56)	851	1,276
SILO (Morton's Wet)	851	1,354

An important variable or index which it is timely to introduce is rainfall deficit. Rainfall deficit is simply potential evaporation minus rainfall, expressed on an annual basis. Rainfall deficit is one of the many possible indexes that can be used to quantify rainfall and potential evaporation, Ellis and Hatton (2008) in their study relating vegetation-density to climate-variables included: rainfall alone; potential evaporation alone; the negative of rainfall deficit known as 'available rainfall'; wetness index which is rainfall divided by potential evaporation; and Specht's soil evaporative index which uses the inverse of potential evaporation. While the other indexes from Ellis and Hatton were considered, the following study found that in the case of the northern jarrah forest rainfall deficit was the most useful. It needs to be noted that for many of the following individual analyses, rainfall alone can provide as good a representation of climate as rainfall deficit. However, if just rainfall is used, then there is incomplete accounting for spatial and temporal changes in climate; this is particularly important given the north-south trend in potential evaporation (Figure 13(b)) and also when future climate scenarios are considered as these include significant changes in potential evaporation.

Figure 14(a) is a plot of the average rainfall-deficit using SILO rainfall and SILO (FAO56) potential evaporation for the period 1961 to 1990. While the rainfall deficit plot is very close in form to the rainfall plot, it is still interesting that the lower values of rainfall deficit are concentrated about the Dwellingup area. In Figure 14(b) the rainfall deficits have been plotted for the period 2000 to 2012; this period has been adopted as the 'recent' period and was preferred over the slightly shorter 2001 to 2012 period, because it does not place the very low rainfall years of 2001 and 2010 unrealistically close together when used in a repeating sequence to generate future-climate scenario-data. The difference between Figure 14(a) and (b) is about 100 to 200 mm of rainfall deficit depending on the location in the maps. While these do not sound particularly large as absolute values, it needs to be remembered that the hydrological processes of the northern jarrah forest are dominated by plant evapo-transpiration, and therefore small changes in available water can lead to large changes in hydrological outputs such as streamflow. In particular, the 200 mm/yr rainfall-deficit isohyet in Figure 14(a) is approximately aligned with the 1,100 mm/yr rainfall isohyet in Figure 13(a); the 1,100 mm/yr isohyet marks the line beyond which streamflows start to rapidly decline. In Figure 14(b) the 200 mm/yr rainfall-deficit isohyet has retreated to become a small area at Dwellingup and immediately to its south. The modelling in the following sections will show just how significant this shift is.

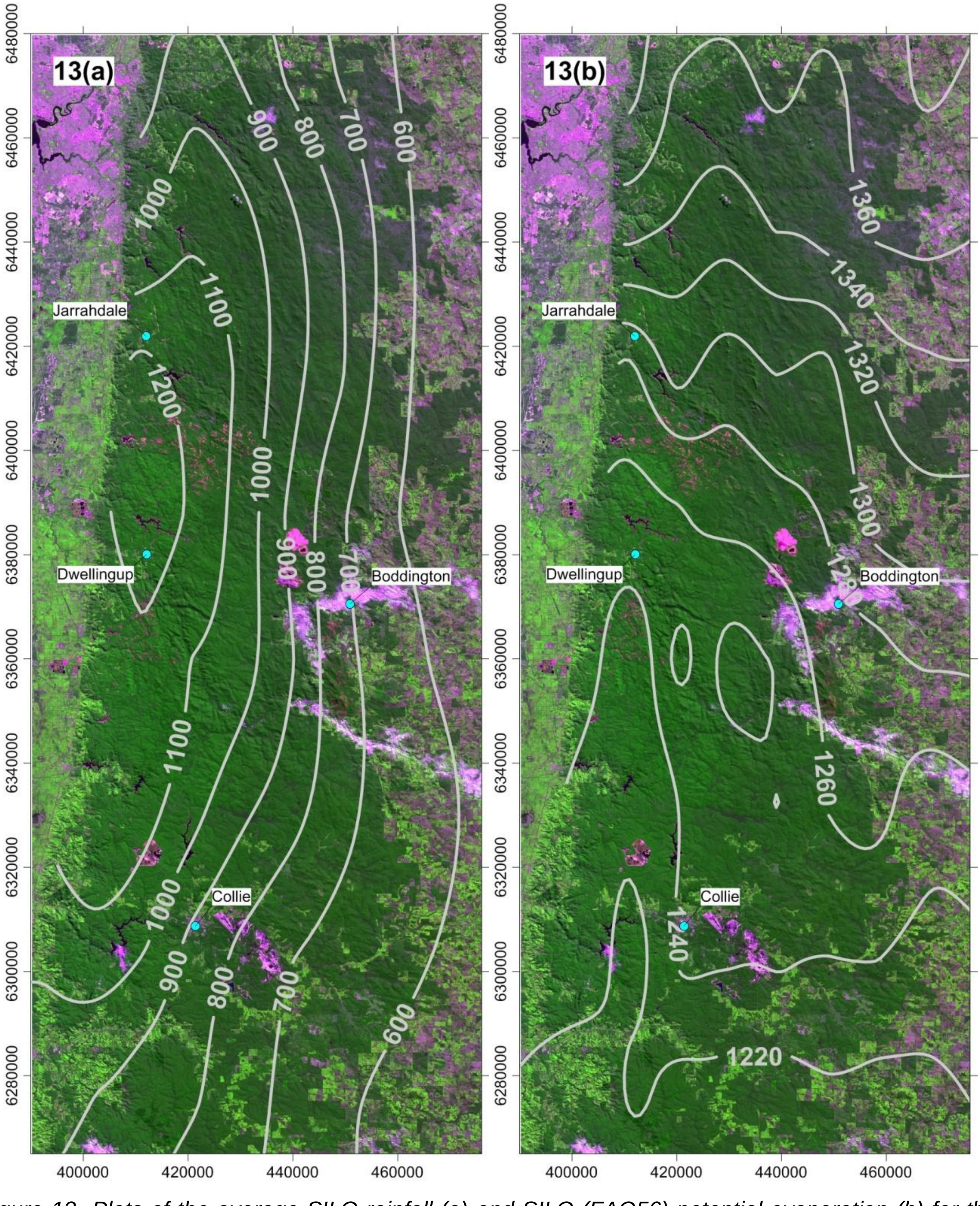


Figure 13 Plots of the average SILO rainfall (a) and SILO (FAO56) potential evaporation (b) for the period 1961 to 1990.

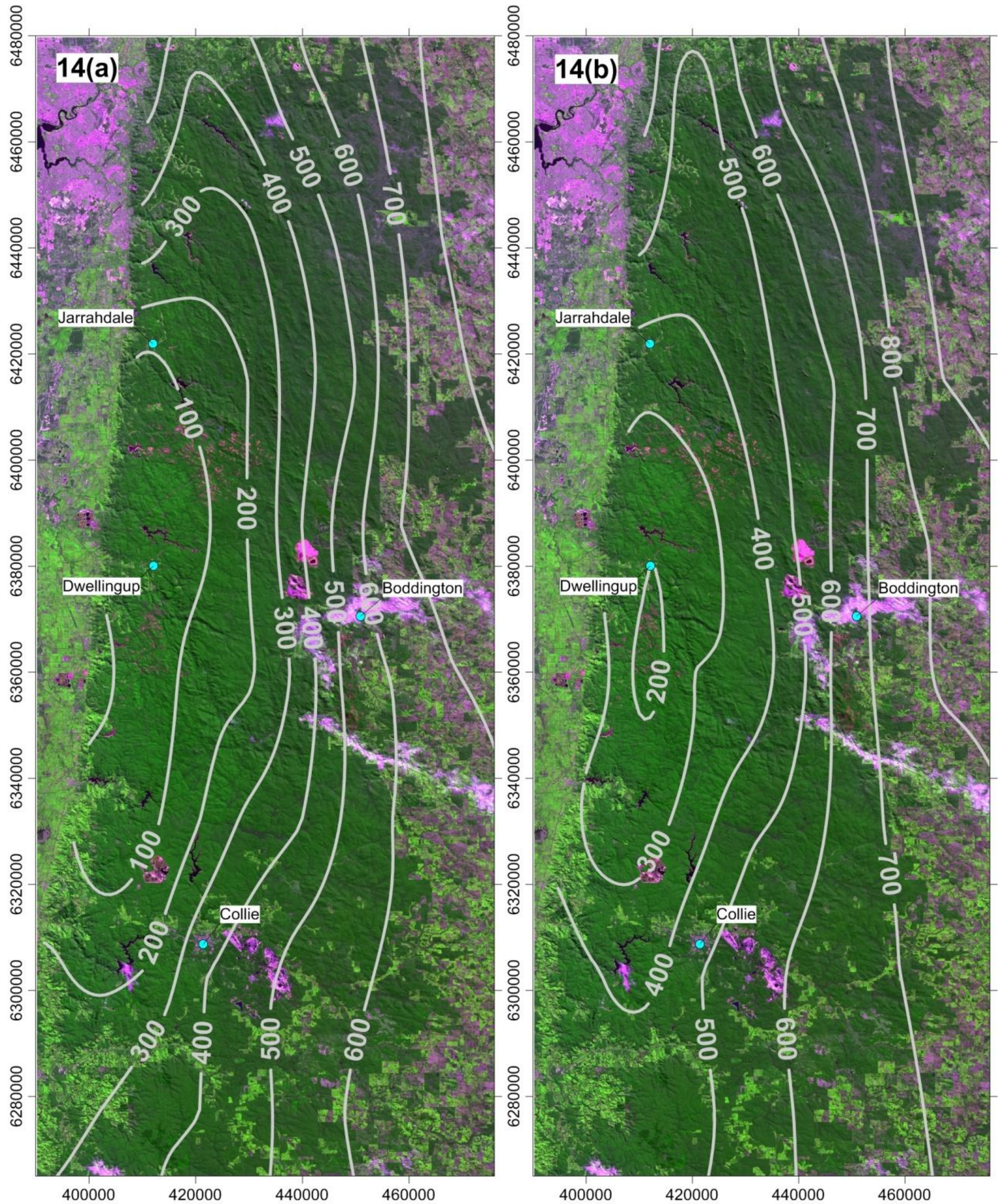


Figure 14 Plots of the average rainfall deficit using SILO rainfall and SILO (FAO56) potential evaporation for: (a) the period 1961 to 1990, and (b) the period 2000 to 2012.

6.2 Trends in Seasonal Distribution of Monthly Climate Data

A topic which needs to be considered is the changes that have occurred, and are predicted to occur, in the distribution of rainfall and evaporation through the year. Figure 15 is a plot comparing SILO rainfall and SILO FAO56 potential evaporation for the period 1961 to 1990 with that for 2000 to 2012. It can be seen that there is little difference in potential evaporation between the two periods, but the difference in rainfalls is very significant for the months of May to July inclusive. The lesser rainfall in this period is consistent with the findings of IOCI Science Management Team (2010). To quote from their online update report:

'In the south-west of WA – once considered Australia's most reliable wheat growing region – rainfall during winter has been declining since the late 1960s. Figure _ shows that since that time, there has consistently been below average rainfall in the months from May to July. In recent years, this increase in aridity has also expanded spatially.

In early winter in the south-west, atmospheric conditions have become more stable. There have been fewer low pressure systems, more prevalent high pressure systems and, since 2000, the rainfall associated with each system has decreased. The changes that have already being experienced in the south-west are projected to continue at the same rate over the next century under increasing levels of atmospheric greenhouse gases.'

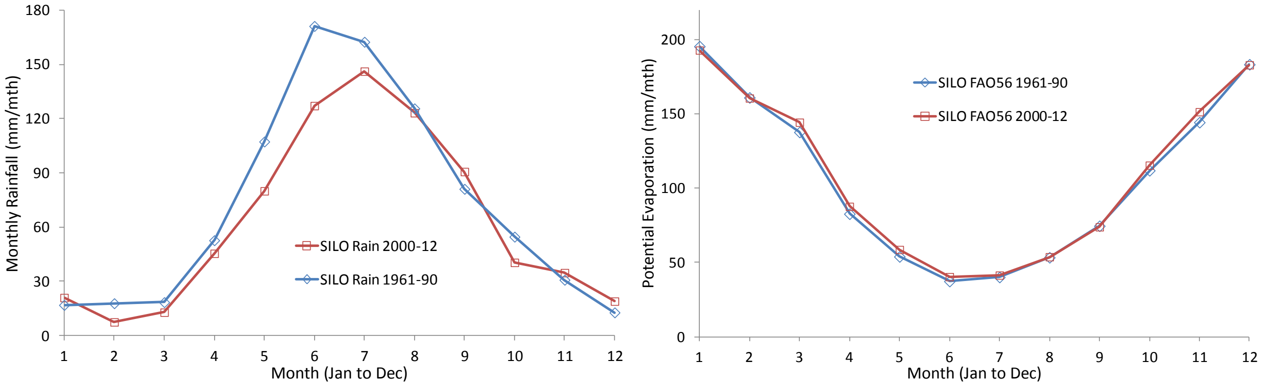


Figure 15 Comparison of SILO rainfall and SILO FAO56 potential evaporation for the period 1961 to 1990 to that for 2000 to 2012.

The conclusion from the above is that the distribution of rainfall through the year has changed from the historic period for our SILO dataset (1961 to 1990) to that occurring in the recent past for our SILO dataset (2000 to 12), and it is predicted that this new trend will continue into the future. This last point is important because the monthly distribution of rainfall for the future scenarios for both the provided Yates *et al.* and CSIRO datasets was similar to the historic period 1961 to 1990 and differed from the recent-past distribution given above. There is a ready explanation; these datasets were prepared in 2007 and 2008 and only used data up to that time in defining likely future seasonal distributions. To overcome this we will use the annual rainfall rates of the Yates *et al.* and CSIRO datasets to define annual rainfalls for their future scenarios, but use the within-year distribution obtained from the recent period 2000 to 2012 of the SILO datasets to provide an updated seasonal-pattern for their scenarios.

6.3 Future Scenario Climate Data

In this section the three climate scenarios supplied by DPaW from Yates *et al.* (2010) and the 15 scenarios supplied by CSIRO will be assessed and a determination made as to their usefulness in the study. The 15 scenarios supplied by CSIRO are for 15 climate models with each having three variations in temperature increase by 2030 (0.7, 1.0 and 1.3 degrees). The three Yates *et al.* scenarios were selected by them from the results for three emission scenarios (B1, A1B and A1FI), three climate sensitivities (low, medium and high) and for eight GCMs provided by CSIRO (2007). The three climate-change scenarios selected by Yates *et al.* were:

1. Low-impact model MIROC-H (Centre for Climate Research, Japan) combined with the B1 emission scenario and low climate-sensitivity (the most optimistic scenario),
2. Moderate-impact model MIROC-M (Centre for Climate Research, Japan) combined with the A1B emission scenario and medium climate-sensitivity (the middle scenario), and
3. High-impact model CSIRO Mk 3.5 (CSIRO, Australia) combined with the A1FI emission scenario and high climate-sensitivity (the worst case scenario).

In the previous section, differences between the historical data within the datasets were identified, and it was considered that these were too large for the datasets to be treated as a single data group. Instead it was decided to use a system of ratioing where the historical period 1961 to 1990 became the standard within each dataset, and other data periods were related to it by ratioing. This has been done for the CSIRO and Yates *et al.* datasets and Figure 16 shows the comparison of future-predicted rainfall for the climate-datasets ratioed to the historical period 1961 to 1990; these are averages for the 62 reference sites. Also included is the average for the recent period, 2000 to 2012, for the SILO dataset. The results are expressed as a rainfall ratio, that is the ratio of the future rainfall to the historical period with 1.0 being the same, and less than 1.0 being a future rainfall less than the historical rainfall. Probably the most significant observation from Figure 16 is that recent rainfall has a lower ratio than any of the Yates *et al.* 2030 rainfall scenarios. It is also lower than most of the 0.7 degree rise scenarios for the CSIRO models.

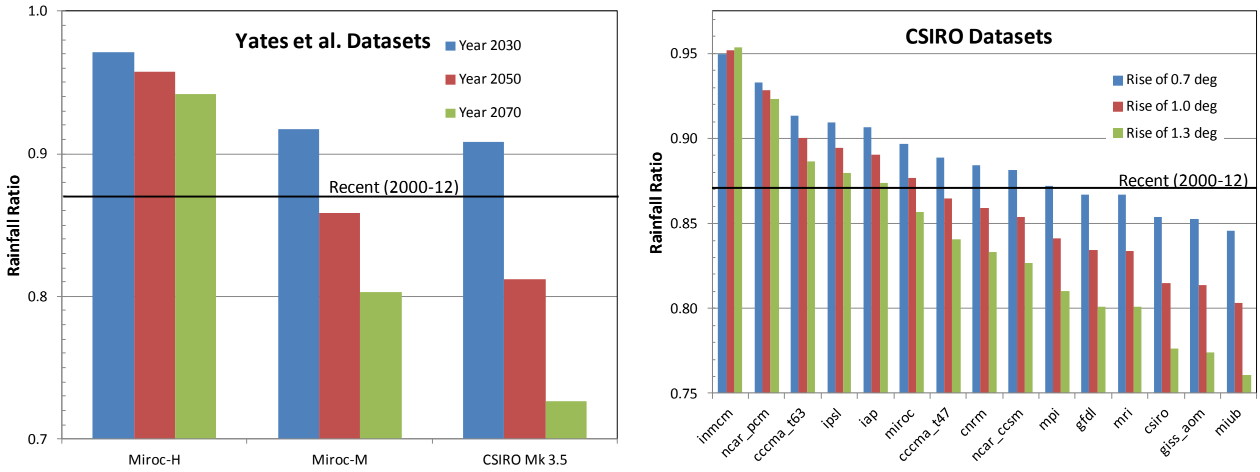


Figure 16 Future predicted rainfall for the climate datasets as ratios to the historical period 1961 to 1990; these are averages for the 62 reference sites. Also included is the average for the recent period, 2000 to 2012, for the SILO dataset.

Figure 17 shows the comparison of future-predicted potential evaporation for the climate datasets with the historical period 1961 to 1990 as averages for the 62 reference sites; also included is the average for the recent period, 2000 to 2012, for the SILO dataset for both FAO56 and Morton's Wet. The results are expressed as an evaporation ratio, that is the ratio of the future potential-evaporation to the historical period with 1.0 being the same, and greater than 1.0 being a future evaporation that is greater than the historical evaporation.

In viewing Figure 17 it needs to be noted that all the CSIRO scenarios are just for 2030, whereas the Yates *et al*. datasets scenarios extend out to 2070. It can be seen that while the Yates *et al*. dataset has a 14% increase in potential evaporation (ratio of 1.14) for 2070 for its most extreme scenario, the values for 2030 are similar to those for the CSIRO dataset and have ranges of 1.01 to 1.04.

The concept of rainfall deficit (potential evaporation minus rainfall) has already been introduced, and this has been plotted in Figure 18 for the Yates *et al.* and CSIRO future climate scenarios. Also plotted in Figure 18 are the average rainfall-deficits for the recent period, 2000-2012, and for the period 1975 to 1999. It can be seen that the recent-period, 2000-2012, rainfall-deficit exceeds that for all the Yates *et al.* scenarios for 2030, though only by a small margin for the Miroc-M and CSIRO Mk 3.5 scenarios. The Miroc-H climate scenario 2030 is exceeded by a small margin by the 1975-1999 period value. For 2050 and 2070, the Miroc-H scenario remains close to the 1975-1999 period value, while the Miroc-M and CSIRO Mk 3.5 scenarios rise well above the recent-period, 2000-2012. In summary in terms of rainfall deficit, the Miroc-H scenario can be viewed as a return to the climate of the last quarter of the 20th century, while the Miroc-M and CSIRO Mk 3.5 scenarios can be viewed as a maintenance of the recent period, 2000-2012, extending out till 2030, with a significant worsening after that. It needs to be noted that for the Miroc-M and CSIRO Mk 3.5 scenarios for 2030, this result has been arrived at by a circuitous route. In both scenarios, both the rainfall and potential-evaporation ratios in 2030 are above those for the recent period, so while neither the rainfall nor potential-evaporation for these scenarios matches the recent period values, their difference expressed as rainfall deficit does. This again shows the weakness of considering rainfall or potential evaporation in isolation and the utility of rainfall deficit as a more general parameter.

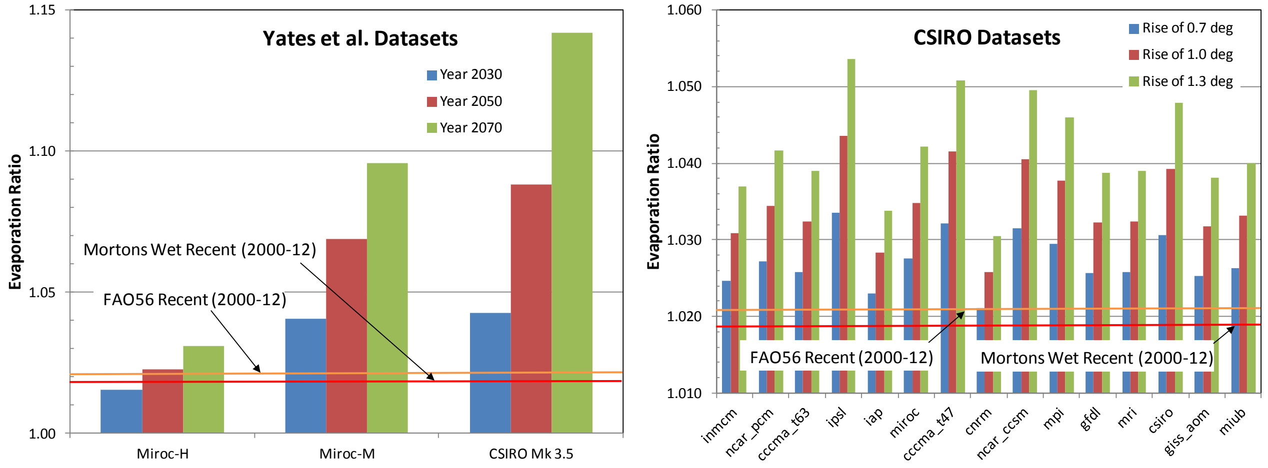


Figure 17 Future predicted potential evaporation for the climate datasets as ratios to the historical period 1961 to 1990; these are averages for the 62 reference sites. Also included is the average for the recent period, 2000 to 2012, for the SILO dataset.

While the Miroc-H scenario has been carried forward and considered in the following analysis, given the climate since 2000 it probably now should be considered the least likely of the Yates *et al.* scenarios. The Miroc-M and CSIRO Mk 3.5 scenarios, which were developed in 2007 and short-listed in 2010, seem to have been confirmed by the recent-climate behaviour which occurred after their generation. This last point can also be viewed conversely; that is that the Miroc-M and CSIRO Mk 3.5 scenarios have implied that the recent climate, 2000-2012, is probably going to continue into the near future, that is until 2030.

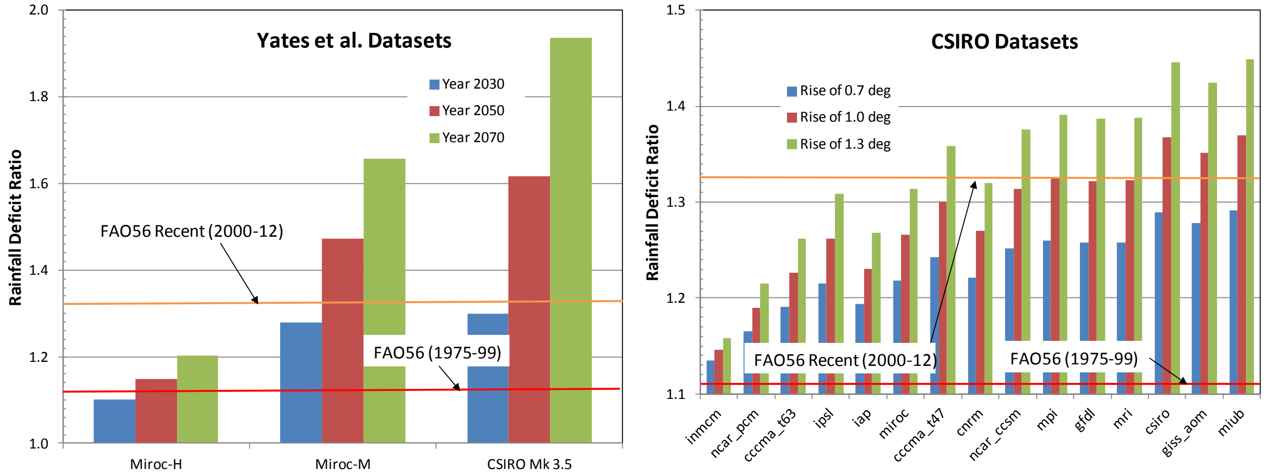


Figure 18 Future predicted rainfall-deficit for the climate datasets as ratios to the historical period 1961 to 1990; these are averages for the 62 reference sites. Also included are the averages for the recent period, 2000 to 2012, and for 1975 to 1999.

For the CSIRO scenarios, the recent period, 2000-2012, exceeds all of the 0.7 degree rise scenarios, all but three of the 1.0 degree rise scenarios, and seven of the fifteen 1.3 degree rise scenarios. It was decided that while the 15 CSIRO scenarios were interesting in themselves, their range was fully covered within the three Yates *et al.* scenarios, so the CSIRO scenarios were not carried forward to the modelling stage.

In total four scenarios were modelled, the three Yates *et al.* ones and a fourth where the recent past was continued into the future without adjustment. To create the series, the SILO daily data for rainfall and potential evaporation (FAO56) for the period 1st January 2000 to 31st December 2012 was repeated five times to create a series from 1st January 2013 to 31st December 2077. For the three Yates *et al.* climate scenarios, the daily values were weighted by linear interpolation based on the ratios given in Figures 16 and 17. Note that these ratios contain two sub-ratios, one to adjust the data to the reference historic period of 1961 to 90 and the second to ratio it to the recent period 2000 to 12. In an effort to keep things simple, the emphasis in reporting has been given to the recent-past scenario as it is the worst case, by a slight margin, for 2030 when compared to the Miroc-M and CSIRO Mk 3.5 scenarios.

7 Vegetation History

Vegetation density was sampled across the study area using Leaf Area Index (LAI) derived from Landsat 5 TM data for the period 1988 to 2011 and Landsat MSS data for the period 1973 to 1987. The method of translation from Landsat to LAI was based on a modified Normalised Difference Vegetation Index (NDVI) that had been developed by Mauger *et al*. (2013). The Landsat images used were those from January for each year an image was available. Figure 19 is the average LAI for the 61 reference sites given in Figure 7(b); note that reference site 59 has no sample area as there was insufficient remnant forest at its location. The sample areas were subjectively selected to be a representation of intact upland forest in that locality. For a number of representative sites, the sample area consisted of multiple polygons, this was necessary to reach the desired area-minimum of 150 ha per sample.

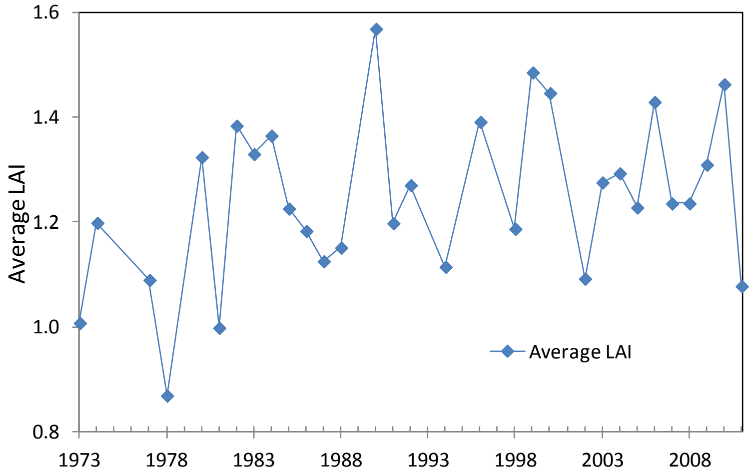


Figure 19 Average LAI for the 61 reference sites.

Figure 19 shows a high level of year to year variation in the estimated LAIs. There are many possible causes for variation, from year-to-year natural variability due to rainfall variability and factors such as flowering, to external causes such as fire, either wild or prescribed, and timber harvesting and other such treatments; but also variations due to errors or inaccuracies between the standardisation of images, particularly due to atmospheric effects. In the case of the representative sites, factors due to treatment were largely excluded by site-selection, and when this was not possible, LAIs for post-treatment years were adjusted to bring them into line with pre-treatment values. Years following fires were replaced by interpolation from surrounding years. As well, no representative site was mined for bauxite, at least prior to or during the study period. Even after all these considerations, it is possible that the year 1990 is still unrealistically high; this may relate to image standardisation issues. As well, 1978 may be unrealistically low.

To test whether there is any dependence in the LAIs to climate, Figure 20 is two plots of yearly average rainfall-deficit in the previous year to average LAI in that year; one plot is for all the Landsat TM data post 1990, that is 1991 to 2011, and the other is just for the period 2000 to 2011. Neither relation could be called more than indicative; nevertheless there appears to be some relation between these two variables.

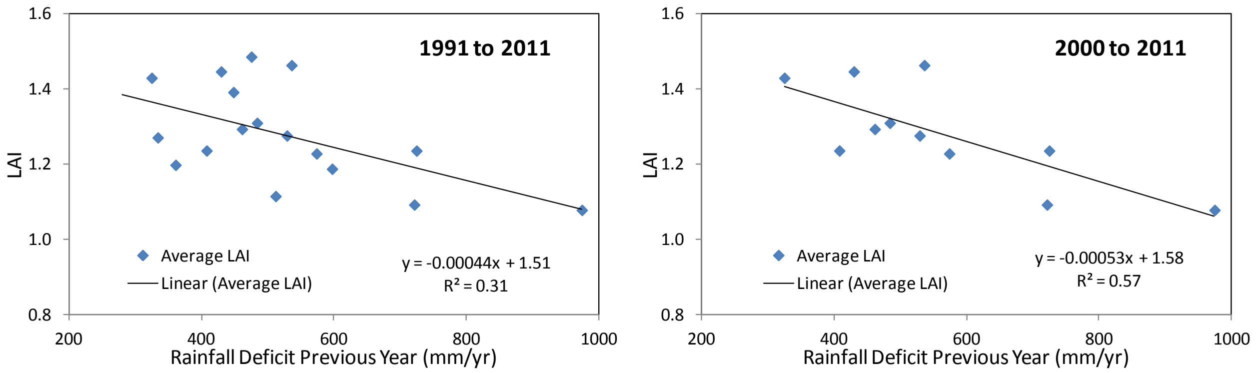


Figure 20 Yearly average LAI for the 61 reference sites plotted against yearly average rainfall-deficit for the previous year for the two periods, 1991 to 2011 and 2000 to 2011 inclusive.

To test further the possible relation between rainfall deficit for previous years, and the LAI for the present year, Figure 21 is a plot of average LAI for each of the 61 reference sites plotted against weighted rainfall deficit for the previous five years, weighting is 1.0 for the previous year, 0.8 for the year prior to that, and so on till zero is reached in the sixth year. The plot has been made for the LAI years 2000, 2006 and 2011. The selection of these years is deliberate to cover the range of climatic conditions: 2000 is the last available year before the recent, low-rainfall period of the 2000s is entered; 2006 precedes the low rainfall of that year so its rainfall deficit is primarily from a period of reasonable rainfall, at least in terms of recent rainfalls; and 2011 follows the historically-low rainfall of 2010 and so represents the worst-case rainfall-deficit of the recent period. When viewing Figure 21 it needs to be remembered that each of the 61 reference sites is represented by three points, one for 2000, one for 2006 and a third for 2011. It can be seen that variation between these three values is occurring, but in doing so the points are moving along the regression line and remaining within the same general relation. Figure 22 is the same as Figure 21, but for the years 1980, 1990, 2000 and 2011. Perhaps the most interesting point with this graph is that 1990 does not look as anomalous as it did in Figure 19; it appears that the high LAI of this year is at least in part due to the low value of the weighted rainfall-deficit for that year.

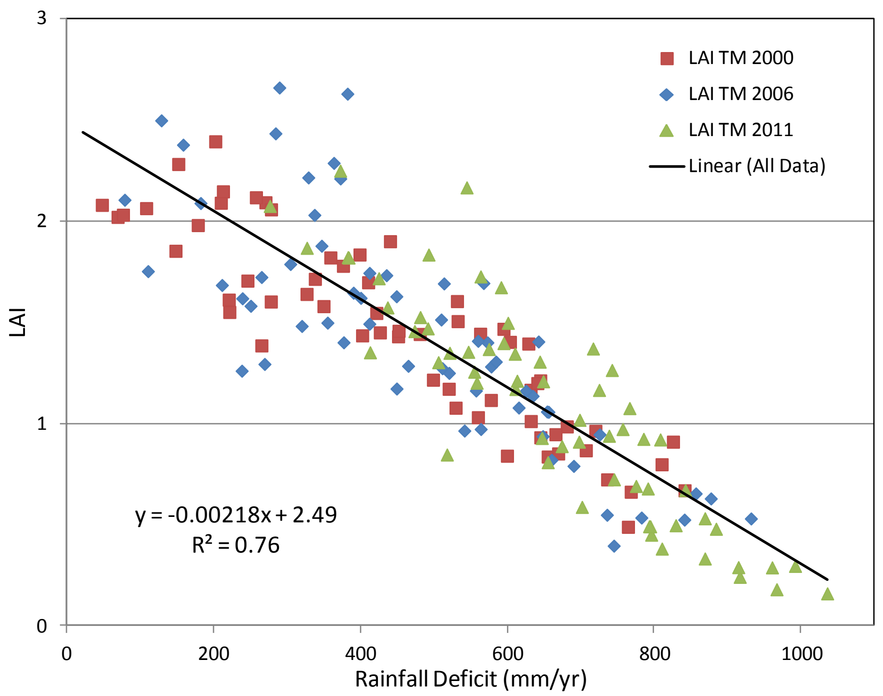


Figure 21 Average LAI for each of the 61 reference sites plotted against weighted rainfall-deficit for the previous five years.

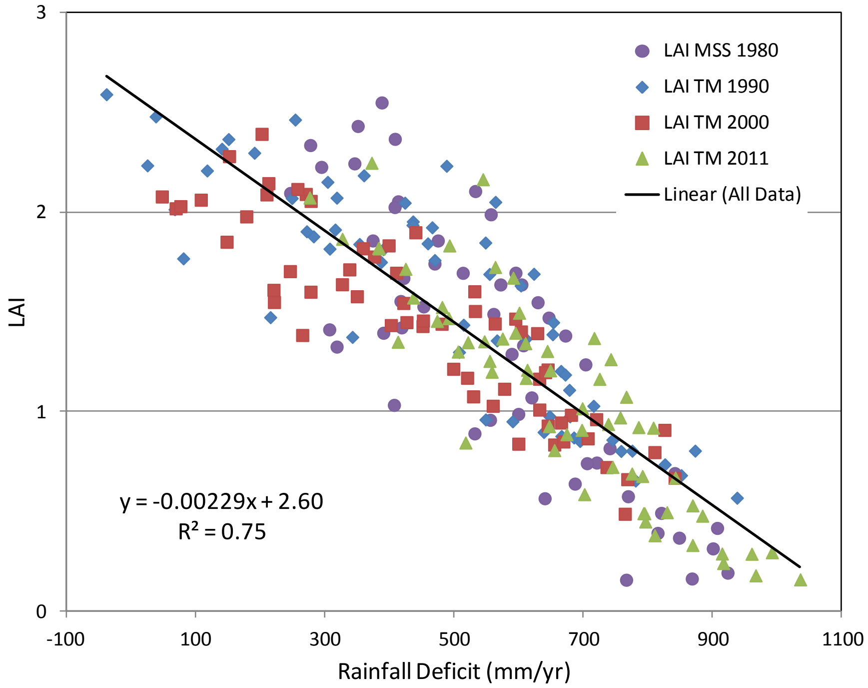


Figure 22 Average LAI for each of the 61 reference sites plotted against weighted rainfall-deficit for the previous five years.

What is being implied by Figures 21 and 22 is particularly important, that is that LAIs of the northern jarrah forest are already adjusting upwards and downwards to climate. A similar finding was made by Smettem, *et al.* (2013) for the forest of far south-west of WA, that is the forest to the south of the present study. Smettem, *et al*. studied monthly satellite-derived LAIs and used them on a catchment basis; they found that "*interannual changes to LAI in response to changes in annual rainfall were far less than expected from the long-term LAI-rainfall trend*", and they postulated that "*this buffered response …. attributed to availability of deep soil-moisture and/or groundwater storage*". The five-year weighting of rainfall deficit in the present study is intended to take this buffering into consideration. As well, it appears that rainfall deficit may be a better parameter in defining the climate to LAI relation than rainfall alone, at least for the northern jarrah forest. Rainfall deficit is also a more general parameter in that it considers changes in potential evaporation as well as rainfall.

8 Historical Modelling Results

The modelling system is based on strip models that are 600 m long cell-centriod to cell-centroid, and with a grid cell-size of 50 m, making them 13 cells long. Each strip model has seven layers for a 25 m deep soil-profile and each layer has dual-porosity, that is a soil matrix and a preferred pathway structure. The model parameterisation is the same as that already applied to catchment models across the northern jarrah forest.

The models were run for each of the 62 reference sites shown in Figure 7(a) and from 1st January 1900 to 31st December 2012, 113 years. As the models run on a daily time-step, and as the WEC-C model is capable of reporting a large number of hydrological parameters, both on an individual cell/layer basis as well as for a strip or a whole catchment, the possible outputs from such an exercise is enormous. It will be seen from the Terms of Reference, that the primary interests are the water-balance and its effect upon streamflow, groundwater levels and soil-water storage. It was decided to concentrate therefore on: depth-to-water (DTW, m) for the groundwater in the cell of the strip representing the valley-floor, streamflow (mm/yr) from the strip, soil-water storage (mm) for the strip, and average transpiration-ratio for the strip. This last item, transpiration-ratio, is the ratio of actual transpiration within the model to potential transpiration; a value of 0.7 say, means that actual model transpiration is only 70% of what it would be if there were no limits, such as available soil-water causing a reduction. Transpiration-ratio is particularly useful as it allows an assessment of water stress on the vegetation. Figure 23 shows the above four parameters plotted against rainfall deficit (RD) for the 62 reference sites. The data has been plotted for two time-periods, 1961 to 1990 (the historic period for all the climate scenarios) and 2000 to 2012 (the recent period for all the climate scenarios). While Figure 23 shows some general trends, the relation with rainfall deficit is obviously not the complete explanation.

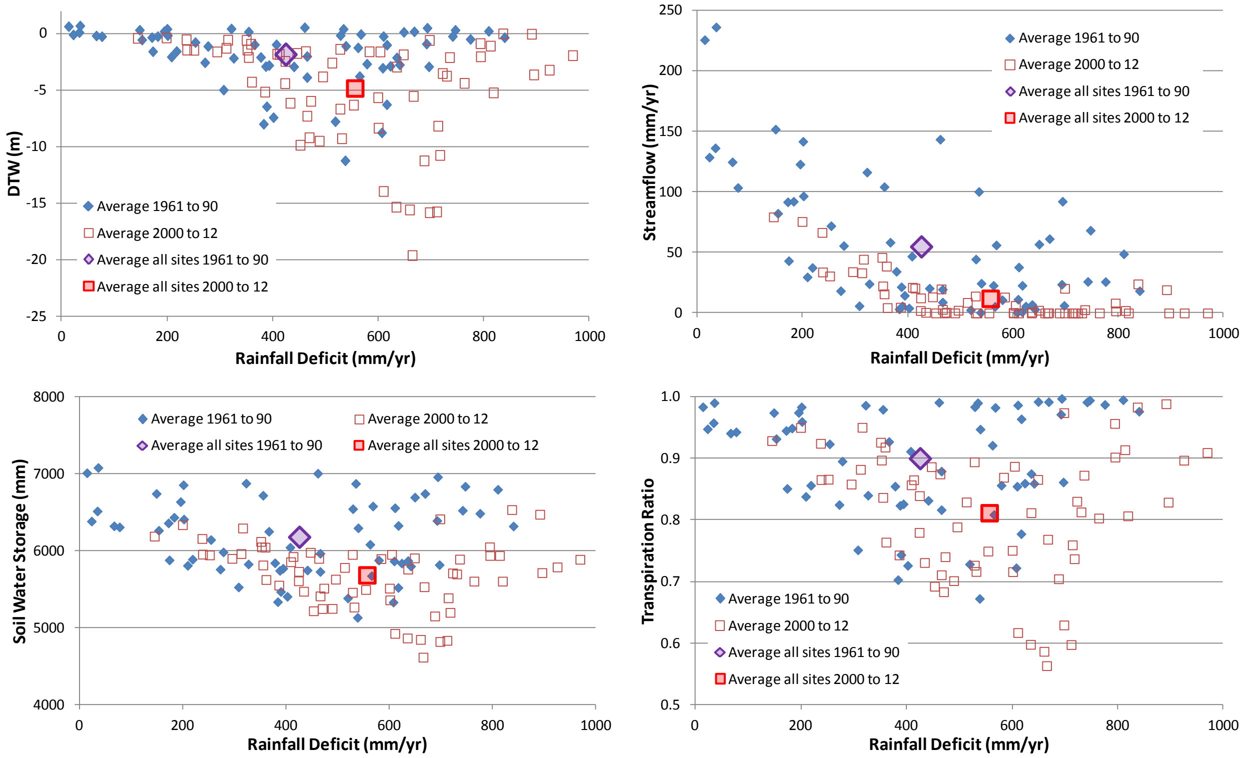


Figure 23 Results of the 62 reference site strip-models for depth-to-water (DTW), streamflow, soil-water storage and transpiration-ratio plotted against rainfall-deficit.

If LAI is introduced to the x-axis of the plots, then markedly tighter plots result (Figure 24); this is because while rainfall deficit is describing the effects of climate, it isn't considering the local conditions in terms of forest density. If the LAI is low, then the vegetation will have a lower evapo-transpiration than if it is high, this is regardless of the rainfall deficit. In the previous section it was noted that there is a relation between rainfall deficit and LAI, so the placement of LAI on the x-axis is the inclusion of a dependent variable to the x-axis. However, there is significant variation in the relation between LAI and rainfall deficit driven by a variety of factors, so there is validity to including LAI on the x-axis.

In Figure 24 LAI is raised to the power 0.5. The form for the x-axis of $RD*LAI^{0.5}$ was arrived at from a back calculation of the results from the later analysis for future climate-scenarios; alternative forms can be found within the solution space, though the present is almost certainly the simplest. A physical explanation is provided by Figure 8 where it can be seen that low LAIs have proportionally more transpiration per unit leaf-area than high LAIs; the square root form approximates this.

In Figure 24 there is a point at about 600 which once x-axis values rise above it, all parameters start to enter a zone marked by lack of hydrological activity: groundwater at depth; streamflow near zero; soil-water storage dropping to what appears to be a minimum; and transpiration-ratio falling to 0.7 or less. However, there is still scatter present in all plots. This scatter is largely due to the hydrological system and its components being non-stationary, in particular these historical simulations have varying LAIs from year to year, that is the variation shown by Figure 19, and also the natural variation in rainfall from year to year. So while the historical simulations indicate the existence of a threshold point, it is going to be the future simulations with their constant LAIs and repetitive rainfall which will more accurately quantify it.

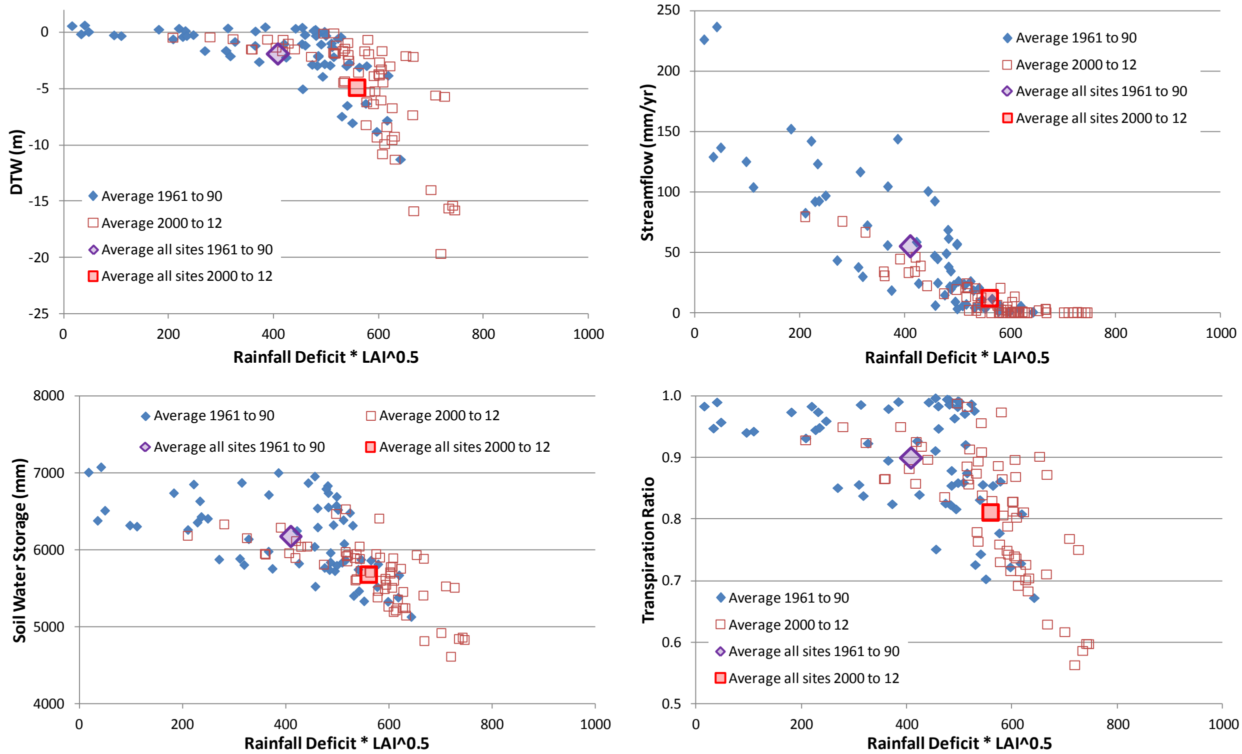


Figure 24 Results of the 62 reference site strip-models for depth-to-water (DTW), streamflow, soil-water storage and transpiration-ratio plotted against $RD*LAI^{0.5}$.

9 Future Climate scenario Modelling Results

9.1 Future Scenario Initial Results

The future scenarios have been simulated using four climate scenarios: the three Yates *et al.* scenarios of Miroc-H, Miroc-M and CSIRO Mk 3.5; plus the recent period, 2000 to 2012, repeated. We saw already from Figure 18 that the recent repeated is actually the worst-case scenario for the near future, that is 2030, and it isn't until 2050 that Miroc-M and CSIRO Mk 3.5 exceed it in severity. Miroc-H never exceeds it.

Starting with the scenario of the recent period repeated, Figure 25 is a plot of similar form to Figure 24 but for the future rather than the past. The 2030 value is actually the average for the period 2024 to 2036, and the 2050 value is actually the average for 2044 to 2056. Using an average for a period of 13 years duration makes the future values directly comparable to the averages for the recent period 2000 to 2012. What is interesting in Figure 25 is the lack of variation between the two periods. While differences are apparent between the recent period in Figure 24 and the values in Figure 25, the two periods in Figure 25 have little difference between them. By 2030 the hydrological system seems to have settled down to a constant state. The threshold value of 600 for the x-axis can be clearly seen in Figure 25.

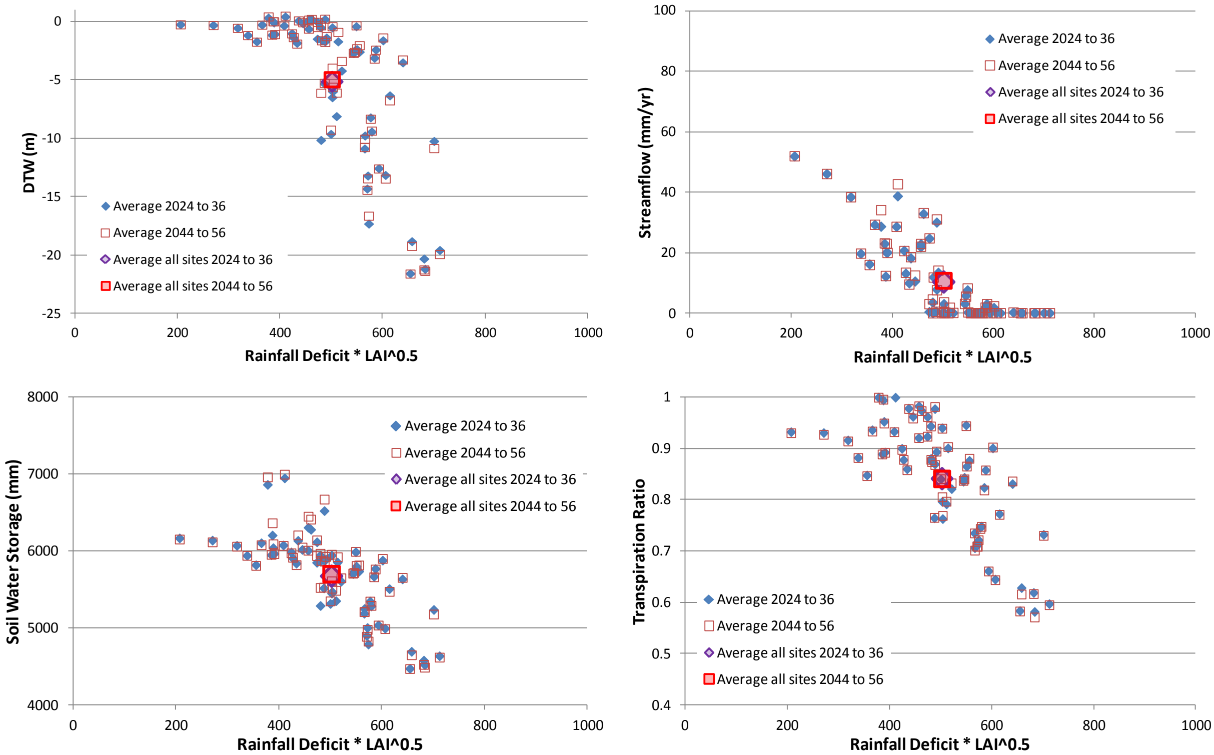


*Figure 25 Results of the 62 reference site strip-models for depth-to-water (DTW), streamflow, soil-water storage and transpiration-ratio plotted against RD*LAI$^{0.5}$ for the future scenario using the recent period repeated without modification.*

Figure 26 are similar plots to Figure 25 except that they are for the Miroc-H (most optimistic) scenario. It may seem at first glance that Figure 26 has been plotted incorrectly, as the 2050 (2044 to 2056) values are above those for 2030 (2024 to 2036); but these values are correct because this scenario has a protracted recovery from the low rainfalls of the recent period. Figure 27 is the same plots for the Miroc-M (middle) scenario and Figure 28 is for the CSIRO Mk 3.5 (worst case) scenario. The recovery seen in Figure 26 is now absent, with Figures 27 and 28 showing increasing severity with time.

The LAIs in all these scenarios are the 2011 values from the sample areas, maintained as a constant throughout the simulations. This results in some low transpiration-ratio values, particularly in Figures 27 and 28; in reality the LAI would diminish and the transpiration-ratio wouldn't drop significantly below a value of 0.7. It would be possible to account for this within the modelling if a dynamic LAI were used, however, the present modelling uses measured LAIs.

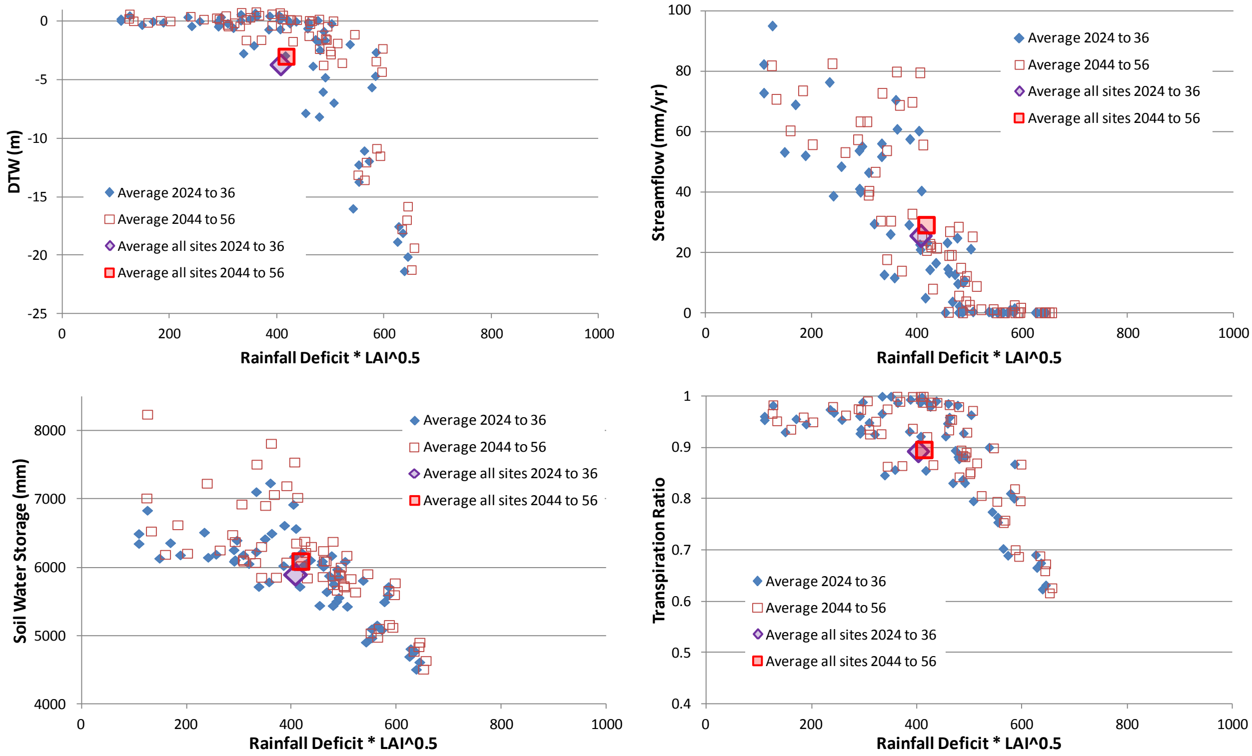


*Figure 26 Results of the 62 strip-models for depth-to-water (DTW), streamflow, soil-water storage and transpiration-ratio plotted against RD*LAI$^{0.5}$ for the Miroc-H future scenario.*

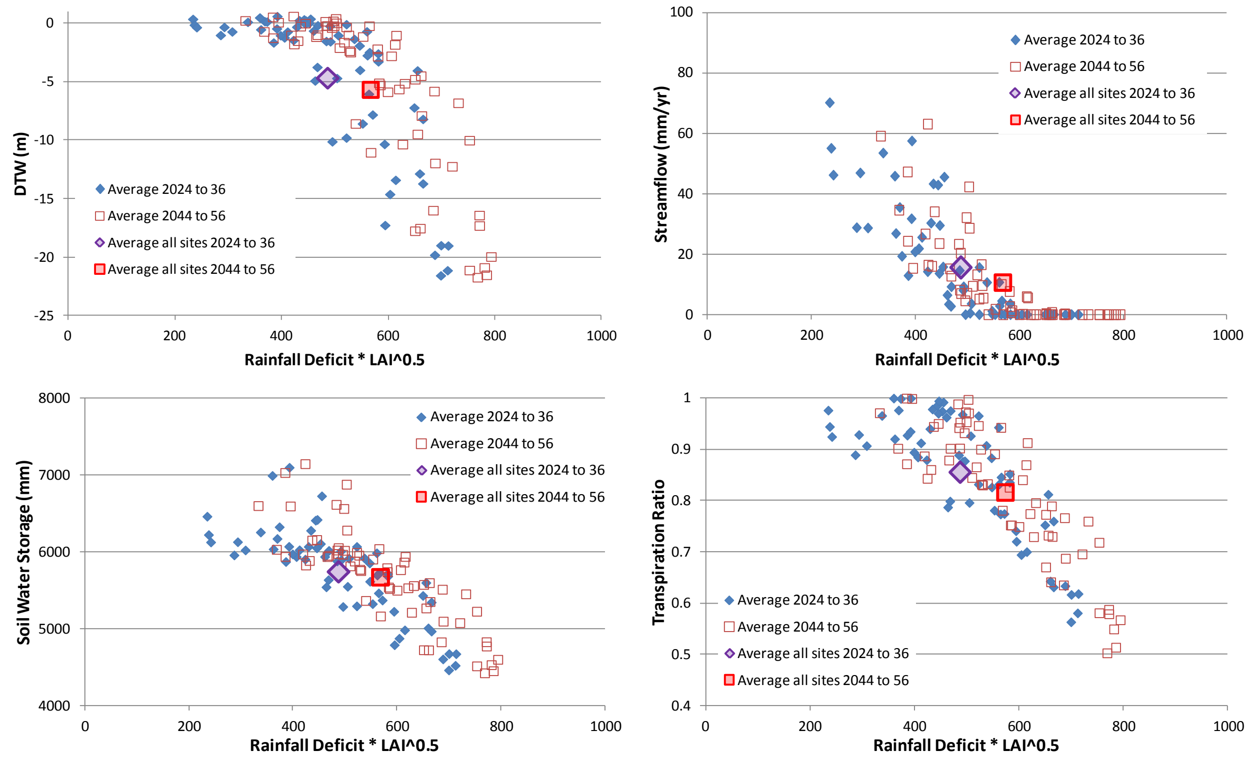


*Figure 27 Results of the 62 strip-models for depth-to-water (DTW), streamflow, soil-water storage and transpiration-ratio plotted against RD*LAI$^{0.5}$ for the Miroc-M future scenario.*

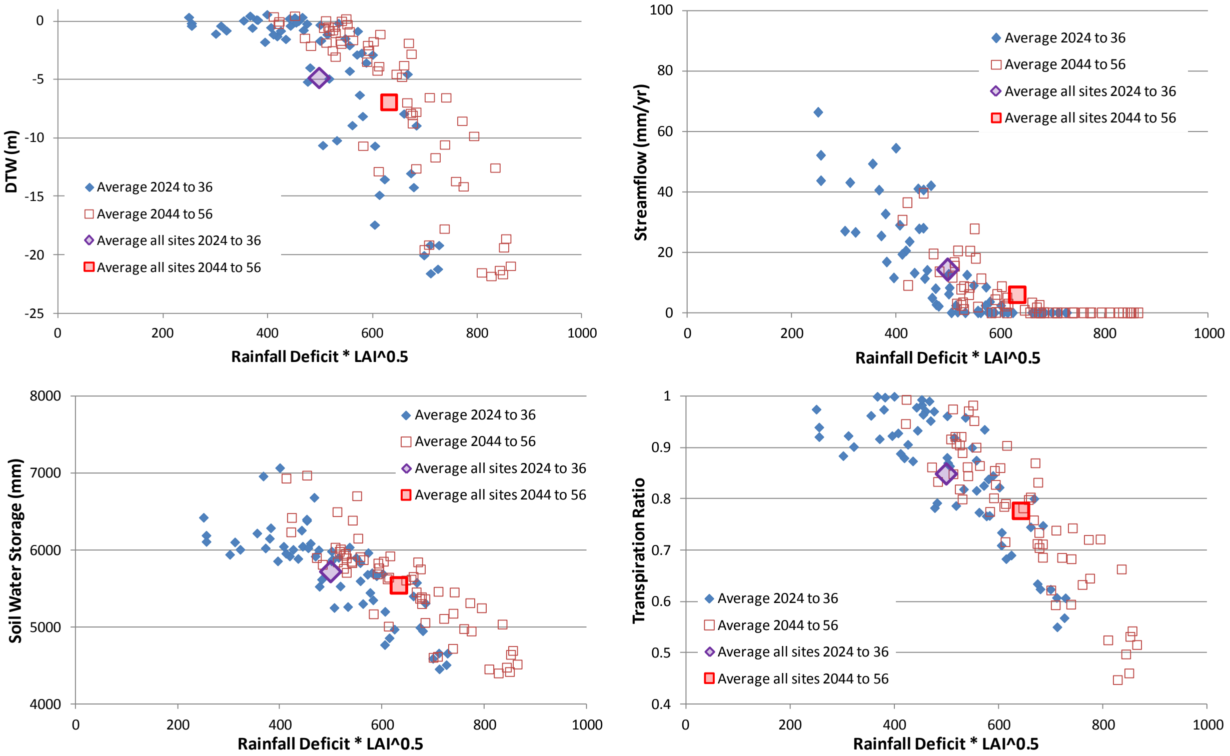


*Figure 28 Results of the 62 strip-models for depth-to-water (DTW), streamflow, soil-water storage and transpiration-ratio plotted against RD*LAI$^{0.5}$ for the CSIRO Mk 3.5 future scenario.*

It can be seen in all three scenarios shown in Figures 26 to 28 that a threshold value of about 600 is ever present. The value is slightly lower in Figures 27 and 28 for the 2030 (2024 to 2036) value compared to the 2050 (2044 to 2056) value; because the rainfall is reduced within the series by linear interpolation, there results a gradual reduction with time.

9.2 Future Scenario Constant LAI Results – Recent Period Climate

In all simulations presented so far, the LAIs have been estimated from the LAI sample areas at each of the representative sites. What will now be presented is a series of plots where the LAI is set to a constant value for each scenario set. The values used were 0.5, 1.0, 1.5, 2.0, and 2.5. These are given in Figures 29 to 33 for the recent-period climate repeated without modification. As each of these plots has a constant LAI, the LAI term on the x-axis can now be dropped and the plots done against rainfall deficit alone. For each LAI there is a defined value of rainfall-deficit above which all the parameters start to enter a zone marked by a lack of hydrological activity: groundwater at depth; streamflow near zero; soil-water storage dropping to what appears to be a minimum; and transpiration-ratio falling to 0.7 or less. Table 2 is a tabulation of these against LAI.

Table 2 Table of threshold rainfall deficit values for given LAIs. This is based on Figures 29 to 33.

LAI	Rainfall Deficit Threshold Value (mm/yr)
0.5	820
1.0	600
1.5	500
2.0	450
2.5	400

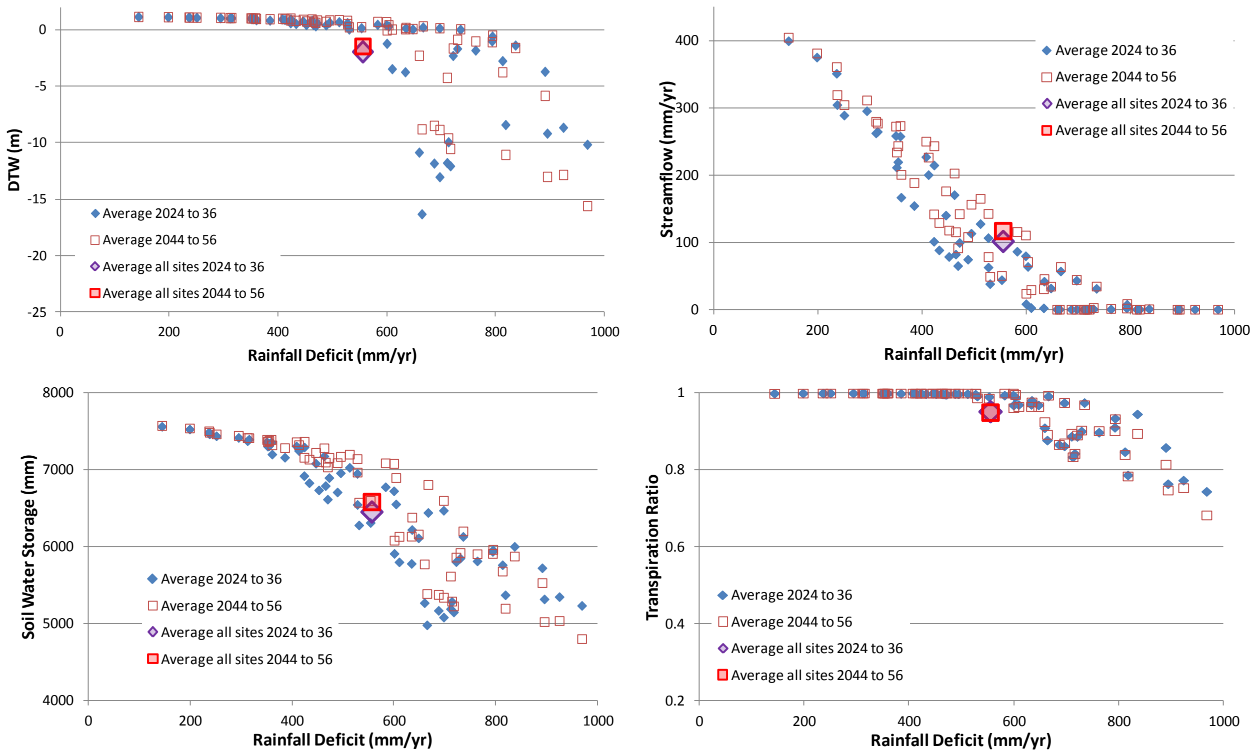


Figure 29 Results of the 62 reference site strip-models for an LAI of 0.5 for the recent-period climate repeated without modification.

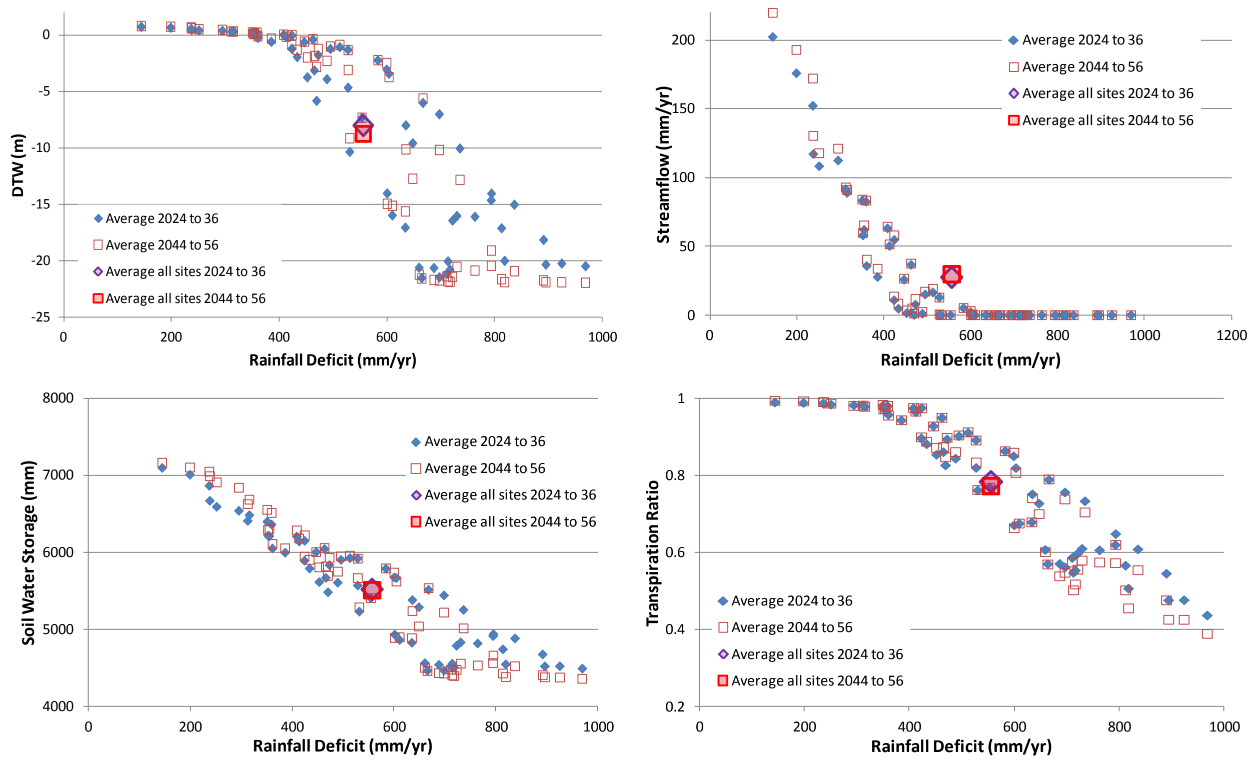


Figure 30 Results of the 62 reference site strip-models for an LAI of 1.0 for the recent-period climate repeated without modification.

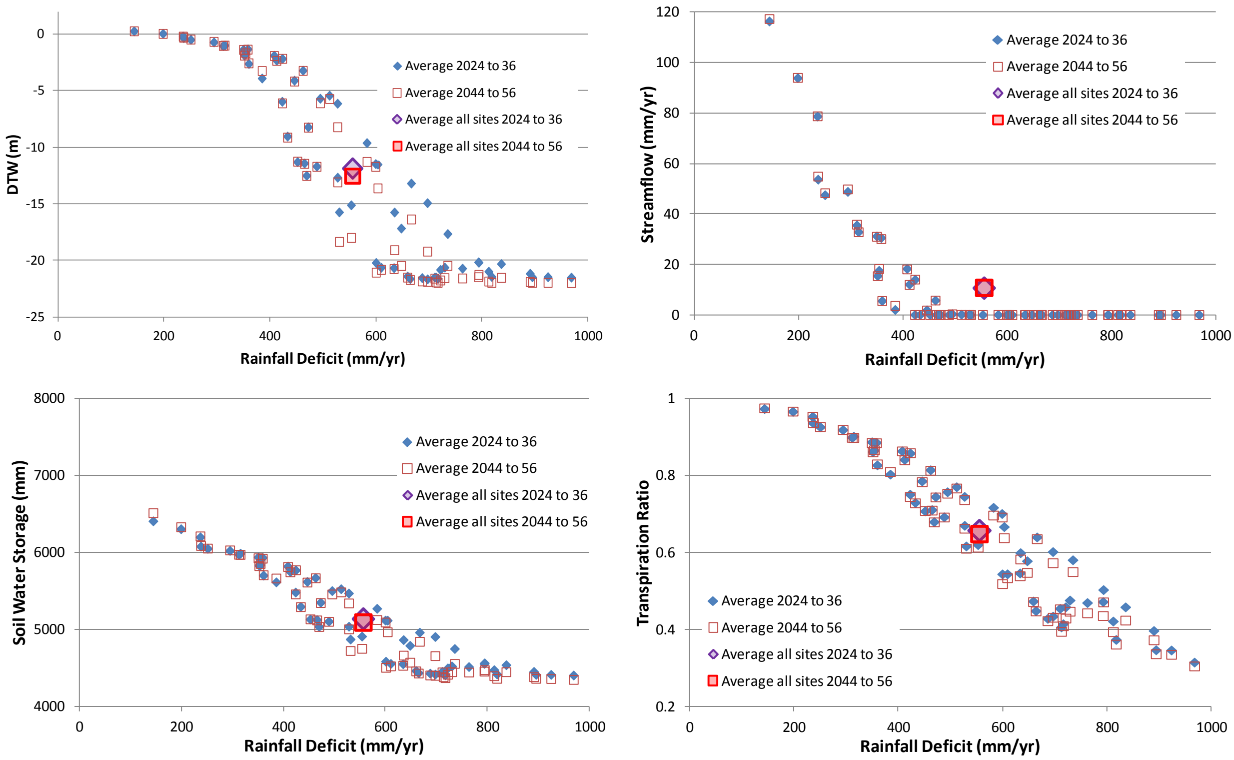


Figure 31 Results of the 62 reference site strip-models for an LAI of 1.5 for the recent-period climate repeated without modification.

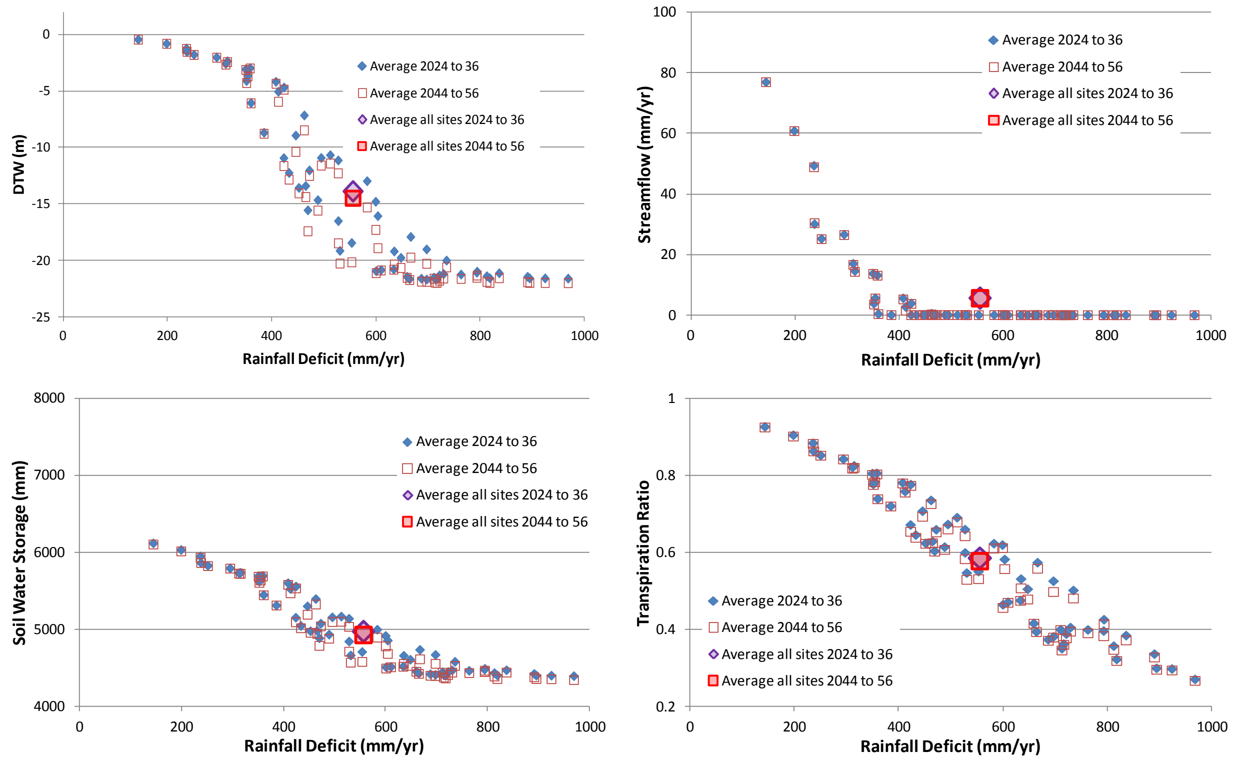


Figure 32 Results of the 62 reference site strip-models for an LAI of 2.0 for the recent-period climate repeated without modification.

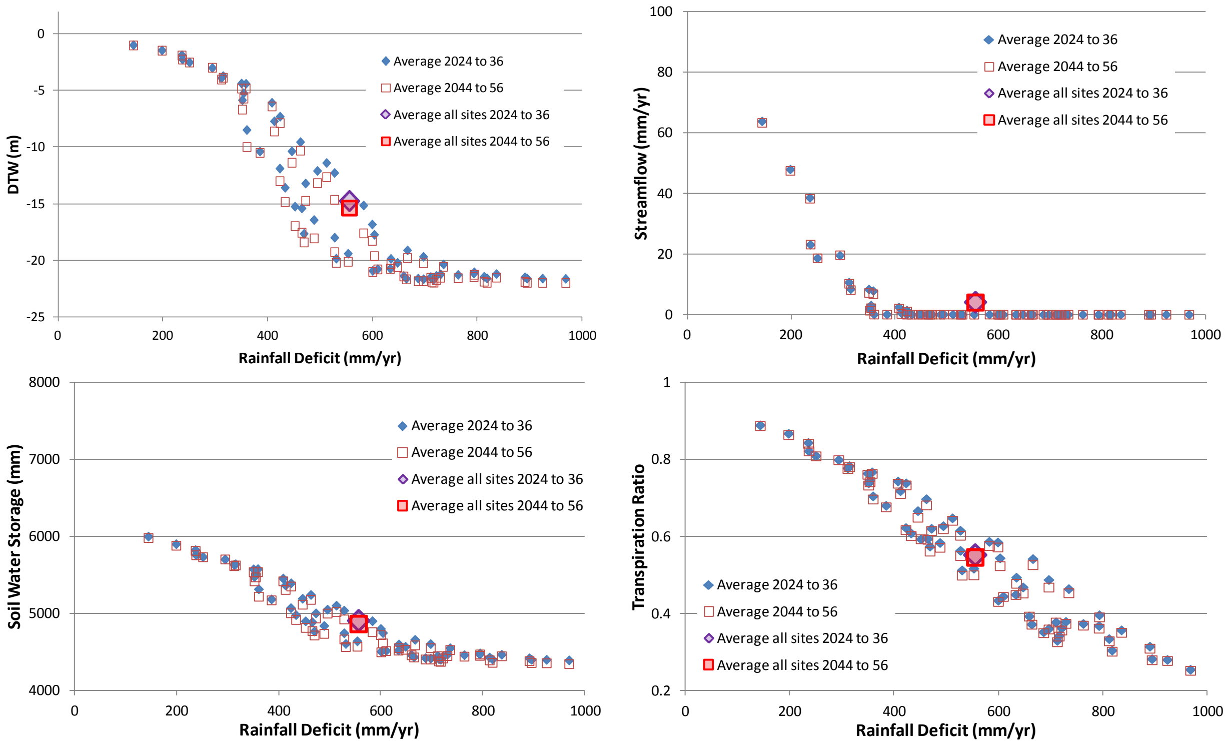


Figure 33 Results of the 62 reference site strip-models for an LAI of 2.5 for the recent-period climate repeated without modification.

If streamflow is singled out as it the easiest to quantify threshold values for, then Figure 34 can be created to give the LAI vs. rainfall-deficit values for four levels of streamflow; zero, 10 mm/yr, 50 mm/yr and 100 mm/yr. The regressions given are limited to the range of data, for instance if the zero streamflow regression is extrapolated to a rainfall deficit of 200 mm/yr, then the resultant LAI is 13, an obviously impossible value. However, with these limitations in mind, Figure 35 shows the LAI values required to generate streamflows of zero and 100 mm/yr for the rainfall scenario based on the recent-rainfall repeated.

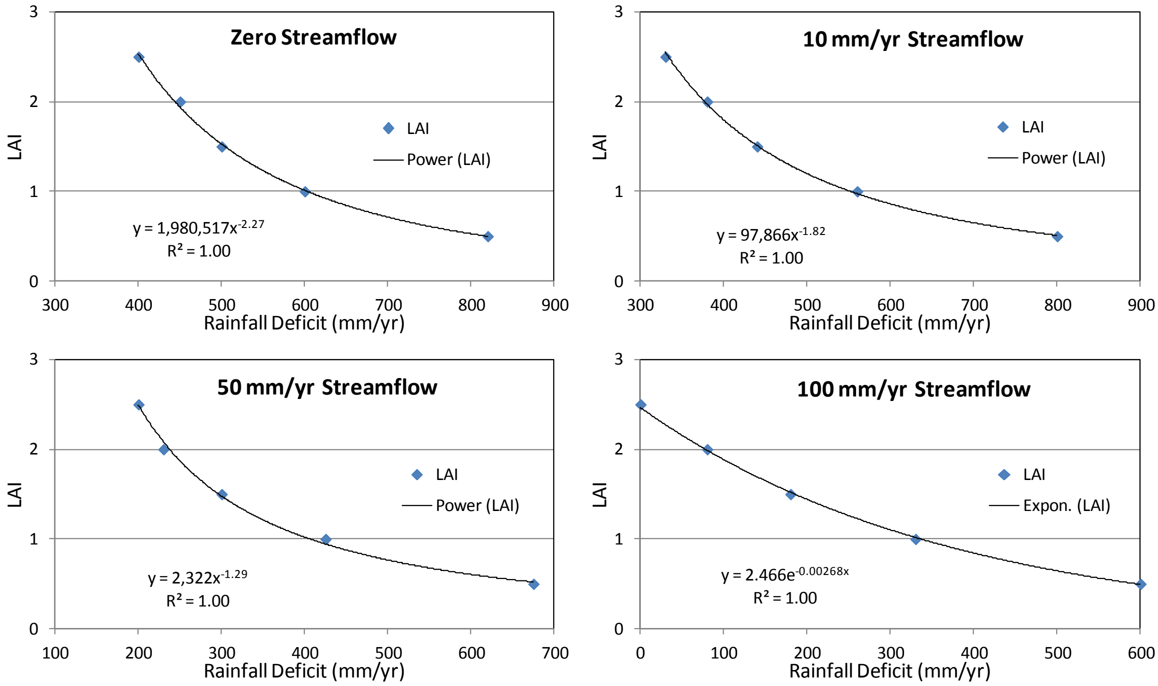


Figure 34 LAI vs. rainfall deficit values for four levels of streamflow; zero, 10 mm/yr, 50 mm/yr and 100 mm/yr.

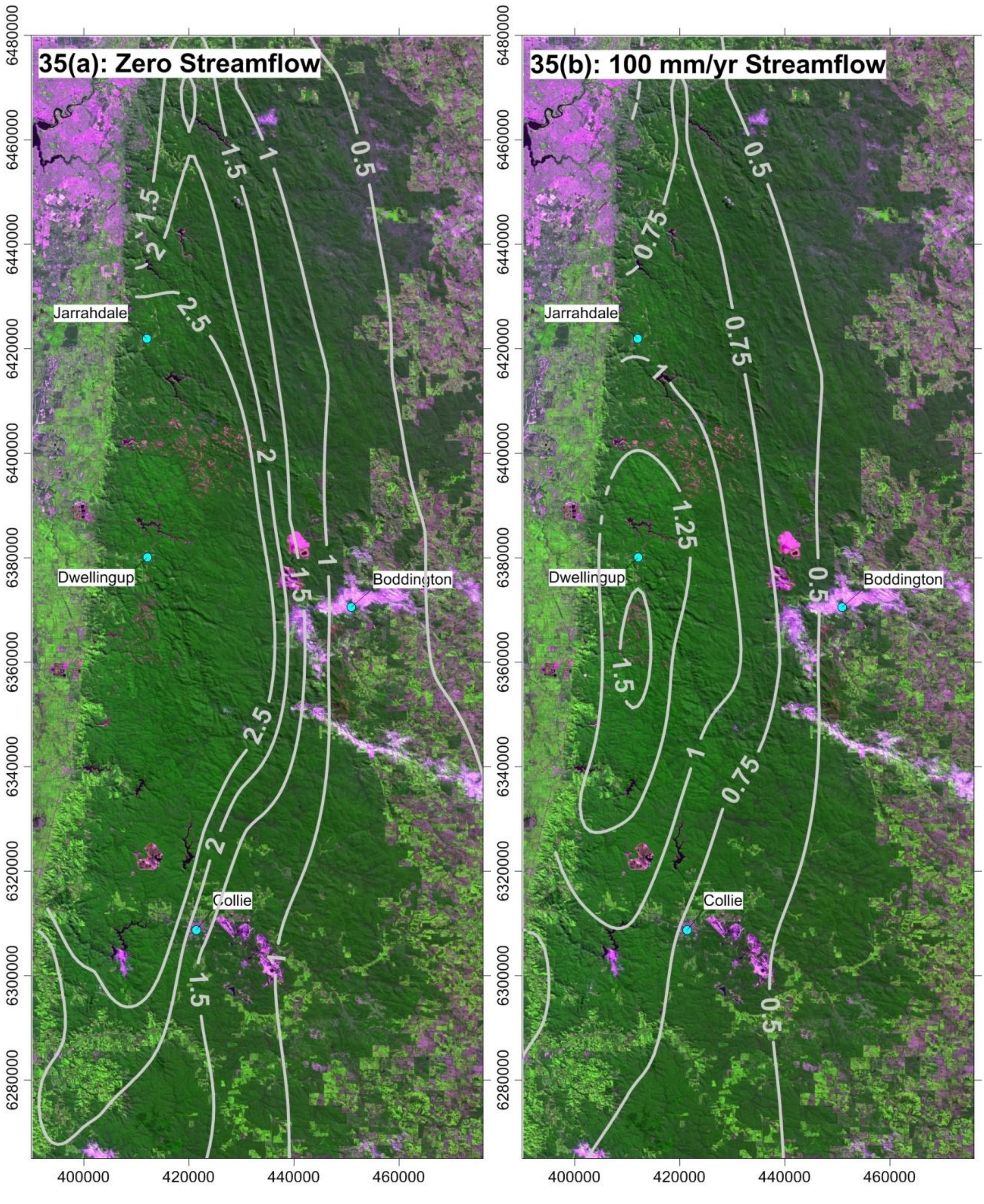


Figure 35 LAIs that would result in zero and 100 mm/yr streamflow; climate is the 2000-2012 repeated.

It can be seen from Figure 35 that for the zero streamflow case, a considerable area of the northern jarrah forest can support an LAI of 2.5 or above. This area extends from Jarrahdale in the north to past Collie in the south. However, it needs to be understood that were the LAI to be at this level and the rainfall of the recent past were to continue into the future, then the majority of this area would be not only be without streamflow, but would also have groundwater at depth in the valley-floor and soil-water storages would drop to low levels. For the 100 mm/yr streamflow case, the LAIs have a maximum of 1.5 centred just to the south of Dwellingup. Approximately, the LAIs for the 100 mm/yr streamflow case are about half those for the zero streamflow case.

9.3 Constant LAI Results – Miroc-H, Miroc-M and CSIRO Mk 3.5

We have already seen from Figure 18 that the rainfall-deficit ratios for all three Yates *et al.* (2010) climate-scenarios were less in 2030 than they were for the recent period, 2000 to 2012, repeated. For 2050, the Miroc-H rainfall-deficit ratio was still less, while those for Miroc-M and CSIRO Mk 3.5 were greater, with CSIRO Mk 3.5 being the worst case. To provide a simple comparison with Figures 29, 31 and 33, Figures 36 to 38 show the results for constant LAIs of 0.5, 1.5 and 2.5 for the CSIRO Mk 3.5 climate scenario. The main change in behaviour for the CSIRO Mk 3.5 climate scenario is that there is a difference between the 2030 values (2024 to 36) and the 2050 values (2044 to 56). The 2050 values are shifted to the right due to the higher rainfall-deficit for this period and this is accompanied by a reduction in parameter values, particularly for the higher LAIs. There is, however, a complication with Figures 36 to 38. It can be seen that while the 2030 threshold rainfall-deficit values for a given LAI tend to be a good match to those in Figures 29, 31 and 33 and Table 1, the 2050 values are shifted to the right and imply higher threshold rainfall-deficit values. This is, however, an artefact of the climate scenario in that rainfall and potential evaporation ratios are changing with time as they move from the recent values to the 2030 values and then to the 2050 values. In particular, the change between 2030 and 2050 is much larger than between the recent values and the 2030 values (Figure 18, CSIRO Mk 3.5 to recent), and the modelled hydrological-system is not able to reach a new stability by 2050 and is therefore implying a different threshold-value. Given time under a consistent climate, all scenarios would display the same threshold values and the same relations between LAI, rainfall deficit and the four hydrological parameters. It is considered sufficient in the present study to use the threshold values in Table 1 and Figure 34 for all climate scenarios and to leave the more complex questions relating to non-stationarity to the detailed modelling which would be undertaken as part of catchment management, e.g. one of the following steps for the application presented in Section 10.

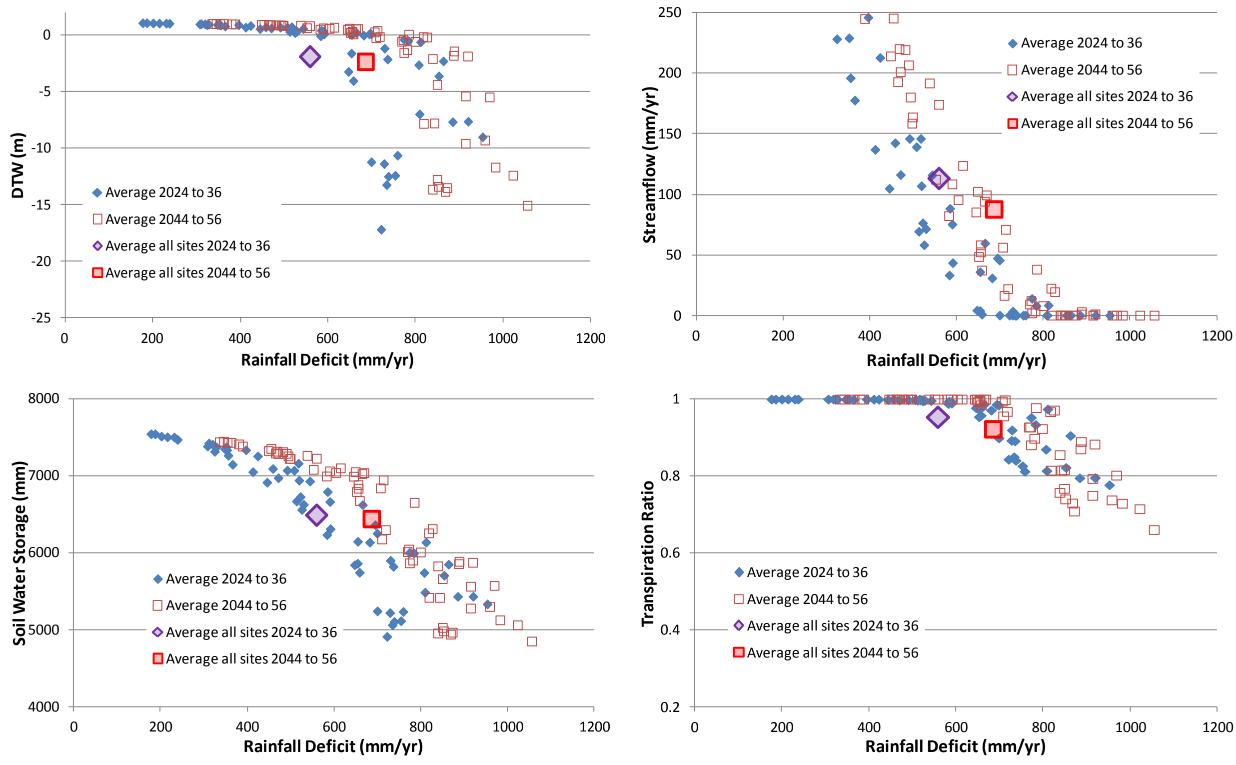


Figure 36 Results of the 62 reference site strip-models for an LAI of 0.5 for the CSIRO Mk 3.5 climate scenario.

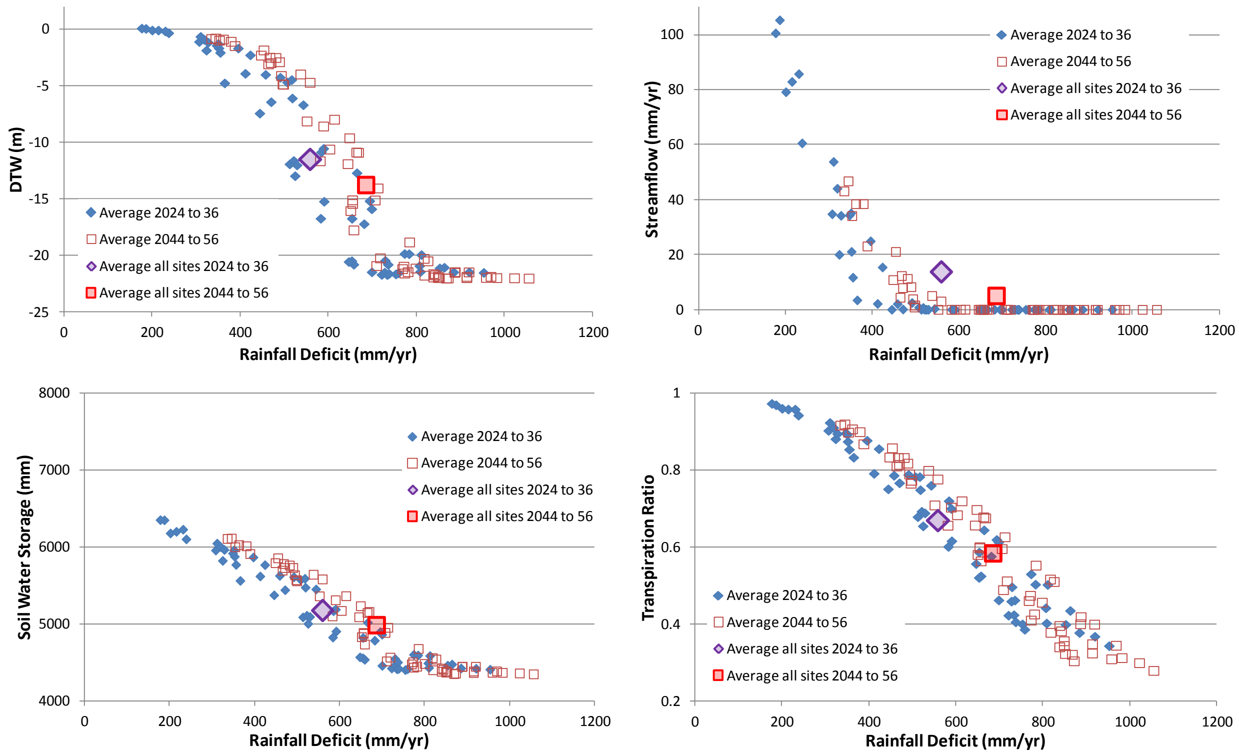


Figure 37 Results of the 62 reference site strip-models for an LAI of 1.5 for the CSIRO Mk 3.5 climate scenario.

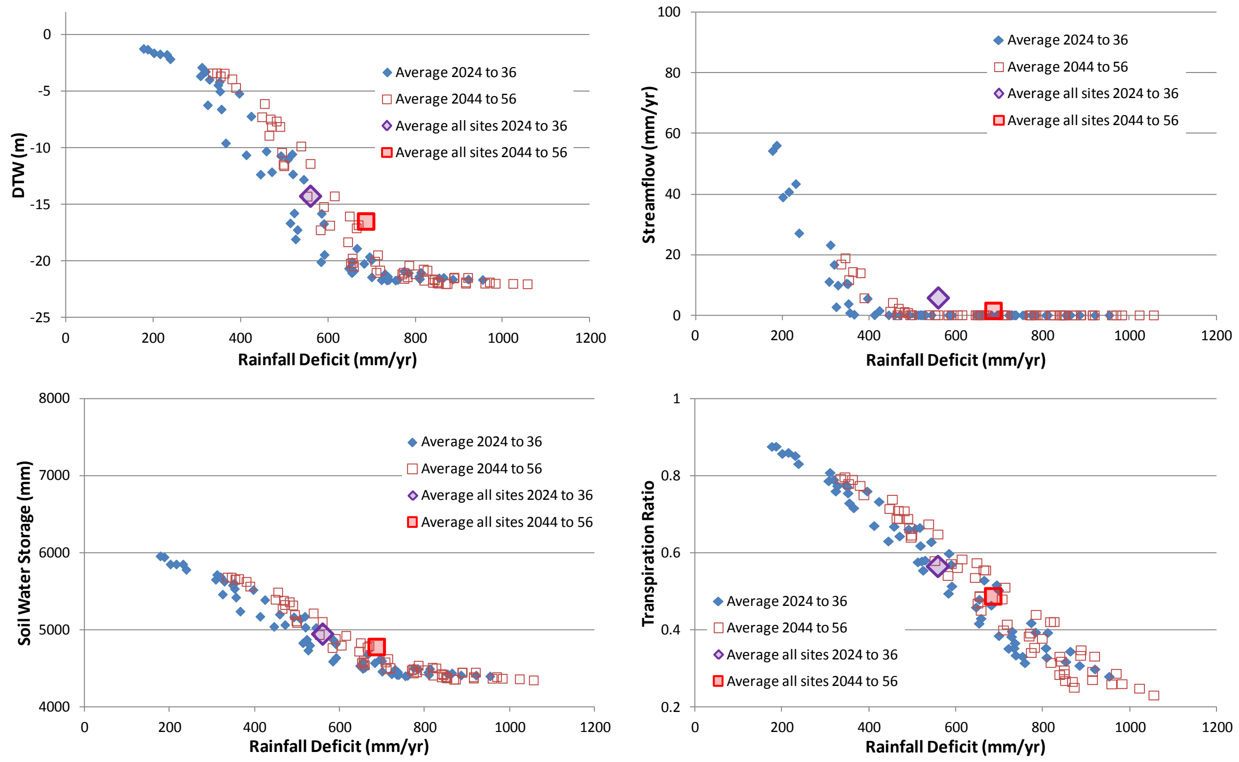


Figure 38 Results of the 62 reference site strip-models for an LAI of 2.5 for the CSIRO Mk 3.5 climate scenario.

Figure 39 shows the 2030 LAIs for the CSIRO Mk 3.5 climate scenario compared to those for the recent-climate repeated from Figure 35(a), and Figure 40 shows the 2050 and 2070 LAIs for the CSIRO Mk 3.5 climate scenario. Both figures are for the zero streamflow case. The differences for 2030 between the two climate scenarios are very slight; the CSIRO Mk 3.5 scenario has small extensions of the 2.5 LAI area to both the north and the south. In contrast, by 2050 there has been a strong contraction of the 2.5 LAI area (Figure 40(a)), and by 2070 the 2.5 LAI area has been replaced by a similar shaped one for an LAI of just 1.25 (Figure 40(b)).

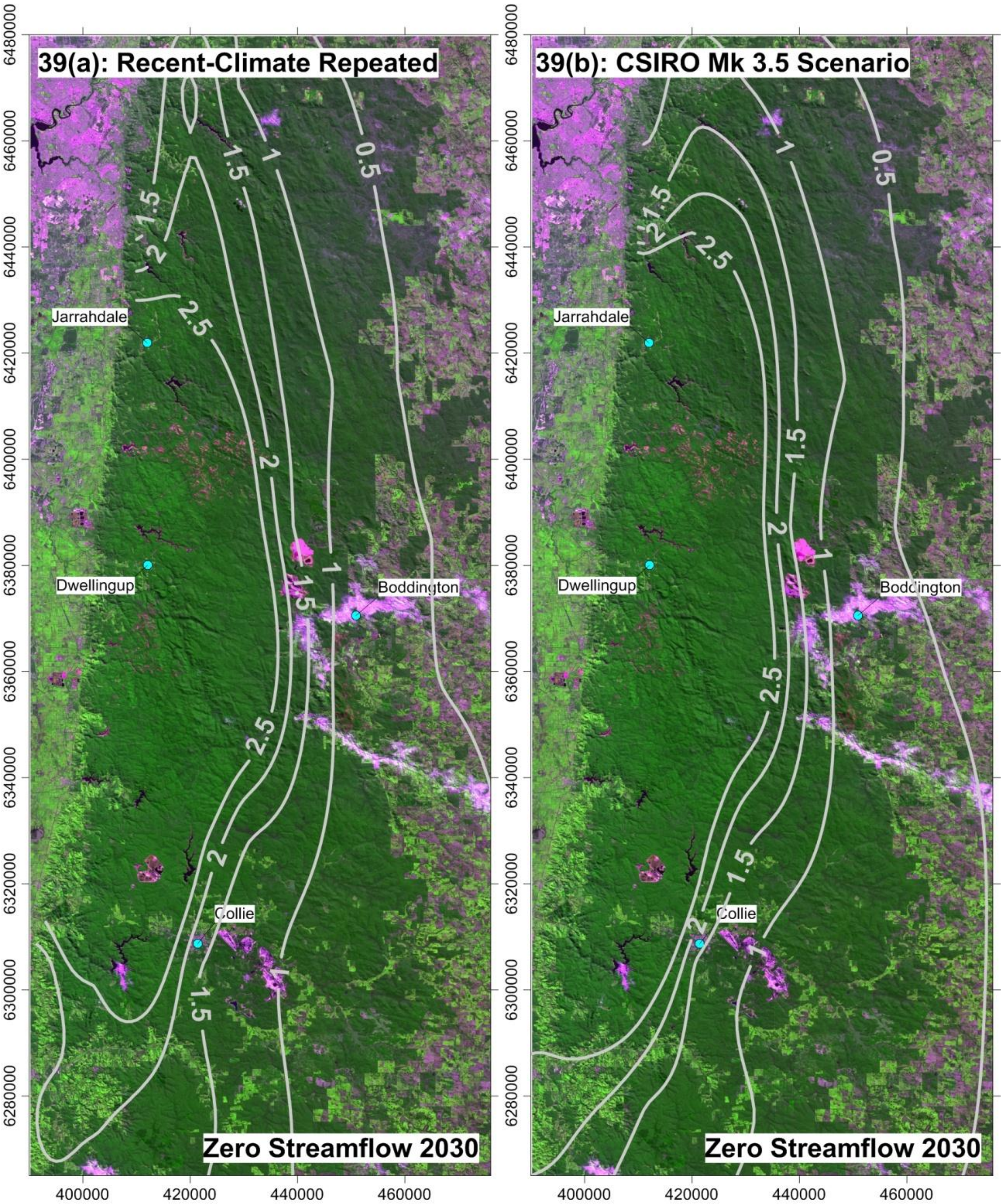


Figure 39 LAIs that would result in zero streamflow in 2030; climates are the 2000-2012 repeated and the CSIRO Mk 3.5 climate scenario.

The implications of Figure 40 are clear: if the CSIRO Mk 3.5 climate scenario were to occur in the absence of major reductions in LAI, then all streamflow within the northern jarrah forest would disappear by 2070, and even by 2050 the majority of the northern jarrah forest would be producing no streamflow. For the other two climate scenarios, the Miroc-H is always less extreme than the recent-climate repeated (Figure 18), so if plots similar to Figures 39 and 40 were made for it, then they would always have slightly higher LAIs than Figure 39(a). For Miroc-M, its 2070 rainfall-deficit ratio is equivalent to that for the CSIRO Mk 3.5 scenario for 2050 (Figure 18), so it would have a similar LAI map in 2070 for zero streamflow as does the CSIRO Mk 3.5 scenario in 2050.

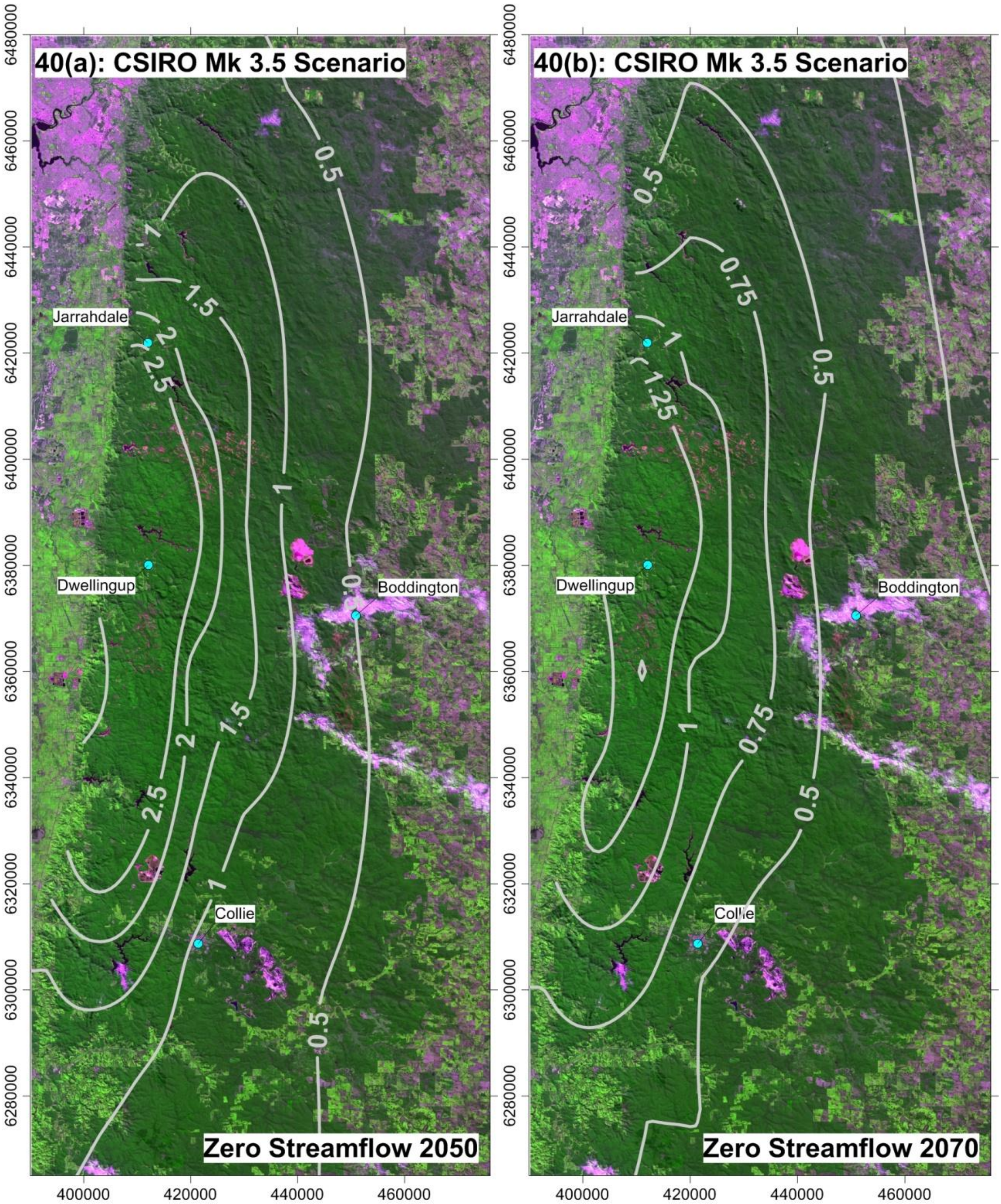


Figure 40 LAIs that would result in zero streamflow in 2050 and 2070; climate is the CSIRO Mk 3.5 climate scenario.

9.4 Northern Jarrah Forest Target LAIs

In this section we will produce maps of the target LAIs required to produce particular hydrology outcomes for the northern jarrah forest. The first map is for restoration to the full functionality of the historical period, 1961 to 1990, but under the rainfall scenario based on the recent past, that is 2000 to 2012 repeated into the future. Simply put, can the hydrology of the past in terms of streamflows, groundwater levels and soil-water storages be sustained under the rainfall of the present. This was calculated by creating an equation for each site with 2000 to 2012 LAI as the unknown for the equation with the two rainfall deficits and the 1961 to 1990 LAI from Figure 24 as the knowns; the resultant LAI map is shown in Figure 41(a).

It is obvious from Figure 41(a) that restoration to the 1961 to 1990 hydrology levels is impractical under the rainfall of the recent past. LAIs would have to be dropped to very low levels, which even the most enthusiastic treatment programme could not maintain. What is interesting, however, in Figure 41(a) is the variation for the target LAIs across the northern jarrah forest; this is driven in large part by the variations in LAI measurements for the period 1961 to 1990, as these are used in the calculation.

A possible treatment option for the northern jarrah forest would be to target a streamflow of 100 mm/yr for the High Rainfall Zone (HRZ - >1,100 mm/yr rainfall), 10 mm/yr for the Intermediate Rainfall Zone (IRZ – 900 to 1,100 mm/yr rainfall) and 1.0 mm/yr for the Low Rainfall Zone (LRZ - <900 mm/yr rainfall). Figure 41(b) shows what the target LAIs would be like for such a streamflow regime. The average value of 100 mm/yr for the HRZ was selected as a reasonable target-minimum based on a review of historical streamflows for the three untreated experimental catchments in the HRZ: 31 Mile Brook catchment (115 mm/yr average flow for 1985 to 2012, this average included simulated data for missing years), Bates catchment (144 mm/yr average flow for 1988 to 2012), and Waterfall Gully catchment (220 mm/yr average flow for 1964 to 2012). The streamflow of 10 mm/yr for the IRZ is considered to be a typical value for catchments about midway across the zone, that is at about 1,000 mm/yr average annual rainfall. The control Gordon catchment with an average rainfall of 1,000 mm/yr has an average streamflow of 9 mm/yr, and the treated catchment of Jayrup, also with an average rainfall of about 1,000 mm/yr, has an average streamflow of 14 mm/yr; these are for data up to and including 2009. For the LRZ, the value of 1.0 mm/yr reflects the very low streamflows for this zone and represents a likely value midway across the zone. The control catchment of Tunnel Rd (800 mm/yr average rainfall) averaged 0.6 mm/yr streamflow for the period 1975 to 1996.

An interesting observation for Figure 41(b) is the way the 1.5 LAI isohyet appears to encapsulate a lighter coloured, and therefore higher LAI, area of forest in the underlying false-colour Landsat image (this variation in LAIs may not be as obvious on some printed versions of this report as it is on the electronic PDF). Similar light-coloured areas are directly to the north of Jarrahdale and Dwellingup, but these are areas of bauxite mine rehabilitation. While this colour difference in the Landsat image for the area inside the 1.5 LAI isohyets may easily have a cause not related to the slightly elevated rainfall-deficit our mapping has defined for this area, it is still interesting to note its existence.

A common way of expressing forest density is basal area. A conversion of 15 was used in the Wungong Catchment Trial studies (1.0 LAI = 15 m^2/ha basal area), and this value has been used to produce the basal-area maps in Figure 42 from the LAIs in Figure 41. It needs to be noted that the relation between basal area and LAI for a given forest type is dependent on many factors such as stand age, past management, etc. Mauger (2009) obtained a conversion of about 15 for LAIs around 1.0, and about 20 for LAIs of 2.0. The value of 15 has been used to generate Figure 42 as it is derived from the LAIs of Figure 41 which are in the range 0.25 to 1.5.

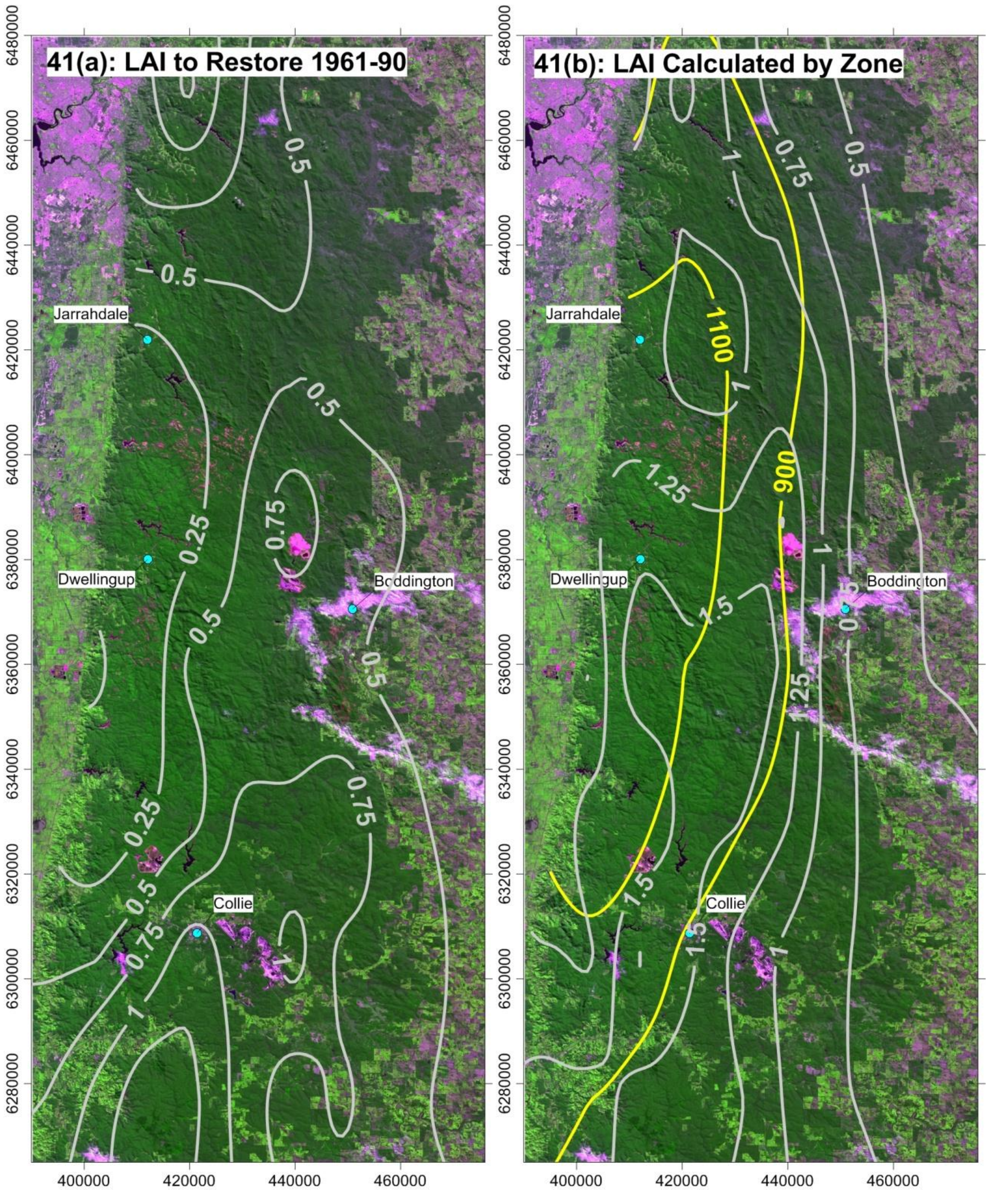


Figure 41 (a) Map of required LAI to restore 1961 to 1990 hydrology, and (b) required LAI to generate rainfall-zone specific streamflows of 100 mm/yr for the HRZ, 10 mm/yr for the IRZ, and 1.0 mm/yr for the LRZ; climate is the 2000-2012 repeated.

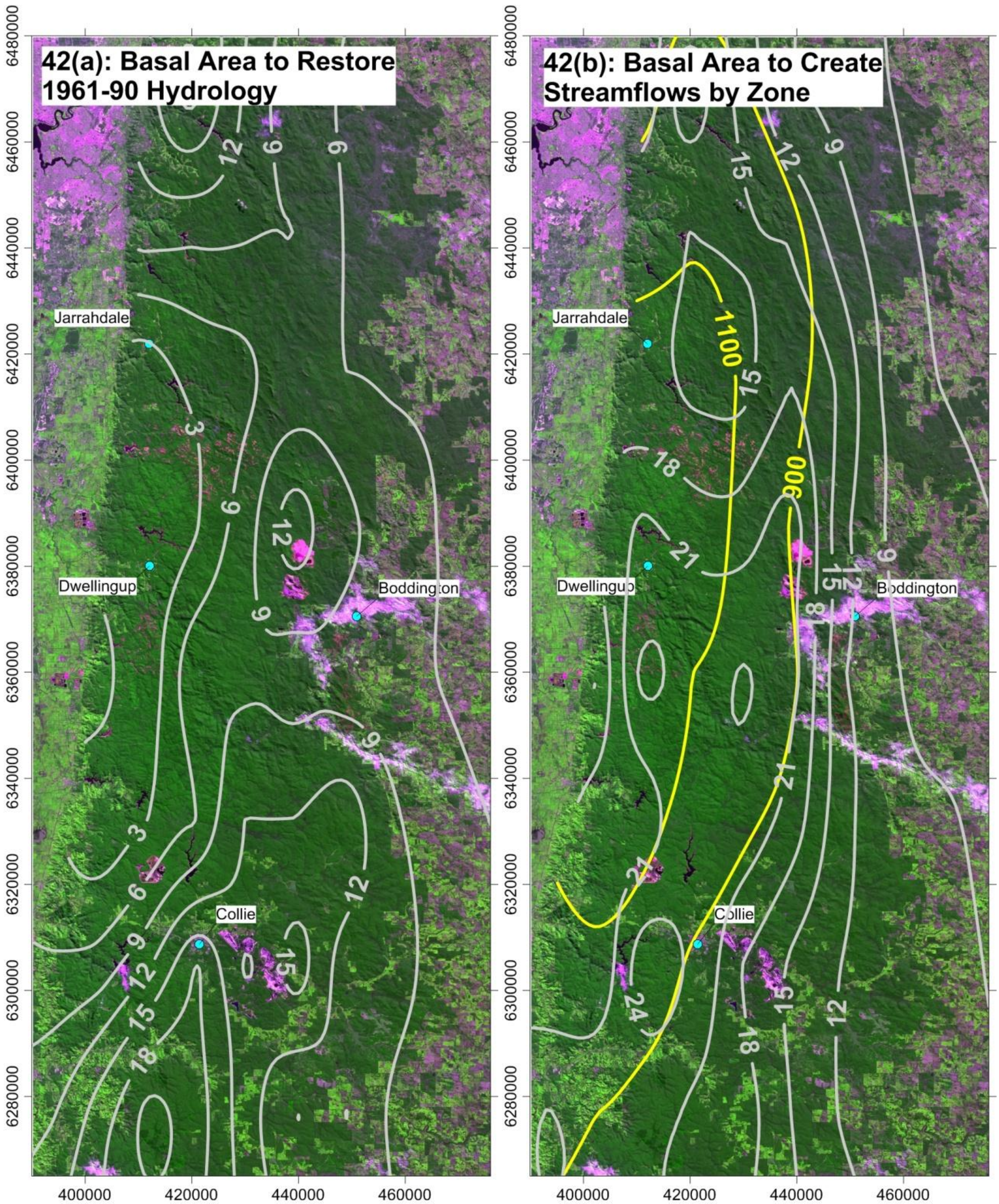


Figure 42 (a) Map of required basal area to restore 1961 to 1990 hydrology, and (b) required basal area to generate rainfall-zone specific streamflows of 100 mm/yr for the HRZ, 10 mm/yr for the IRZ, and 1.0 mm/yr for the LRZ; climate is the 2000-2012 repeated.

9.5 Possible Future Vegetation Scenarios

In the preceding section, Figure 41(b) was provided which was a map of LAIs that would generate rainfall-zone specific streamflows of 100 mm/yr for the HRZ, 10 mm/yr for the IRZ, and 1.0 mm/yr for the LRZ.; it was for the climate scenario of the recent-period (2000-2012) repeated. The intention in this section is to define options in terms of vegetation scenarios that would generate the required LAIs.

From a streamflow viewpoint, the area of most interest to such an exercise is the High Rainfall Zone (HRZ - >1,100 mm/yr rainfall); while the HRZ is only one-fifth of the area of the water-supply catchments operated by the Water Corporation (they are shown in Figure 7(a)), the HRZ has been estimated to generate 60% of the stream inflow to the water-supply reservoirs. It is thus important to the continued use of the northern jarrah forest as a water-supply option that the HRZ stream yields be maintained. Figure 43(a) shows as isohyets the LAI values required to maintain an average streamflow of 100 mm/yr in the HRZ for the climate scenario of the recent period (2000-2012) repeated; this map is a subset of Figure 35(b). Regarding the other hydrological parameters of groundwater depth, soil-water storage and transpiration-ratio, the LAIs shown as isohyets in Figure 43(a) would maintain the groundwater at the soil surface in the valley-floor, would provide soil-water storages of over 6,000 mm, and would maintain transpiration-ratios close to 1.0, that is no real vegetation water-stress.

The first question with regard to Figure 43(a), is “how far from the present forest density are these target LAIs”? Figure 43(b) uses the Landsat LAI map for 2011 to create a required LAI reduction map for the HRZ to make the 2011 observed LAIs match those in Figure 43(a). While it is easy to create such a map, it will be somewhat more difficult to execute; principally because the forest is dynamic, and attempts to grow towards the threshold values given in Figure 35(a), basically LAIs of above 2.5 for the whole of the HRZ. While there has been observed reversals within this growth process, Figure 21 in particular shows the reduction in LAIs in 2011 following the historically low rainfall of 2010, overall the forest is attempting to grow towards this threshold.

Studies done by Croton *et al.* (2012.a) as part of the Wungong Catchment Trial found that a short treatment-cycle was required to sufficiently suppress the LAI to get a useful response. The 31 Mile Brook catchment, adjacent to the Wungong catchment and in the extreme north of the HRZ, has a target LAI in Figure 43(a) of 0.8; it was suggested by Croton *et al.* that a thinning treatment to an LAI of 0.6 was required and that this had to be repeated every nine years. The form of the growth function used by Croton *et al.* was; a growth after treatment of 0.179 LAI units each year for the first two years, 0.0775 LAI units in the third year, and 0.0275 LAI units each additional year (Jack Bradshaw, pers. comm.). Figure 44 shows what this looks like as both a nine-year treatment-cycle and as a once-only treatment. It can be seen how the nine-year cycle-treatment is required to maintain an average LAI close to the target LAI of 0.8 (the treatment still has an average of 1.06). Note that this growth cycle also assumed follow-up silvicultural treatments, including coppice control, without which the recovery would be expected to be much more rapid. To give an indication of recovery rates without extensive follow-up treatments, the average recovery-rate was estimated from Landsat derived LAIs for the treated Conjurunup catchments of Hansen, Higgens, Jones and Lewis (orange line in Figure 44, Mauger - 2009). It can be seen that this recovery-line reaches the 31 Mile Brook untreated line 12 years post-treatment and exceeds the nine-year treatment-cycle maximum-value after just five years (an LAI of 1.24 in year five for the Conjurunup catchments compared to a nine year LAI of 1.20 for the 31 Mile Brook treatment scenario). It is noted that there have been other studies into jarrah-forest growth in response to thinning that have covered the matter in much more detail, e.g. Stoneman *et al*. (1996), so the above quoted growth rates for the Wungong and Conjurunup catchments should be viewed as indicative only.

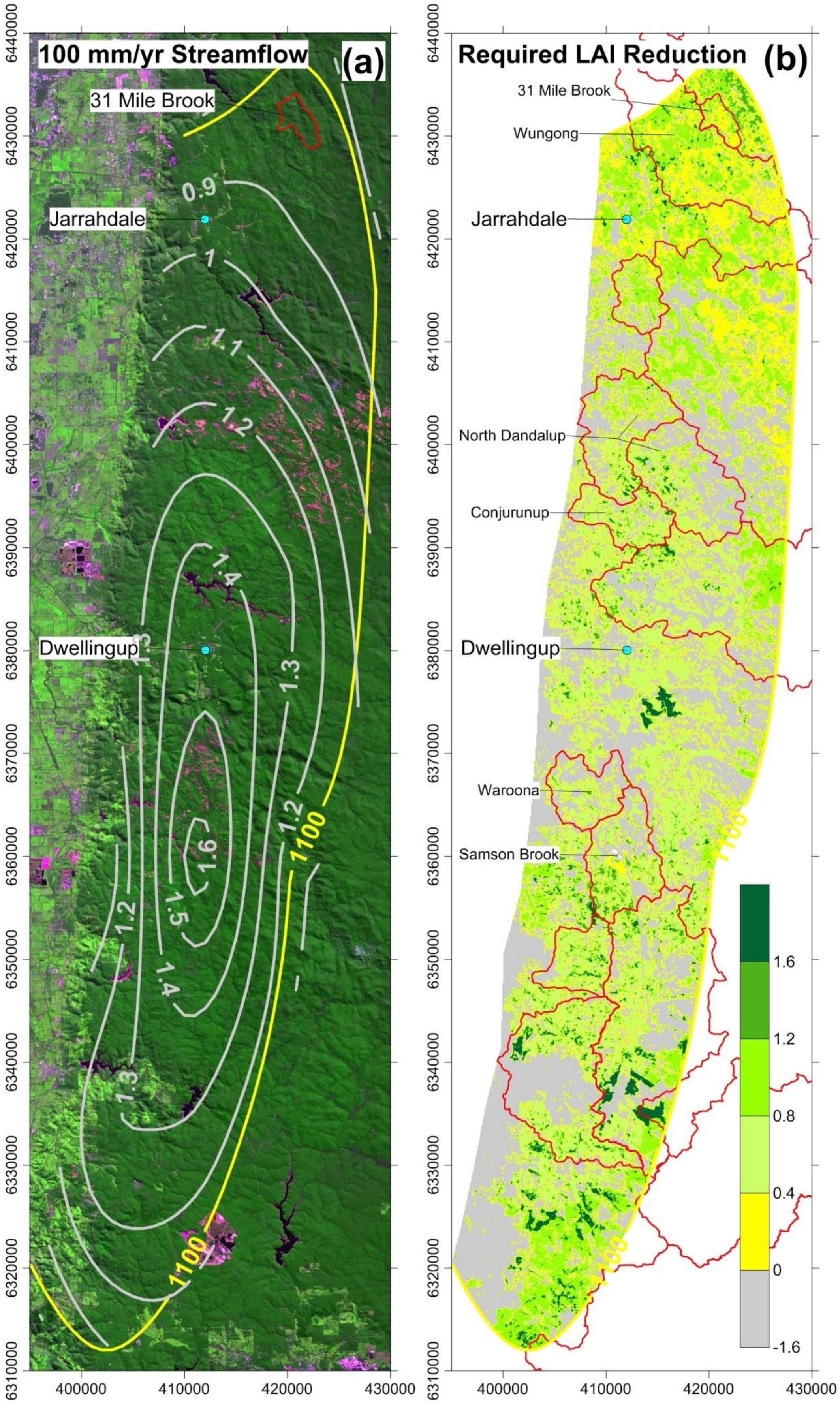


Figure 43 (a) LAIs that would result in 100 mm/yr streamflow in the HRZ; climate is the 2000-2012 repeated. (b) The required LAI reduction from the 2011 LAI to achieve 100 mm/yr streamflow in the HRZ.

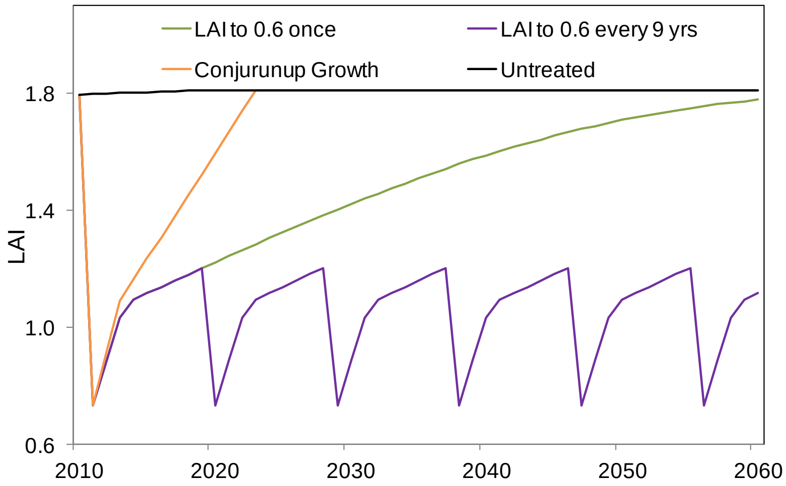


Figure 44 Estimated average LAIs for 31 Mile Brook catchment for suggested forest treatments from Croton et al. (2012.a). Also shown is the average LAI recovery-rate estimated for the Conjurunup catchments of Hansen, Higgens, Jones and Lewis.

The first conclusion from the above is that if a treatment is to create a useful hydrological response, it must include follow-up silvicultural treatments. Without these the LAIs will pass even the maximum of 1.6 in Figure 43(a) within 10 years after treatment. Secondly, undertaking treatments, even with follow-up silvicultural treatments, at places such as 31 Mile Brook with its threshold LAI of about 0.8 is going to require frequently reoccurring treatments to a low LAI, whereas undertaking the same treatment, or a lesser treatment with follow-up silvicultural treatments, on a much longer treatment cycle in the centre of the HRZ could keep the LAI below the target value for that area and produce a useful response.

In hindsight, the Wungong catchment in the extreme north of the HRZ was not a good choice for a catchment trial targeted at demonstrating a treatment response. Better choices would have been either: the North Dandalup reservoir catchment or the Conjurunup pipe-head dam catchment, both of which are closer to the centre of the HRZ and have target LAIs in Figure 43(a) of about 1.2; or the Waroona or Samson Brook dam catchments which are at the high point of target LAIs in Figure 43(a).

9.6 Inclusion of Mine Areas in Management Scenarios

A factor not readily apparent when viewing Figures 43(a) and (b) is the existence of bauxite mine areas within the HRZ, both active and rehabilitated. These are centred on the now closed Jarrahdale mine in the far north of the HRZ, the Huntly mine to the north of Dwellingup, and the Willowdale mine to the south of Dwellingup (black outlines in Figure 45).

In the previous section, the North Dandalup reservoir catchment and the Conjurunup pipe-head dam catchment were suggested as being possibly better sites than Wungong for trials into treatment responses. Figure 46 shows the two catchments in detail, in the false-colour Landsat image the rehabilitated mine areas in the Conjurunup and North Dandalup catchments appear as light green vegetation and the presently active mine areas appear as red/pink; there is additional future mining in the northern half of North Dandalup catchment that isn't shown. In both these catchments a significant proportion of the rehabilitation is still in juvenile form.

The modelling so far as part of the Wungong Catchment Trial (see reference list in the Appendix) has implied that mine rehabilitation has a higher plant water-use per unit leaf area when in its juvenile state (Figure 8); however, modelling has also shown that this effect essentially disappears by age ten years. Seeing the present study is concerned with longer timeframes than this, such a temporary, juvenile vegetation effect has little relevance to the study; though it was accounted for in the catchment modelling studies that were provided to prove the suitability of the WEC-C model to the study. As well, modelling has implied that there are changes in the hydrology of the hillslope once mining takes place. These effects also appear to be non-linear where they cause an increase in streamflow and general hydrological activity for low LAIs and a reduction for high LAIs. The inflexion point appears to be an LAI of about 1.7, so if mine-area LAIs are kept at or below the target LAIs in Figure 43(a), this effect would always be a benefit.

Given the extent of the mine rehabilitation in the two catchments of Conjurunup and North Dandalup, combined with the likely lower cost of treatment for existing rehabilitation due to its youth, and the net saving in future rehabilitation costs that would result from establishing a less dense revegetation on the as-yet unrehabilitated areas, it is likely that useful and economic treatments could be considered for these two catchments. Croton *et al.* (2012.b) studied the options associated with the management of mine rehabilitation to address the needs of riparian ecosystems; this included consideration of catchment hydrology in general. They used the 31 Mile Brook catchment as an example and developed a number of management options. The treatments which showed promise for 31 Mile Brook in terms of augmentation of the hydrology were those associated with leaving some or all of the mine areas without an overstory cover, or with only limited overstory cover, that is revegetating with understory as the primary component. Of greatest interest were those where half the mine areas were revegetated with an emphasis on hydrology and half were revegetated for timber production. The mine areas selected for emphasis on hydrology were along the main stream-channel. The result was almost the same response for the groundwater system along the main stream-channel as for the simulations with all the mine-area revegetated with understory. For streamflows, there was a tripling of streamflows in the last decade of simulation and a doubling of flow-days even for the understory case where it was allowed to naturally grow and senesce. These responses were achieved with 53% of the mine area devoted to hydrology, or just 16% of the total catchment area. Given that the 31 Mile Brook catchment is in the northern HRZ and has a low target-LAI for treatments, undertaking similar exercises on the Conjurunup and North Dandalup catchments would result in greater responses, or conversely could be undertaken at a lesser intensity to achieve the same response. The total area of the Conjurunup and North Dandalup catchments is 190 km^2, which at 100 mm/yr streamflow equates to 19 GL/yr of reservoir inflow.

A similar situation to the Conjurunup and North Dandalup catchments exists for the Waroona and Samson Brook dam catchments; they total about the same catchment area and bauxite mining is being, or has been, undertaken in both (Figure 45). However, an important difference is that the Waroona and Samson Brook dam catchments are located at the maximum target-LAI area within the HRZ. Therefore, they can be either: maintained at a higher LAI than the Conjurunup and North Dandalup catchments for the same streamflow per unit area, or they can be managed to a similar level but with the expectation of higher rates of streamflow per unit area.

The Waroona and Samson Brook dam catchments are two of the seven dam catchments operated by the Water Corporation to supply water to the Harvey Water Irrigation Area (HWIA). The HWIA has differing needs to the overall Integrated Water Supply System (IWSS) operated by the Water Corporation in that it is dependent on releases from the seven dams in the northern jarrah forest as its primary supply and presently can't resort to options such as sea-water desalinisation.

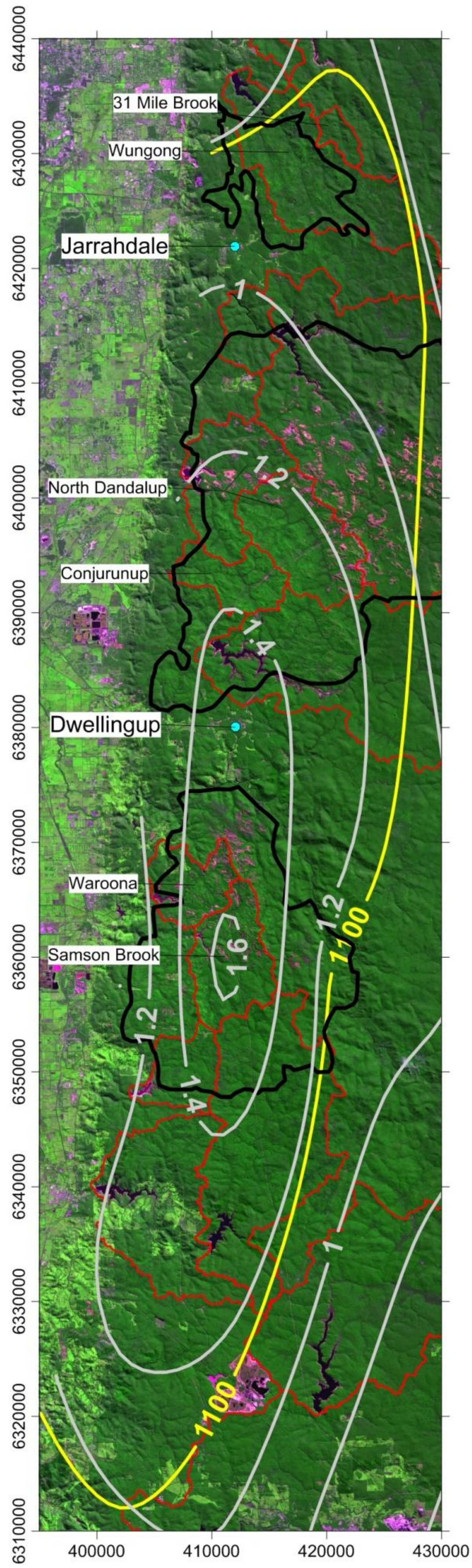


Figure 45 Mine areas overlain on a map of the HRZ, also included as isohyets are the target LAIs to achieve an average streamflow of 100 mm/yr. Mine regions are from http://www.walkgps.com/Bauxite%20Mining%20Impacts.htm.

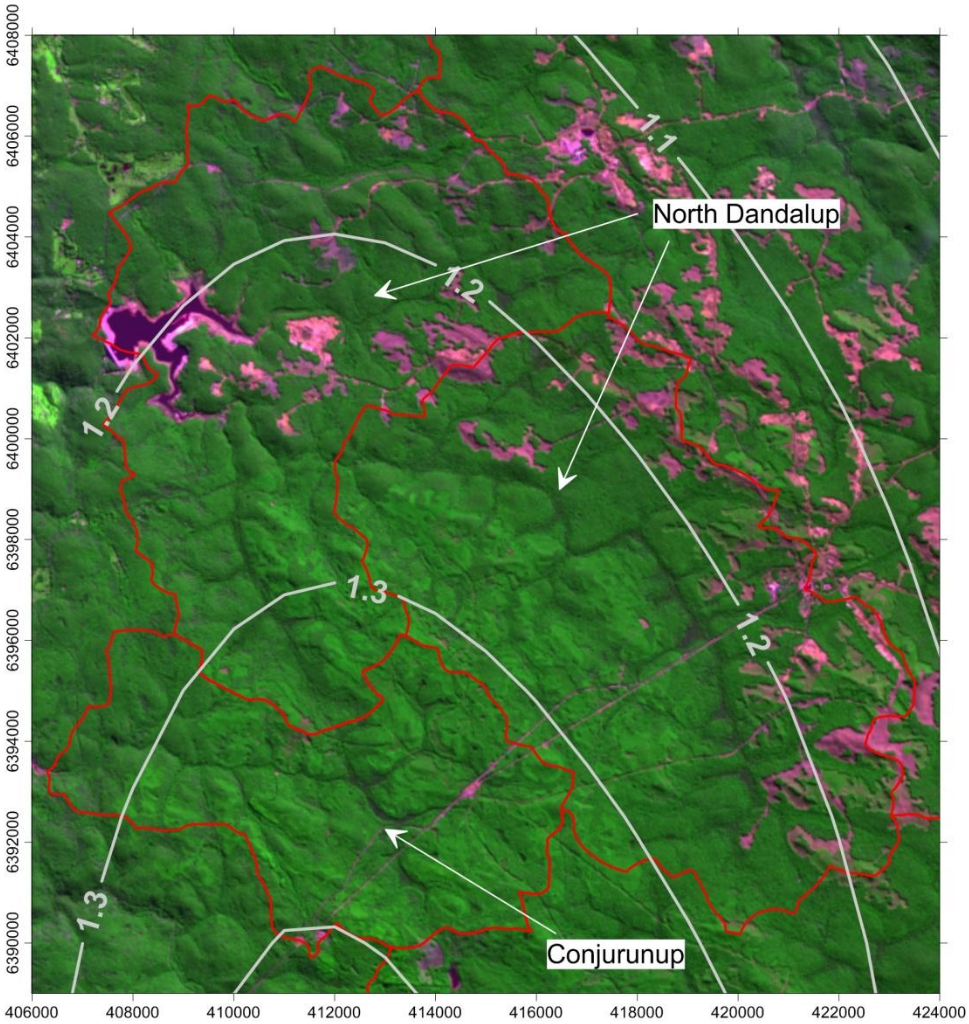


Figure 46 Mine rehabilitation (light green areas) and current mining (red/pink areas) in the Conjurunup and North Dandalup catchments. The target LAIs from Figure 43(a) are also overlaid. (The variation in LAIs that indicate rehabilitated mine areas may not be as obvious on some printed versions of this report as it is on the electronic PDF.)

It is obvious that for treatment scenarios like those discussed by Croton *et al*. (2012.b) to be successful, they have to be correctly targeted to the hydrology of the catchment. The WEC-C modelling in the final stages of the Wungong Catchment Trial, of which Croton *et al*. is an example, showed how to consider catchment-response variation and to effectively undertake treatment design. Conversely, the modelling and analysis done at the outset of the Wungong Catchment Trial using simple parametric models and other basic analysis tools showed the weaknesses of such approaches, including failure to identify the inadvisability of placing the trial at Wungong instead of further south. The knowledge, understanding and experience gained during the Wungong Catchment Trial needs to be retained. Interestingly, similar cautionary sentiments were expressed by Ruprecht & Stoneman (1993) when they reviewed jarrah forest water-yield issues 20 years ago.

To demonstrate the design process, in the next section an example catchment-management application will be presented for the Conjurunup catchment. A number of alternatives to the Conjurunup catchment exist, particularly the Waroona and Samson Brook dam catchments further south.

10 Example Catchment Management Application

As discussed in the previous section, the Conjurunup catchment north of Dwellingup is a good candidate for possible treatment to maintain streamflows within the HRZ. This catchment of 39 km^2 flows to a pipehead dam that feeds into the water-supply system of the Water Corporation. The catchment has been bauxite mined with 17 km^2 cleared (44% of the catchment area); Figure 47 shows the general layout of the catchment with the 2011 Landsat LAI shown as background and the mine-clearing outlines marked in black.

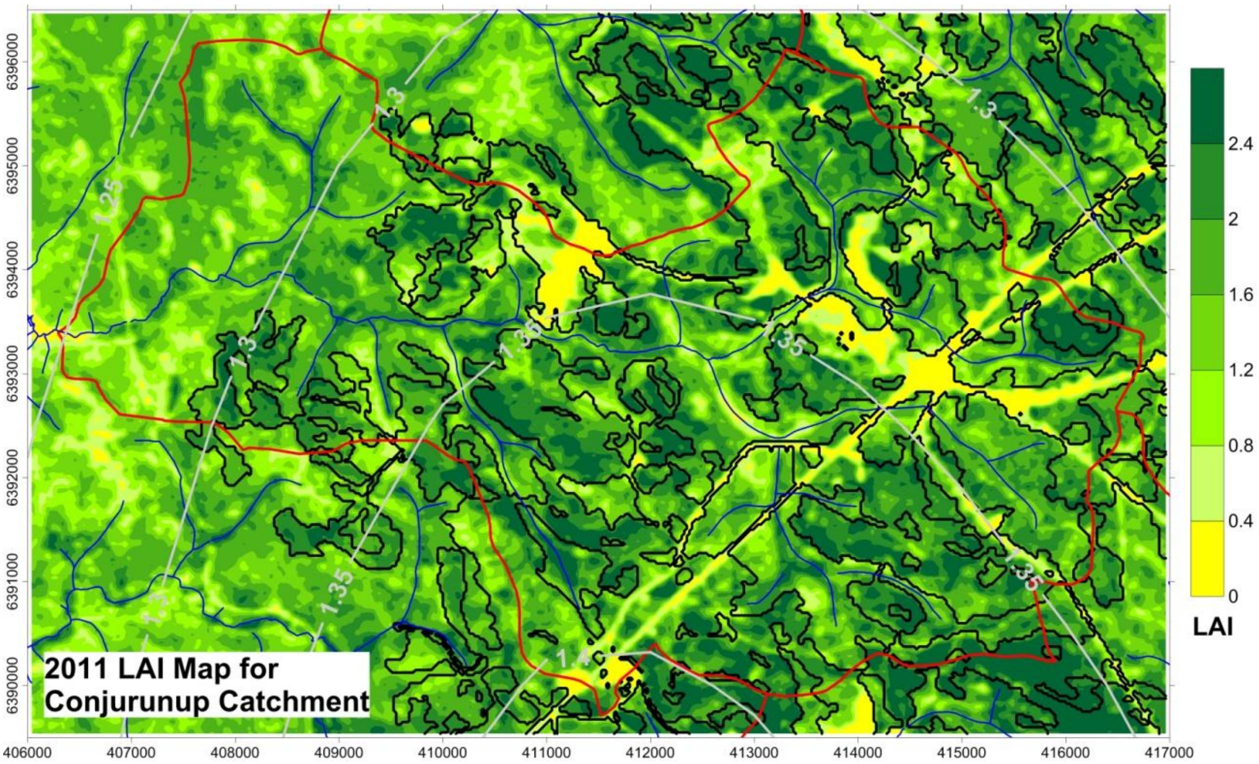


Figure 47 Conjurunup catchment 2011 LAIs with the mine-clearing outlines overlaid. The target LAIs from Figure 39(a) are also overlaid. (The mine-clearing outlines were provided by Alcoa of Australia.)

To give an impression of vegetation history, Figure 48 is the average LAIs for the total catchment, plus a division into the areas cleared for mining and the surrounding forest. For the cleared areas the averages are simple ones and don't consider for any given year whether the area is still to be cleared, has been cleared, or has been rehabilitated.

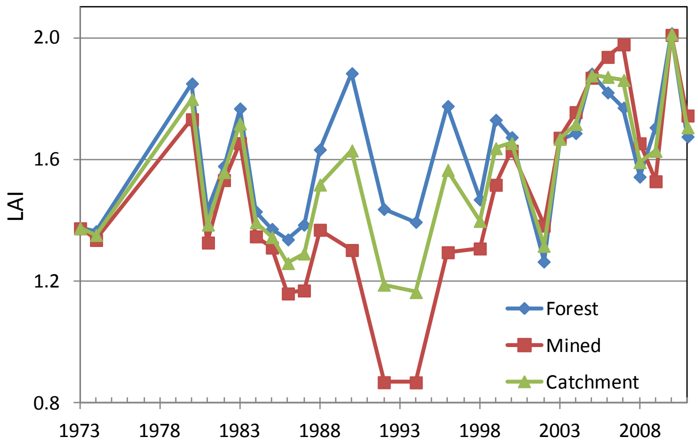


Figure 48 Conjurunup catchment average LAIs.

What is most interesting about Figure 48 is the level of variation within it. For the recent period the three low-rainfall years of 2001, 2006 and 2010 all seem to have temporarily reduced LAIs (it needs to be noted that an image is actually for January of the particular year, so the effects of 2001 can be seen in the 2002 value, that for 2006 in the 2007 value, and that for 2010 in the 2011 value). To provide a spatial impression of such changes, Figure 49 is the same plot as Figure 47, but for 2010 instead of 2011; there are a number of areas in Figure 49 which are much higher in LAI than Figure 47.

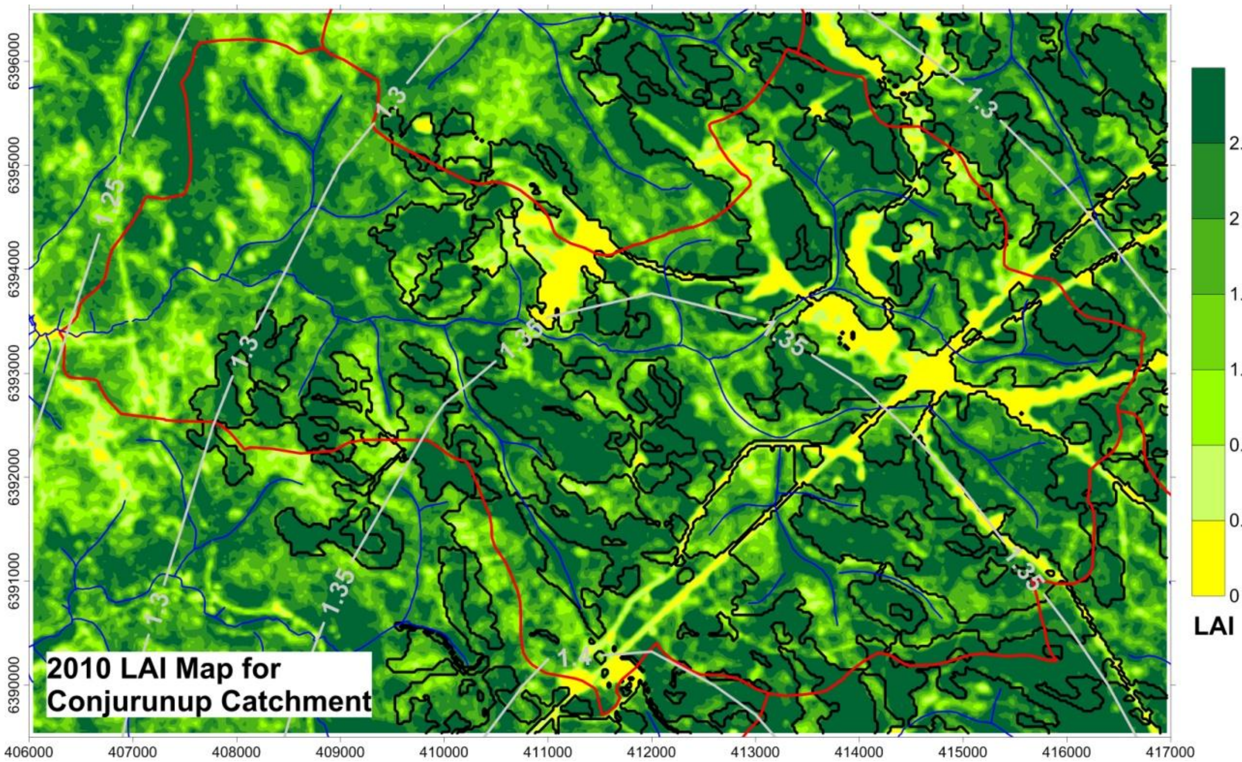


Figure 49 Conjurunup catchment 2010 LAIs with the mine-clearing outlines overlaid. The target LAIs from Figure 39(a) are also overlaid.

In terms of a catchment management plan, the objective could be to move the catchment towards an average LAI that is close to the target LAIs from Figure 39(a). The easiest way to do this isn't to treat the whole catchment area uniformly, but rather to: treat the high LAI forest areas in one way, the already established mine rehabilitation areas in another way, and to establish on the unrehabilitated mine areas a revegetation that will maintain a low LAI from the outset.

For the treated areas, we will assume that the treatment will be to an LAI of 1.0, this is 0.35 units less than the required target and so allows for a growth component. If we are able to suppress the LAI recovery to the growth function used by Croton *et al.* (2012.b), which assumes follow-up silvicultural treatments including coppice control, then the target LAI of 1.35 will be reached by the forest at the end of the second year after treatment (Figure 50). A value of LAI of 1.75, 0.4 LAIs units above target, won't be reached according to the growth-curve until 15 years after treatment, at which time a follow-up treatment would be required if the intention is to return to the target range. While this treatment cycle is not ideal in that the majority of it is spent at LAIs above the target, it is probably a good compromise.

For treatment of the forest areas, Figure 51 shows a map of required treatment to reduce the 2010 LAIs to a value of 1.0. For existing areas of mine rehabilitation, Figure 52 shows a map of required treatment to reduce the 2010 LAIs to a value of 1.0.

Given its lower stature, mine rehabilitation treatment should be much easier and cheaper than forest treatment, so there is a logic in leaving the forest areas untreated and instead concentrating the effort upon the mine areas alone, perhaps lowering them to an LAI less than 1.0. For the mine areas, some are still at low LAIs, though a number of patches are starting to rise and enter the 2.4 plus range. Even so, this catchment is presently in a state where modest management could easily address the denser rehabilitation areas and slow the rate of LAI rises in the mine areas which are still below the threshold. Rehabilitation of the still-cleared areas to low-density rehabilitation from the outset should result in a net saving compared to present rehabilitation methods. For options regarding the actual treatment of mine rehabilitation on Conjurunup, Croton *et al.* (2012.b) provided a comprehensive review of possible mine-rehabilitation options and their implications on catchment hydrology; the reader is referred to this document as a good starting point for discussion. The next step would be to develop a detailed catchment-management plan that includes detailed modelling to assess the likely effectiveness of the short-listed options. Like Croton *et al.* (2012.b), it will need to consider local variations in geomorphology and hydrology, and their resultant effects on streamflow generation and groundwater levels.

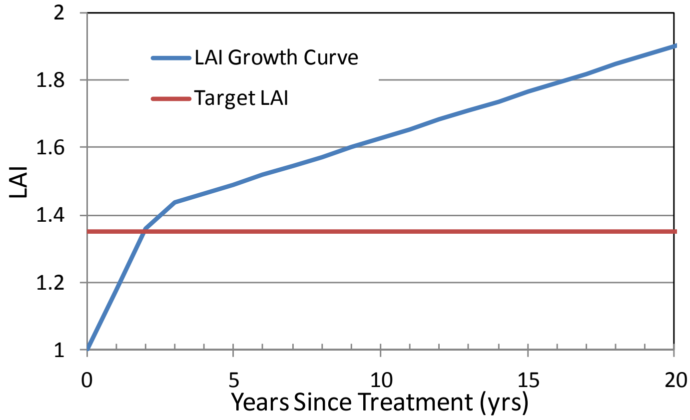


Figure 50 Assumed LAI growth curve following treatment for the Conjurunup catchment (Jack Bradshaw, pers. comm.). The catchment average target LAI of 1.35 is also overlaid.

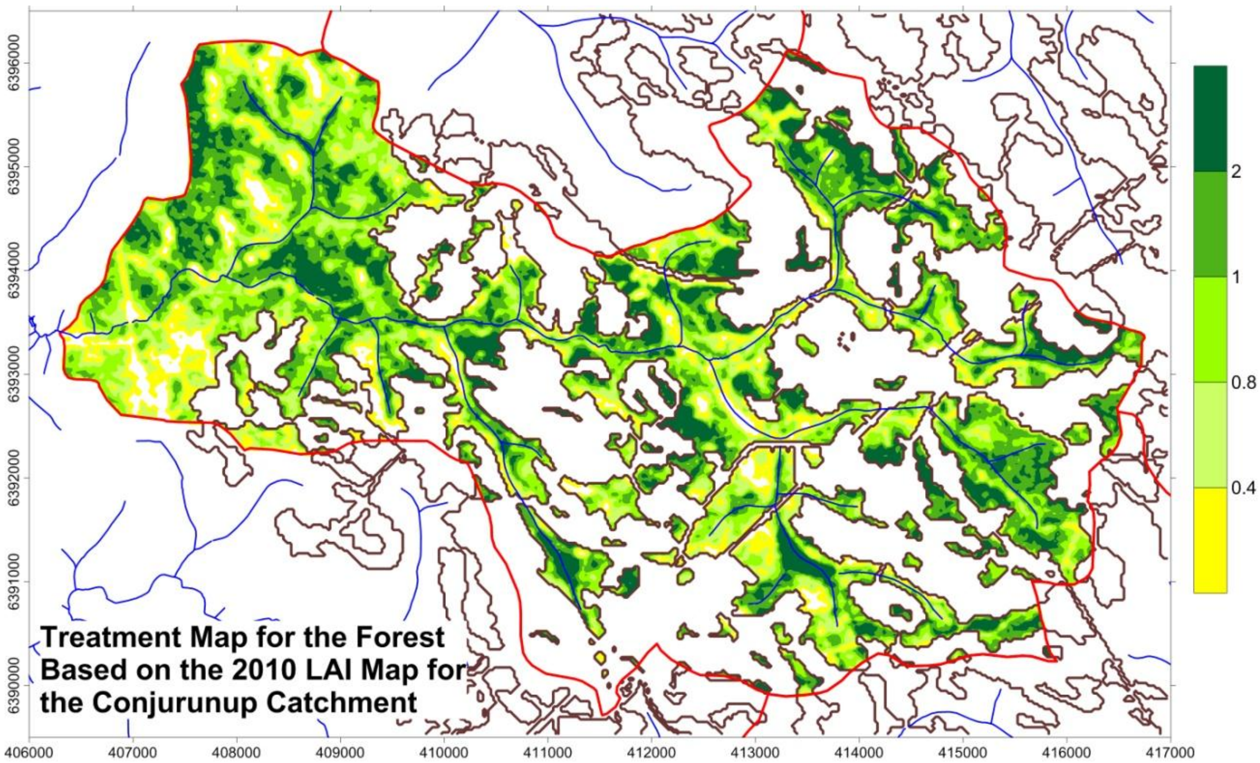


Figure 51 Map of required treatment to reduce the LAIs of the forested areas to a value of 1.0. Base LAI map was for the 2010 Landsat image. Note that a buffer has not been shown around the streamzones, this would be normal silvicultural practice.

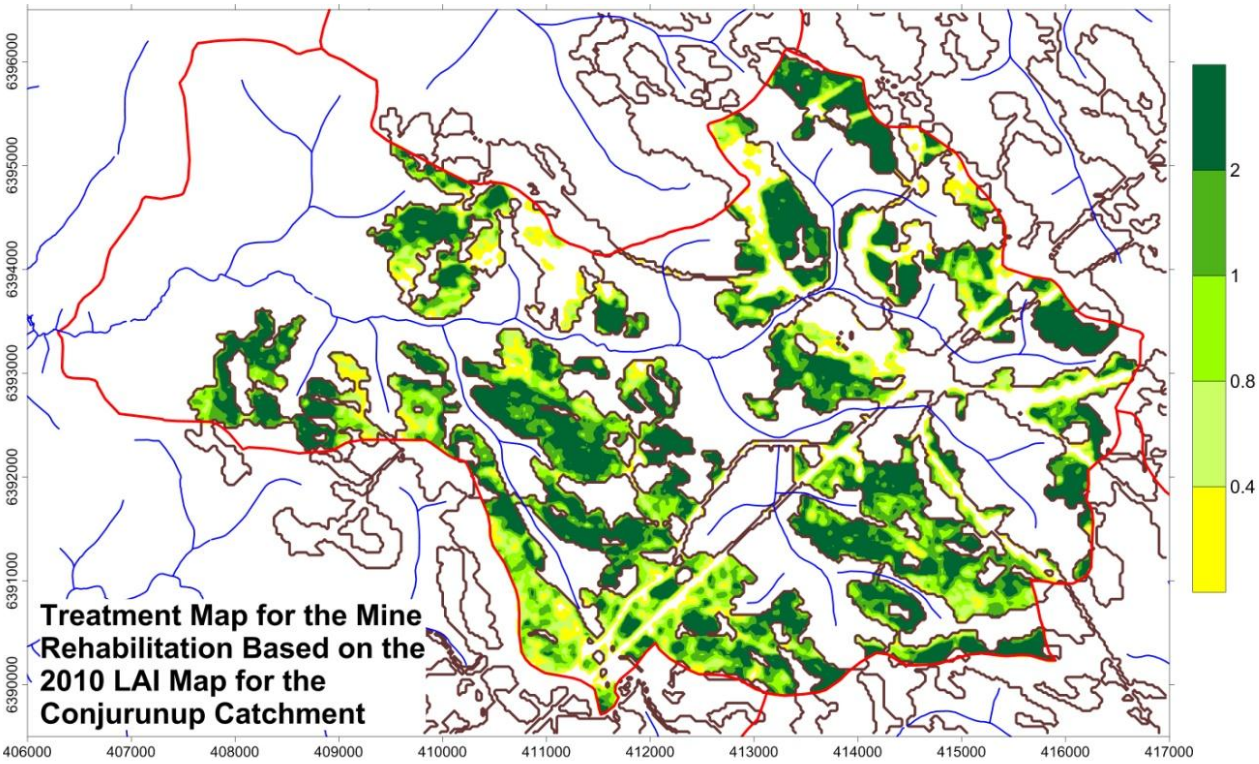


Figure 52 Map of required treatment to reduce the LAIs of the mine-rehabilitated areas to a value of 1.0. Base LAI map was for the 2010 Landsat image.

11 Discussion and Conclusion

The study covered a wide range of topics related to hydrology in the northern jarrah forest; how forest hydrology is linked to forest density, what is the hydrological future prognosis, and what silviculture treatments would be required to achieve various hydrological outcomes. One of the first findings is that climate already affects the vegetation density of the northern jarrah forest, and there is evidence that forest LAIs are responding up and down to variations in climate. Another finding is that for the three climate scenarios obtained from CSIRO & BoM (2007) via Yates *et al.* (2010), the moderate and worst case scenarios of Miroc-M and CSIRO Mk 3.5 scenarios were very similar to recent climate when both rainfall and potential evaporation are considered together. It was concluded therefore that the climate of the recent past (2000 to 2012 inclusive) was probably at least an equal predictor of the likely near future, that is to 2030. A further finding on climate is that the seasonal-rainfall behaviour for the northern jarrah forest is changing in line with climate predictions; the onset of winter rains for the recent past (2000 to 2012 inclusive) was more damped than was observed in the period 1961 to 1990.

When the present hydrology of the northern jarrah forest is assessed, it is a system where soil-water storages, groundwater levels and streamflows have declined from historical levels, and left to its own devices they are likely to decline further. At the same time, the level of intervention required to return these parameters to the historical levels that occurred during the period 1961 to 1990 would probably be too extreme in terms of LAI reduction to be considered. However, if more modest targets are set then it may be practical to achieve useful gains.

While groundwater depths, soil-water storages, and levels of vegetation water stress are all important to the ecosystem health of the northern jarrah forest, the importance of streamflow maintenance for the High Rainfall Zone (HRZ - 1,100 mm/yr rainfall for 1961 to 1990) can be quantified: while the HRZ is only one-fifth of the area of the water-supply catchments operated by the Water Corporation in the northern jarrah forest, it has been estimated that 60% of the stream inflow to these water-supply reservoirs comes from the HRZ. As an example of what could be achieved in the HRZ, the study assessed the practicality of treatments within this area and their capacity to maintain streamflow at a level at least comparable to historical, *viz* of order 100 mm/yr. It was seen that if this level of streamflow was maintained, then the other hydrological parameters would also be maintained at levels comparable to historical; groundwater would be kept close to, or at, the surface in the streamzone, soil-water storages would be within historical ranges, and plant water-stress would remain at low levels. In the assessment process the concept of rainfall deficit was introduced. Annual rainfall deficit is annual potential-evaporation minus annual rainfall. When rainfall deficit was converted by modelling into a carrying capacity of vegetation expressed as an LAI, and into likely streamflow for a given LAI, it became obvious that within the HRZ there were only limited sections for which treatment may be a practical proposition. In particular, it was determined that the northern section of the HRZ fell outside this category; this explained why there had been limited success with the Wungong Catchment Trial.

In assessing the practicality of forest treatments within the HRZ, possible post-treatment growth responses needed to be considered. Regrowth scenarios developed by Jack Bradshaw (Jack Bradshaw, pers. comm.) for the Wungong Catchment Trial showed promise; but they do assume follow-up silvicultural treatments, including coppice control, without which the recovery in LAI would be more rapid and probably render the treatments ineffective after too short a time. There is the need to better understand the dynamics of post-treatment responses in terms of LAI recovery, particularly in the context of follow-up treatment effectiveness.

The narrowing of the possible treatment area to just within the mid-section of the HRZ, introduced a complication. This area has been, and is continuing to be, mined for bauxite. However, the existence of bauxite mining in the possible treatment area also creates an opportunity. If the final rehabilitation target is changed from that of achieving a tall forest consistent with the surrounding jarrah forest, to that of maintaining LAIs consistent with the target LAIs required for streamflow generation, then a hydrological outcome can be obtained. For options regarding the actual treatment of mine rehabilitation, Croton *et al.* (2012.b) provided a comprehensive review of possible mine rehabilitation options and their implications on catchment hydrology; the reader is referred to this document as a good starting point for discussion.

As an initial demonstration of how both forest and mine areas may be managed, the Conjurunup and North Dandalup catchments were discussed. In particular, the smallness of the Conjurunup catchment combined with it presently being in a state which would allow relatively cost-effective management, recommends it for further consideration. It also has a number of existing research catchments within it, and they could yield additional information on treatment responses as well as be sites of future treatments studies. From an operational viewpoint, a number of demonstration alternatives to the Conjurunup catchment exist, particularly the Waroona and Samson Brook dam catchments further south which have the highest target-LAIs for the HRZ.

In closing it needs to be emphasised that care is required before any on-ground activities are considered. For treatment scenarios like those discussed by Croton *et al*. (2012.b) to be successful, they must be correctly targeted to the hydrology of the catchment. The WEC-C modelling in the final stages of the Wungong Catchment Trial, of which Croton *et al*. (2012.b) is an example, showed how to undertake such treatment design. Conversely, the modelling and analysis at the outset of the Wungong Catchment Trial using simple parametric models and other basic analysis tools showed the weaknesses of such approaches, including failure to identify the inadvisability of placing the trial at Wungong instead of further south. The knowledge and experience gained during the Wungong Catchment Trial should be retained and used to drive future processes in the catchment-management area.

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Appendix – The WEC-C Model

Model Description

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 A.1). 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.

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. 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 and its application to the Serpentine Reservoir catchment.

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.

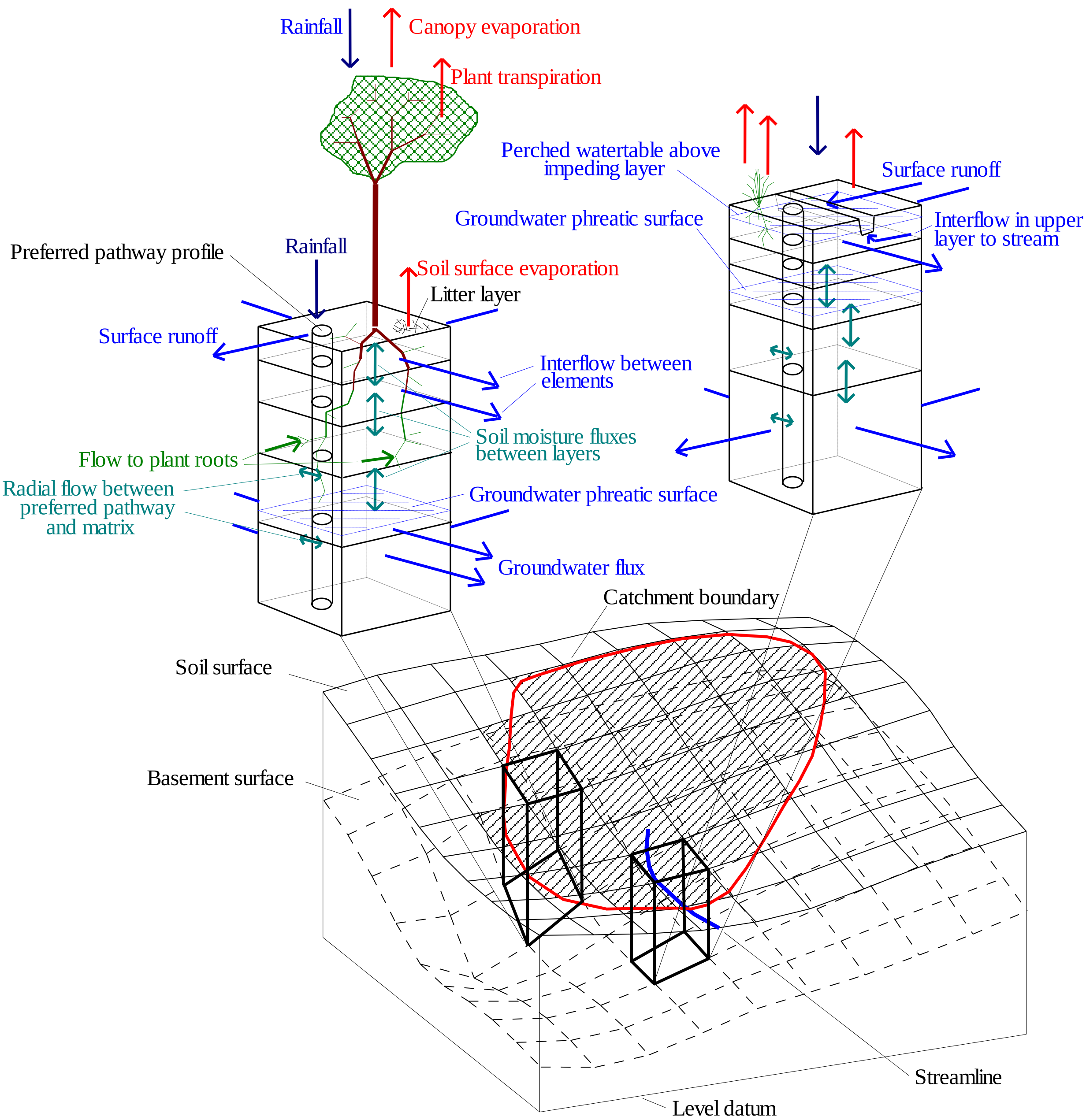

Figure A.1 Schematic of model layout and processes modelled.

Transpiration Model

The fundamental algorithm of the WEC-C transpiration model is given by Equation 1.

$$T_u = \begin{cases} A\ln(E_n) + B, & E_n > T_{lin} \\ \dfrac{E_n\left[A\ln(T_{lin}) + B\right]}{T_{lin}}, & \text{otherwise.} \end{cases} \qquad \text{Eq. (1)}$$

Where:

A & B user input variables in the transpiration relation.

E_n net daily evaporation, now defined by FAO56 from SILO Data Drill (mm/day).

T_{lin} user input variable to ensure the relation passes through zero (mm/day).

T_u transpiration per unit leaf area (mm/day).

The parameter values used in the modelling for normal forest were: A = 0.785, B = 0.5 and T_{lin} = 1.5. For post-treatment forest for the elevated transpiration scenario, the A parameter was increased by 50% to 1.18 to account for increased potential transpiration due to release of the vegetation canopy.

Model Parameterisation

The successful parameterisation of a model is always the most difficult part of any model application. In the present study there is the compounding issue that multiple influences must be simultaneously considered and understood, these include: changing climate, changes in forest cover, and clearing for mining and subsequent revegetation.

In the case of WEC-C, a detailed understanding and quantification of parameters, particularly for vegetation and soil profile conceptualisation, have been developed through the model's application to a wide variety of catchments in the south-west of WA. This allows us in the present study to use this bank of historical information to parameterise this component of the modelling and place it to one side. In the same way, the WEC-C model has been used in a variety of applications for the present below-average rainfall period, and the effects of this in terms of causing a steady depletion of the soil-water storage under full-forest conditions is well understood. The resultant hydrological non-stationarity means that employing the standard model-calibration methodology of dividing the past record into calibration and verification periods will be ineffective under the present climate and provide no real proof of a model's ability. Instead, the approach adopted here where the parameterisation of the model has been developed by the application of the model to a wide variety of catchments appears to be the only workable solution.

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