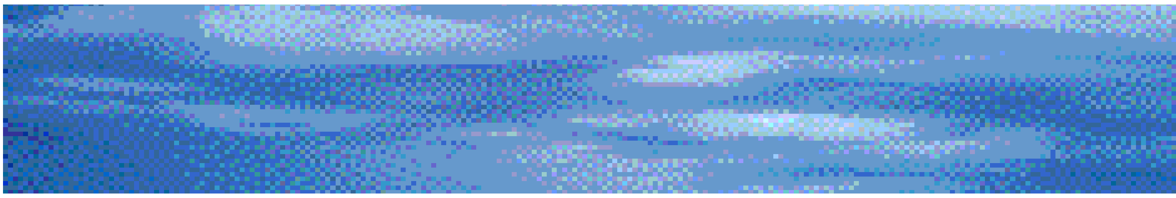
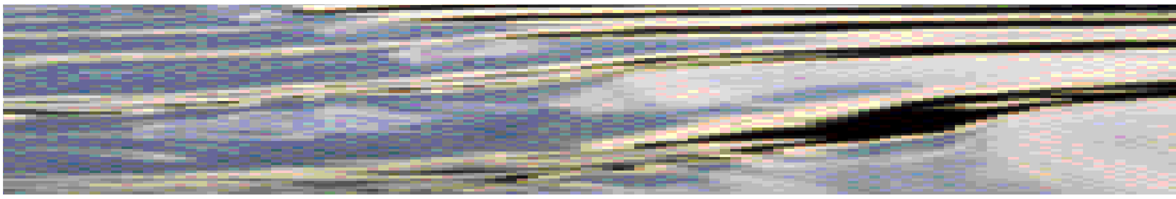
COOPERATIVE RESEARCH CENTRE FOR **CATCHMENT HYDROLOGY**

IMPLEMENTATION OF A MEAN ANNUAL WATER BALANCE MODEL WITHIN A GIS FRAMEWORK AND APPLICATION TO THE MURRAY-DARLING BASIN

TECHNICAL REPORT
Report 01/8
September 2001

Andrew Bradford / Lu Zhang / Peter Hairsine





Implementation of a Mean Annual Water Balance Model Within a GIS Framework and Application to the Murray-Darling Basin

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Foreword

Water is becoming an increasingly valuable commodity. In Australia, like elsewhere, the increasing demands for water for both consumptive and environmental uses are resulting in competition for water. All users of water recognise the variability of water availability as a result of climate and man's intervention in rivers and groundwater systems. Few users recognise the impact of land-use on water availability, so this report is an important step forward in this area. With the tools described in this report, we are able to assess the changes to mean annual streamflow as a result of changing vegetation within that catchment. This information is vital in assessing the trade offs between the benefits and costs of major land-use change.

This report describes some of the work conducted by the Cooperative Research Centre for Catchment Hydrology's program concerning land-use impacts on rivers. The program is focused upon the impact of man's activities upon the land and stream environment upon the physical attributes of rivers. We are concerned about managing impacts for catchments ranging in size from a single hillslope to several thousands of square kilometres. The specific impacts we are considering are changes in streamflow, changes to in-stream habitat by the movement of coarse sediment and changes to water quality (sediment, nutrients and salt). If you wish to find out more about the program's research I invite you to first visit our website at http://www.catchment.crc.org.au/landuseimpacts.

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CSIRO Land and Water
Program Leader
CRC for Catchment Hydrology

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Abstract

Partitioning of rainfall into evapotranspiration and runoff is strongly affected by landuse and vegetation characteristics. Generally, trees use more water than pastures and crops. In the Murray-Darling Basin there are plans to convert large areas of pastures to forestry plantations in the coming decades; a range of commercial and environmental considerations motivates these plans. This report describes the implementation of a simple water balance model in a GIS framework for assessing average annual streamflows (water yield) under different landuse scenarios. The model requires only catchment percentage forest cover and mean annual rainfall. This report describes the water balance model, its input data and the process required to prepare those data.

To demonstrate the use of the model, a case study is presented. The study utilises average rainfall data for the period 1980 to 1995 and vegetation cover data under different landuse conditions obtained from MDBC, AUSLIG and CSIRO Division of Forestry. Estimated mean annual catchment water yields agreed with measured stream flow data for medium to high rainfall catchments within the Murray-Darling Basin. However, the model tended to overestimate water yield for low rainfall catchments. The model was used to evaluate likely impact of the clearing of native vegetation in the Murray-Darling Basin on water yield; the results showed that there was significantly less water yield from most of the catchments within the Basin. This study also examined the effect of afforestation on future catchment water yield, and indicates that broad-scale afforestation in the basin may reduce mean annual water yield by up to 40 mm per year. This study showed that the GIS version of the water balance model could be used as a practical tool for assessing the effect of major vegetation changes on mean annual catchment water yield.

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1. Introduction

Land-use in the Murray-Darling Basin has undergone massive changes following European settlement and these changes have significantly modified the hydrological regime of the catchment. The replacement of perennial deep-rooted native vegetation with shall-rooted vegetation including perennial grasses, annual grasses and annual crops has resulted in major changes to the catchment-wide evapotranspiration, and stream flow (Zhang et al., 1999, 2001, Vertessy and Bessard, 1999). As a result of changes to the water balance, changes in vegetation have also resulted in major changes to the salt balance and stream salinity within catchments (Jolly et al., 1997, 2001, Natural Heritage Trust, 2001).

In the Murray-Darling Basin there are plans to convert large areas of pastures to forestry plantations in the coming decades (e.g. DPIE, 1997). A range of commercial and environmental considerations, including the management of dryland salinity, motivates these plans. As this report demonstrates, the spatial distribution of plantations within catchments greatly influences the resulting change in hydrology.

A number of studies have shown that evapotranspiration from a forested catchment is generally greater than that from a grassed catchment with the same climatic conditions (Holmes and Sinclair, 1986, Turner, 1991, Zhang et al., 2001). Thus, land-use management strategies will have an impact on catchment water balance. The key factors controlling evapotranspiration include rainfall interception, net radiation, advection, turbulent transport, leaf area and plant available water capacity. Moreover, the relative importance of these processes is likely to be dependent on climate, soil and vegetation conditions. Zhang et al. (2001) have developed a simple water balance model that requires only vegetation, annual total streamflow and rainfall data with the intention of assessing impacts of land-use changes on mean annual water yield. The model agreed with independent water balance estimates from more than 250 catchments. To facilitate the application of the model, a GIS framework was developed. The purpose of this report is to describe the GIS framework and to demonstrate how the model can be used for estimating catchment water yield under different vegetation conditions, with the Murray-Darling Basin as a case study.

2. GIS Framework for the Water Balance Model

This section describes the mean annual water balance model developed by Zhang et al. (2001) and how the model is implemented in a GIS environment. The GIS implementation is designed to be a user interactive method requiring three input grid datasets. The three required data inputs are catchment boundaries, rainfall, and current forest cover. The user is then able to predict the mean annual water yield (streamflow) of the catchment. The GIS implementation is also designed to enable scenario testing so that the user can predict changes in water yield as a result of changes in landuse.

2.1 Mean Annual Water Balance Model

Zhang et al., (2001) developed the catchment balance model used in this study, based on an examination of annual rainfall and evapotranspiration relationships. It is assumed that, under very dry conditions, potential evapotranspiration exceeds precipitation and actual evapotranspiration equals precipitation, while, under very wet conditions, water availability exceeds potential evapotranspiration and actual evapotranspiration equals potential evapotranspiration. Based on these assumptions, mean annual evapotranspiration (ET) can be calculated from mean annual rainfall (P) and potential evapotranspiration (E_0):

$$ET = P\{\frac{1 + w(E_0 / P)}{1 + w(E_0 / P) + (E_0 / P)^{-1}}\} \quad (1)$$

where w is the plant available water coefficient.

Following Eagleson (1982), we assumed that mean annual evapotranspiration from a catchment is the sum of the evapotranspiration from herbaceous vegetation ($ET_{non\text{-}forest}$) (including soil evaporation) and that from forest (ET_{forest}), weighted linearly according to their percentage areas. The general equation can be expressed as:

$$ET_{total} = f \times ET_{forest} + (1 - f) \times ET_{non-forest} \quad (2)$$

where f is percentage forest cover. It should be noted that the non-forest part of a catchment could be further divided into woodland and grasses if such data were available.

To simplify the calculation, the parameters in Equation (1) were established for forested and non-forested catchments:

$$ET_{forest} = \{\frac{1 + 2.0 \times 1410 / P}{1 + 2.0 \times 1410 / P + P / 1410}\} \times P \quad (3)$$

$$ET_{non-forest} = \{\frac{1 + 0.5 \times 1100 / P}{1 + 0.5 \times 1100 / P + P / 1100}\} \times P \quad (4)$$

These relationships are shown in Figure 1 together with observed evapotranspiration from the catchments listed in Zhang et al., (1999). The size of these catchments varied from less than 1 km^2 to 6×10^5 km^2 and they span a variety of climates. The vegetation ranges from same-aged plantation trees to native woodlands, open forest, rainforest, eucalyptus, through to native and managed grassland and agricultural cropping.

It is clear that most of the forested catchments plotted around the upper curve described by Equation (3) and non-forested catchments plotted around the lower curve described by Equation (4) with mixed vegetation catchments in the middle. The relationships described by Equations (3) and (4) are very similar to the empirical curves proposed by Holmes and Sinclair (1986) for Victorian catchments.

Assuming that the change in catchment water storage over a long period of time is zero, catchment average water yield is calculated as the difference between long-term average rainfall and evapotranspiration. Figure 2 shows the resulting relationship between water yield and rainfall.

2.2 The GIS Program

The water balance model has been programmed into ArcInfo via the AML language. The initial AML's concentrated on data preparation and resulted in duplication of data (data redundancy). Further progress in the efficiency and flexibility of the program motivated the movement from the initial framework to this final implementation. The design of the final framework used in the final data analysis will be discussed in this section. The GIS program (one ArcInfo AML) developed can be applied to any catchment with the three essential spatial datasets of rainfall, forest percentage cover, and catchment boundary (Appendix A).

The AML used for all analysis prompts the user for three input grid surfaces and a name for the result table (line 2 - 5, Appendix A). The input grids required are the tree grid, catchment grid and precipitation grid. The catchment grid is used as a template from which the rainfall surface and the forest cover statistics are generated as inputs for the calculation of ET.

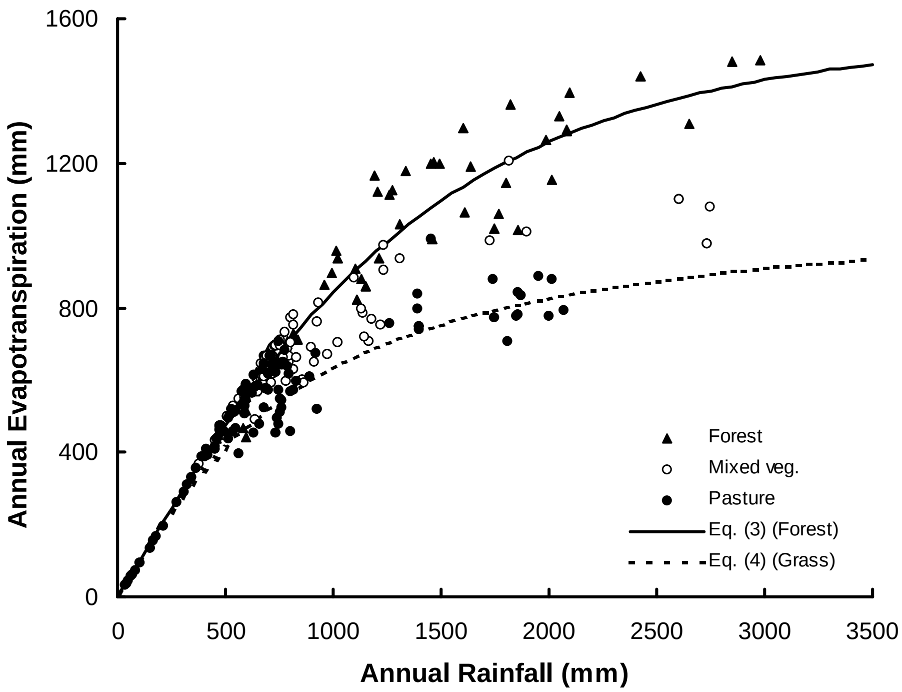

Figure 1 Relationships between annual evapotranspiration and rainfall (Zhang et al, 1999)

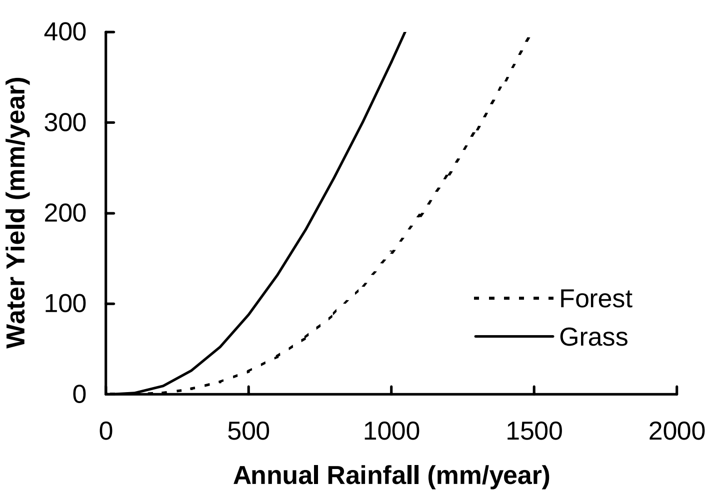

Figure 2 Relationship between catchment water yield and rainfall

2.3 Forest Cover Statistics

Cells in the GIS dataset containing forest coverage information (heretofore referred to as tree grid) have two states that represent the presence (=1) or absence (=0) of trees. This AML utilises the Zonalstats sum function (line 9, Appendix A), which does not recognise null values in the 'count' field. The 'count' field sums all the cells that fall within the template grid (catchment grid), which is used to calculate the percentage area of the catchment under forest. Figures 3 to 9 build up an example for the fictitious subcatchment 23, where the input value grid of tree/ no tree are represented by ones or zeros in each cell.

The Zonalstats sum function produces 'veg.tab', a result table with three fields (Figure 4). The first is the grid number, second is the count and the last is the sum. The 'Value' field is the catchment number. The next field named 'Count' is the sum of all the cells that fall within the catchment grid. Finally the 'Sum' field is the sum of the values in the input tree grid.

In the next stage, the table generates two new fields to calculate the percentage of forest (Percf) and percentage no forest (Percnf) (Line 12 - 19, Appendix A). The example table appears in the form of Figure 5.

1	1	1
1	0	1
0		0

Tree Grid

23	23	23
23	23	23
23		23

Zonal Catchment Grid

Figure 3 Example of inputs to the Zonalsum ArcInfo function to calculate the tree area

Value	Count	Sum
23	8	5

veg.tab

Figure 4 Resultant table veg.tab produced from the Zonalsum function

Value	Count	Sum	Percf	Percnf
23	8	5	0.63	0.37

veg.tab

Figure 5 Resultant table veg.tab with the percentage forest and no forest added and calculated

2.4 Rainfall Statistics

The mean annual rainfall statistics are calculated using the Zonalstats mean (line 8, Appendix A) command. Like the calculation of tree areas, the zonal catchment grid acts as the template from which the mean rainfall values will be calculated. In the continuing example, Figure 4 shows the rainfall values range from 500 to 530 for zonal catchment 23. The table is named the same as the input rainfall surface with a '.tab' extension. In this example the surface is called 'rainfall' (Figure 6).

The Zonalstats sum function produces a resultant table with three fields for each catchment. The first is the catchment number, second is the count and the third is the mean annual rainfall. The generated field name 'mean' is altered to 'mean-rain' to avoid confusion. The resulting table is shown in Figure 7.

500	500	500
520	515	520
530		530

Rainfall Grid

23	23	23
23	23	23
23		23

Zonal Catchment Grid

Figure 6 Example of inputs to the Zonalmean ArcInfo function to calculating the mean rainfall value of a catchment

Value	Count	Mean-rain
23	8	514.4

rainfall.tab

Figure 7 Resultant table rainfall.tab with the mean rainfall value

2.5 Calculating Evapotranspiration and Runoff

Once the statistics are calculated, the table's veg.tab and rainfall.tab are used to calculate evapotranspiration. The 'Value' field is the catchment number and serves as the primary key to join the tables (line 22, Appendix A). The user specifies the name of the resultant table (Figure 8).

Four fields are added to each row in this table to allow for the calculation of evapotranspiration and runoff (line 24 - 29, Appendix A). These are evapotranspiration of forest (Evapot), evapotranspiration of non-forest (Evapont), total evapotranspiration (Evapotot) and runoff (RO_veg). The calculation of evapotranspiration is performed for forest and no forest areas using the two equations (3 and 4) described earlier (line 30 - 31, Appendix A). The two evapotranspiration fields are summed to give the total evapotranspiration field (Evapotot) (line 32, Appendix A). Finally, runoff (RO_veg) is calculated by subtracting evapotranspiration (Evapotot) from total rainfall (mean-rain) (line 33, Appendix A). Depending on the input vegetation dataset name, the runoff field name changes. For example, a vegetation dataset named 'Precarn' will result in the runoff field name to be 'RO_Precarn'. This unique field naming strategy is important if the result

Value	Count	Mean-rain
23	8	514.4

rainfall.tab

Value	Count	Sum	Percf	Percnf
23	8	5	0.63	0.37

veg.tab

=

Value	Count	Sum	Percf	Percnf	Mean-rain
23	8	5	0.63	0.37	514.4

username.res

Figure 8 The example of the generated statistics of both the forested areas and rainfall merged into a final table tables of several scenarios are to be joined and analysed at a later point. Figure 9 illustrates how the final result table will appear.

The final GIS implementation improved program and data management and involved two key improvements over the initial one. Firstly, several AML programs were consolidated into one program. All processing and results are conducted in a home project directory. This is a more efficient approach than the initial framework of processing in different data directories. It is advantageous to reduce data redundancy in the home work directory. The final framework is more user friendly. The second improvement involves the use of the consolidated program to create a dynamic user environment. The program provides the user with the ability to input different vegetation, catchments and rainfall datasets. This program enables very rapid calculation of spatial water yields for a range of actual or predicted vegetation scenarios.

Value	Count	Sum	Percf	Percnf	Mean-rain	Evapot	Evapont	Evapotot	RO_veg
23	8	5	0.63	0.37	514.4	306.8	155.6	462.4	52

Figure 9 Example of the merged final table showing the calculated value of evapotranspiration and runoff

3. Case Studies

This section will present the results of three landuse scenarios: current forest cover, pre-European forest cover and a scenario for a major increase in the area of forestry plantations as described below. The next section in this report offers detailed descriptions of how each input dataset was captured and finally applied to the model. To estimate the impact of land-use changes on catchment water yield for main drainage divisions within the Murray-Darling Basin, spatial datasets of rainfall and forest cover were required. This section describes the sourcing and manipulation of these datasets, which were obtained from various government agencies and captured for different purposes. We also describe the methods and procedures for estimating the distribution of rainfall across the catchment and percentage forest cover based on these source datasets. Current, pre-European and potential plantation forest areas of different temporal and spatial scales were used to characterise forest cover for a given catchment. Problems associated with initial vegetation classification were overcome by reclassifying the data into two main categories to satisfy the requirements of the project for comparing past, present and potential future vegetation coverage. ArcInfo programs (AML's) were written to automate the resampling, reprojecting of data and the model itself. These programs are referred to throughout the following sections and listed in Appendix A and B.

3.1 Rainfall Surface

Monthly-interpolated rainfall surfaces were combined to give mean annual rainfall surface for the period of 1980 to 1995. Each grid cell is 0.05 of a degree or approximately 5km across (Jolly et al, 1997). The grid point analysis technique used to derive surfaces provides an objective average for each grid cell and provides useful estimates of rainfall in data-sparse areas. However, in data-rich areas, such as south east Australia or in regions with strong rainfall gradient, "data smoothing" will occur resulting in values at point locations which may differ slightly from the exact rainfall recorded. Figure 10 shows the range and spatial distribution of long term mean annual rainfall across the Murray-Darling Basin. Detailed information about the rainfall surface can be found at http://www.bom.gov.au/climate/austmaps/mapinfo.shtml.

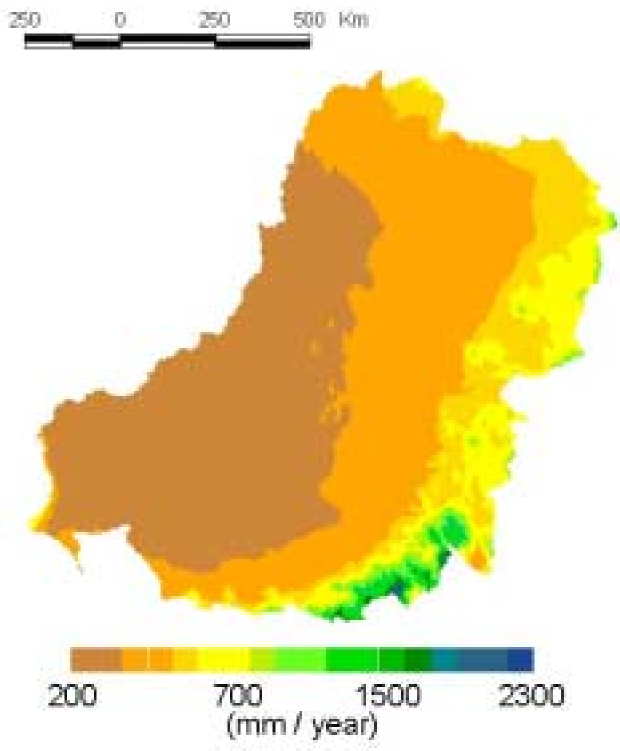

Figure 10 Distribution of mean annual rainfall throughout the Murray-Darling Basin

3.2 Catchment Boundaries

This project is based on 26 drainage divisions of the Murray-Darling Basin with catchments ranging in size from 700km^2 to 130,000km^2 (Figure 11). These catchment boundaries were taken from a pervious salt load study (Jolly et al, 1997) that delineated catchments using a watershed analysis. Catchment areas and mean annual rainfall are listed in Table 1.

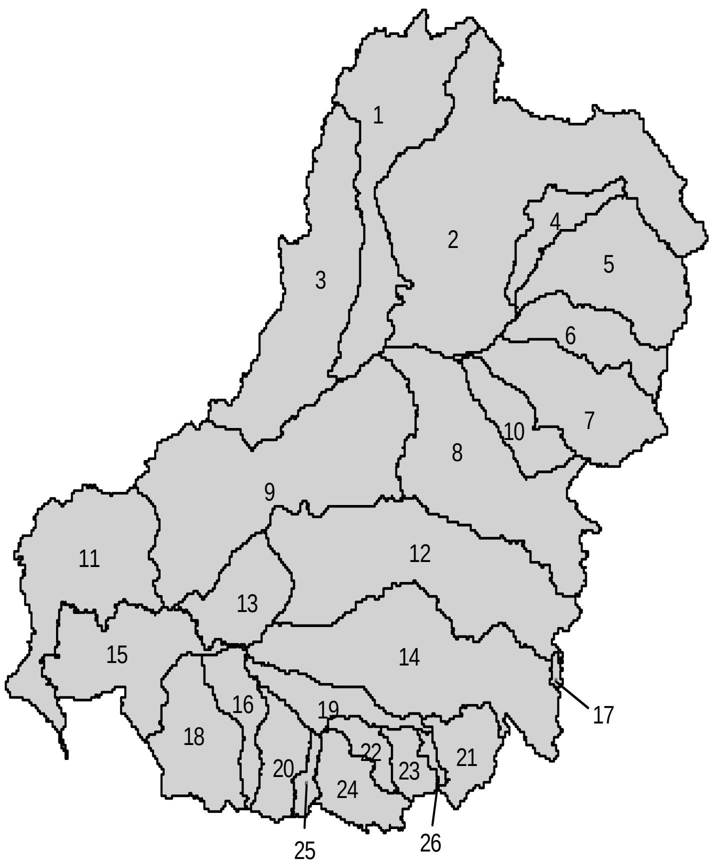

Figure 11 Location map of the main drainage divisions within the Murray-Darling Basin (Jolly et al., 1997)

Table 1 Catchment area and mean annual rainfall for the 26 catchments within the Murray-Darling Basin

ID	Catchments	Rainfall	Area (km^2)
1	Warrego River	408	62940
2	Condamine-Culgoa	482	162597
3	Paroo River	281	73953
4	Moonie River	519	14342
5	Border Rivers	621	48041
6	Gwydir	620	26586
7	Namoi	617	42000
8	Macquarie	523	74792
9	Darling River	295	112832
10	Castlereagh River	537	17423
11	Lower Murray	281	58274
12	Lachlan River	470	90880
13	Benanee	291	21345
14	Murrumbidgee River	556	81643
15	Mallee	301	41488
16	Avoca River	365	14201
17	Lake George	701	942
18	Wimmera-Avon	405	30367
19	Murray-Riverina	395	15039
20	Loddon River	461	15655
21	Upper Murray River	1105	15342
22	Broken River	593	7099
23	Ovens River	992	7981
24	Goulburn	829	16857
25	Campaspe River	590	4048
26	Kiewa	1190	1912

3.3 m305 Vegetation Dataset

The data describing the vegetation in the basin, as described below, was obtained from Ritman (1995). The m305 multi-structured vegetation dataset contains attributes characterising landcover and vegetation. This study is focused on the woody vegetation component of the landcover class. The woody vegetation was mapped from Landsat TM imagery at a 30 metre ground resolution with six bands per scene from as many cloud free days as possible. Between late 1989 and 1991, images were chosen to maximise the number of cloud free days. The imagery was initially resampled from 30 metres to 25 metres. An unsupervised classification into 100 classes was performed on the imagery to derive the woody vegetation. Each map sheet required resampling from 25 metres to 250 metres as the final mosaiced grid would be too data intensive. The resampling method used in this routine was nearest neighbour. This is considered a suitable method of resampling categorical data such as tree and no tree. (Line 3, Appendix B). The resulting woody vegetation layer was filtered to minimum clusters of 0.25 ha. Woody vegetation is represented as 7 in the landcover class and defined as vegetation that has 20% crown cover and over 2 metres in height (Line 4, Appendix B). A consolidated grid surface was created from the 472 1:100,000 scale mapsheets (Line 5, Appendix B). Moreover, each map sheet was reprojected from Australian Map Grid (AMG) to latitudes and longitudes. New South Wales, Queensland and Victoria each had three AMG zones, while South Australia had only one. The recommended coordinate system for the Basin wide area statements is Albers Equal Area (Ritman, 1995). However, the model framework discussed does not require any absolute measured areas. The framework needs only the proportion of catchment under forest as described earlier. Interim grids created in lines 3, 4, and 5 are deleted (line 7 to 9, Appendix B). An example of the program for vegetation data analysis is shown in Appendix B.

3.4 Carnahan pre-European Vegetation Data

The Carnahan pre-European settlement vegetation mapping is stored as a 1:5,000,000 scale map and covers all of Australia in a geographic projection. The Carnahan pre-European polygon coverage is based on the AUSLIG vegetation dataset created from remote sensing data between the years of 1980 to 1985. This base AUSLIG vegetation dataset was created from classification of Landsat MSS imagery at 1:1,000,000 scale. From the base vegetation dataset, polygon updates were added to create a new coverage of pre-European settlement dataset. The Carnahan dataset was updated from historical information. This included explorers and camel driver's diaries and soil and vegetation reports that date to the latter part of the 20th century. The Carnahan source data is an estimation as to what vegetation could have existed prior to European settlement.

The classification attributes present in the 1980 to 1985 data were carried across to the Carnahan dataset. Because of this, a comparison between the AUSLIG base vegetation dataset (1980 to 1985 MSS data) and m305 vegetation dataset was possible. While the differences in spatial scale of current m305 and the Carnahan pre-European vegetation datasets are large, the Carnahan pre-European dataset is the best data available at this time. From a temporal perspective, the AUSLIG current vegetation coverage (1980 to 1985) and the m305 vegetation dataset (1989 - 1991) are comparable. The comparison was undertaken to set classification rules for the polygon attributes when compared to the tree areas of the m305. Finally, these rules are transferred to the Carnahan pre-European dataset to model a possible scenario. Three attribute fields were analysed from the current AUSLIG vegetation dataset. These were Tallest Stratum, Density and Species Growth Form.

Vegetation density foliage cover is expressed in terms of the proportion of the ground that is shaded by the tallest stratum at midday (McDonald et al, 1990). The AUSLIG vegetation dataset expresses this in four classes from < 10% to >70%. Class 1 is 0% - 10%, which is defined as crowns well separated. Class 2 is 10% - 30% and defined as crowns clearly separated. Class 3 is 30% - 70%, crowns touching or slightly separated, and Class 4 is 70% or greater, crowns touching to overlapping. The density of foliage cover of the lower stratum is not recorded in the code. The final categories chosen from the foliage cover attribute field were 2, 3 and 4. Categories 2 and 3 contain the greatest source of potential error of commission. As categories 2 and 3 cover a broad range of vegetation types, it was difficult to compare them against the 20% crown cover of the m305 dataset. As the density of foliage was the first class to be investigated, the liberty of including category 2 was taken on the grounds that vegetation height and species will sufficiently discriminate the tree areas when comparing to the m305 vegetation cover. Moreover, when category 2 was omitted, significant areas that were considered tree by the m305 dataset were not accounted for. In short, there was more category 2 considered as tree than was not tree when comparing to the woody m305 dataset.

The tallest stratum is defined as the uppermost stratum that intercepts most of the incoming solar radiation (McDonald et al., 1990). When testing this data, the tallest stratum data field was tested against the m305 vegetation dataset. Conifers and Eucalyptus were found to have the best correlation with the woody component of the m305 dataset.

Species Growth Form has three primary classifications of vegetation groups. These groups are grasses, shrubs and trees and are further broken down into vegetation height. Grasses and shrubs less than 2 metres were considered as non-woody vegetation and excluded from the classification, as these classes do not fit the m305 woody vegetation criteria. Table 2 shows the letters in brackets associated with Tallest Stratum, Density and Species Growth Form. These are the names of the attribute fields in the GIS. It also shows which classes were chosen from the AUSLIG present vegetation and used in the analysis of the Carnahan pre-European vegetation. Figure 12 shows how the comparison is represented spatially between the two vegetation datasets based on the rules in Table 2.

Table 2 The rules used in the vegetation classification of forest for the AUSLIG vegetation datasets

1.	Tallest Stratum (TS_SD)	Eucalyptus (e) Conifers (p)
2.	Density (TS_D)	10 - 30% (2) 30 - 70% (3) 70% > (4)
3.	Species Growth Form (GF)	Low Trees < 10 metres (L) Medium Trees 10 - 30metres (M) Tall Shrubs > 2 metres (S) Tall Trees > 30 metres (T)

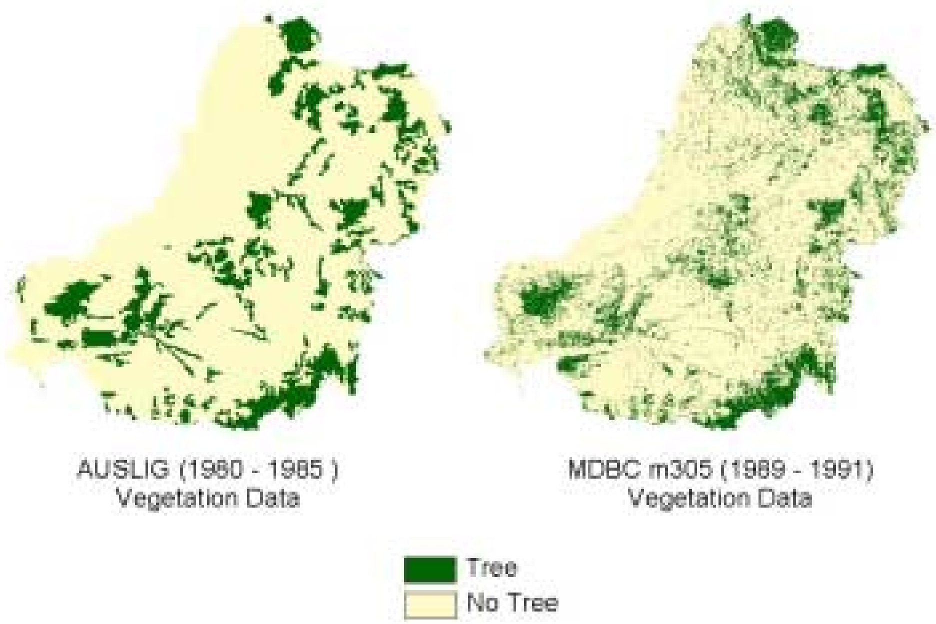

Figure 12 m305 vegetation and AUSLIG Present vegetation shown as tree and no tree

Merging the m305 vegetation dataset with the AUSLIG present vegetation cover dataset generated a new grid. With estimations such as this, there is a chance that errors of omission will occur from the original data. The correlation matrix shown in Table 3 illustrates an 8% error of omission where m305 has forest present and AUSLIG present vegetation does not. Moreover, the table shows an 8% error of commission where m305 has no forest present and AUSLIG present vegetation shows forest. The correlation between the two datasets is 12% for forested areas and 72% for no forest area.

This comparison is encouraging, particularly when considering the m305 vegetation dataset was generated from a classification on a cell by cell basis and the AUSLIG vegetation is polygon dataset of grouped like vegetation classes.

Rules that are described in Table 2 were applied to the Carnahan vegetation dataset. The final classified Carnahan pre-European vegetation dataset of tree and no tree is shown in Figure 13.

Table 3 Correlation matrix of m305 vegetation dataset and the AUSLIG present vegetation dataset with regard to tree and no tree areas

		AUSLIG Present	
		No Tree	Tree
M305	No Tree	72%	8%
	Tree	8%	12%

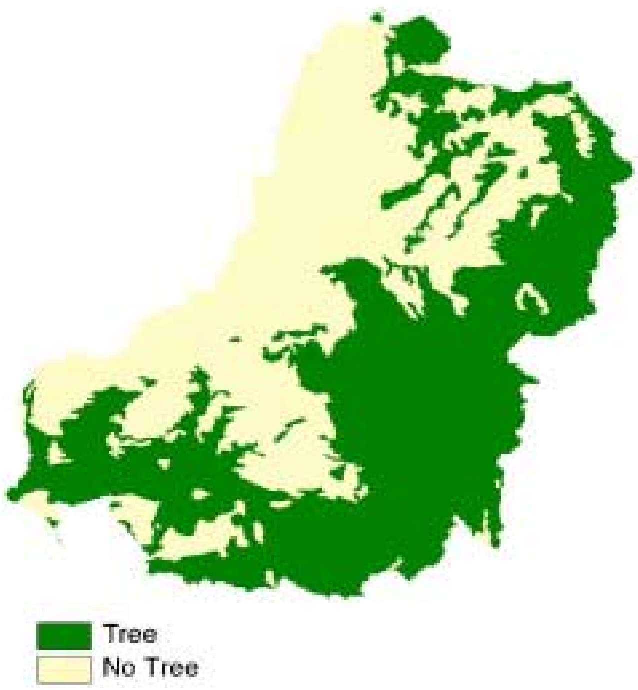

Figure 13 Classified tree/no tree data from the Carnahan pre-European vegetation dataset

3.5 Potential Afforestation Scenario

The potential afforestation dataset was designed to predict areas suitable for hardwood plantation timbers across Australia. The main source datasets used in this analysis considered the environmental factors that favour plantation hardwoods. These include precipitation, topography, soils and pests and diseases (Booth and Jovanovic, 1991). The potential forest plantation dataset involved only the transformation of points to grids and reprojecting from AMG coordinates to latitudes and longitudes. The cell size was 0.05 of a degree in latitudes and longitudes or approximately 5 kilometres in AMG. The resolution of this dataset is far coarser than the source m305 dataset. Due to the complexity of the analysis and broad scale of some source datasets used in the capability dataset, it was unrealistic to store the data at a finer resolution. When converting the point data, it was necessary to carry the attributes of the point dataset across to the grid surface. All areas classified as low, medium and high were to be classified as forest. The m305 vegetation dataset was combined with the potential forest plantation data. Figure 14 shows the combined dataset.

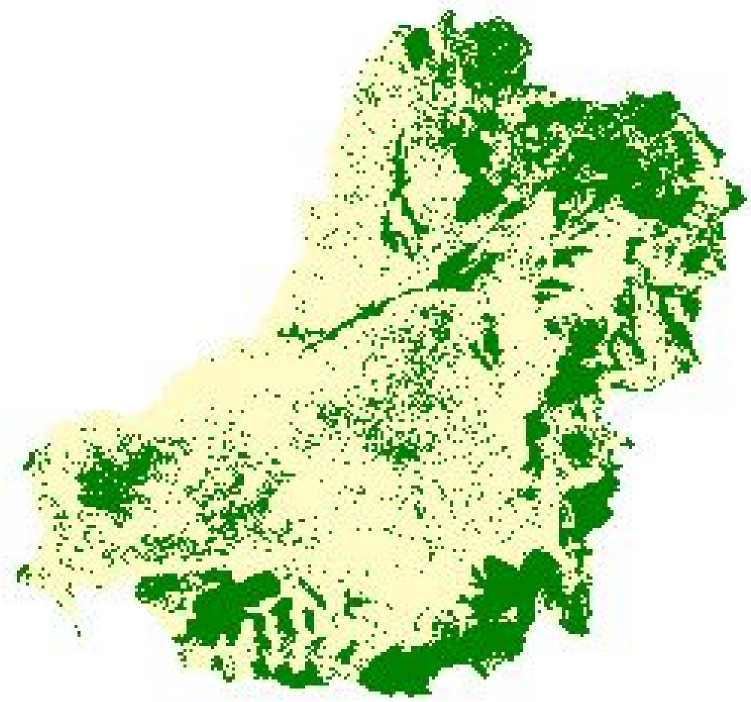

Figure 14 Potential plantation areas and the m305 vegetation dataset combined

4. Results and Discussion

The runoff results generated from the application allowed the comparison of runoff from current vegetation against measured river runoff. Section 4.1 presents a comparison of calculated catchment water yield under current land-use conditions and runoff measurements reported by DNR (1976) and Jolly et al., (1997) for most of the catchments in the Murray-Darling Basin. In Section 4.2, water yield under pre-European vegetation conditions is presented. Finally, the impact of potential forestation on catchment water yield is investigated in Section 4.3.

4.1 Catchment Water Yield Under Current Vegetation Conditions

The m305 woody vegetation dataset of the Murray-Darling Basin provides a coherent dataset across the Murray-Darling Basin. This is imperative when considering the Murray-Darling Basin as whole. Evapotranspiration from each catchment was calculated by combining the vegetation data with the annual rainfall data. In order to compare the results with stream flow measurements, catchment water yield was obtained by subtracting the evapotranspiration from rainfall. Figure 15 shows estimates of the catchment water yield in relation to rainfall for all 26 catchments. The calculated catchment-scale water yields ranged between 14 and 335 mm/year, and were within the mean annual water yield relationships defined by equations (3) and (4). It is clear from Figure 15 that the difference in catchment water yield between forested and non-forest catchments for rainfall up to 700 mm/year is small. However, the difference become larger as rainfall increases, suggesting that changes in vegetation cover will have relatively large impact on catchment water yield in high rainfall areas. This is an important relationship as areas of high rainfall are of great importance in terms of water supply and stream salinity dilution.

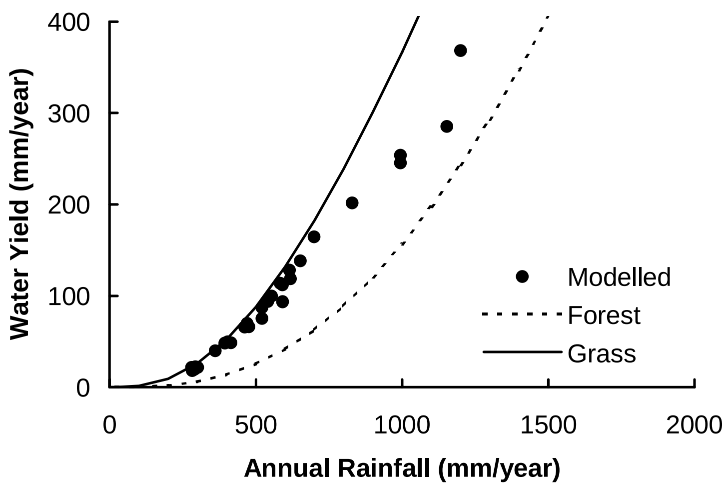

Figure 15 Estimates of water yield under current vegetation cover for the 26 catchments in the Murray-Darling Basin

In Figure 16, the modelled catchment-scale water yields were compared with long-term stream flow measurements reported by DNR (1976) and Jolly et al., (1997). The best fit slope through the origin was 1.03 and the model estimates were statistically consistent with the measurements. However, there were relatively large scatters in the results and the model tended to overestimate water yield in low rainfall catchments. When expressed as a percentage of mean annual rainfall, the error in the estimated water yield ranged between 5% and 16%.

There were a number of factors that could have contributed to the errors in the results. Firstly, estimates of percentage forest cover could affect the evapotranspiration modelled by Equation (3). In low rainfall catchments, average percentage forest cover was a small fraction of the total catchment area and some open woodland were classified as non-forests. This would result in underestimates of evapotranspiration or overestimates of water yield. Secondly, rainfall distribution could also affect the estimates of evapotranspiration and hence water yield. By using mean annual rainfall, the model is likely to underestimate evapotranspiration in catchments with summer dominant rainfall. Examination of the results shows that the model underestimated evapotranspiration in catchments such as Condamine-Culgoa Rivers, Moonie River and Namoi River. Rainfall in these catchments is summer dominant, with 35% of rainfall falling in the period of December to February. Model results can be improved by introducing a seasonality index and this will be investigated in a future study. Finally, diversion of water occurs in many of the catchments in the Murray-Darling Basin and it is extremely difficult to account for the effects of diversions on stream flow measurements.

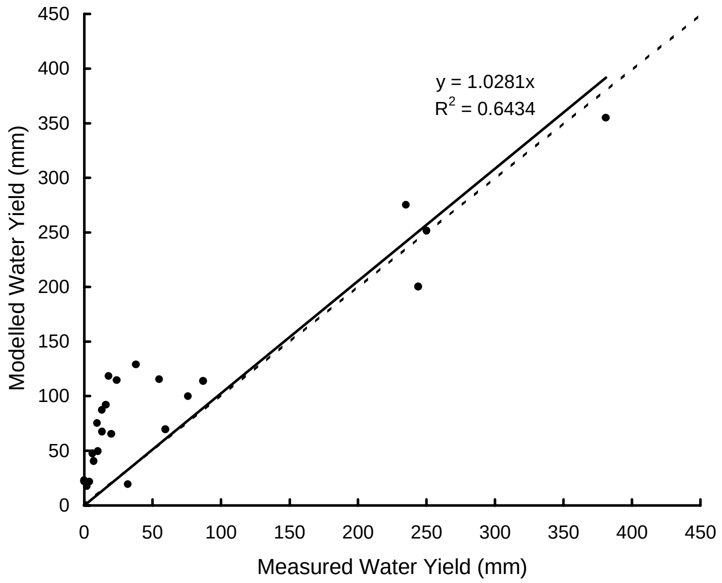

Figure 16 Comparison of calculated and measured catchment water yield for the major catchments in the Murray-Darling Basin

The estimated catchment water yields show significant spatial variation (Figure 17). In the Benanee and Lowe Murray catchments, mean annual water yield was less than 20 mm per year, while in the eastern catchments, such as Ovens and Upper Murray, mean annual water yield was above 250 mm per year.

4.2 Catchment Water Yield Under pre-European Vegetation Conditions

In this section we evaluate the effect of the clearing on mean annual water yield based on current and pre-European vegetation data. Catchment water yields under pre-European vegetation conditions were calculated from the Carnahan pre-European vegetation dataset. It was assumed that mean annual precipitation during that time was the same as the mean annual rainfall for the period of 1980 to 1995. The results are shown in Figure 18. The estimated average forest cover taken from the large scale AUSLIG dataset was 69% before the European settlement. This value is significantly higher than the current forest cover of 20% taken from the m305 woody vegetation dataset. Table 4 illustrates the possible loss in forest cover for each catchment. As a result, estimated water yield under pre-European vegetation conditions was consistently lower than that under current vegetation conditions (Figure 17 and Figure 19). Water yield increased between 0 to 80mm per year and most significant changes occurred in the catchments east of the Darling River (Figure 19). On average, estimated water yield in the Murray-Darling Basin has increased from 46 to 69 mm per year.

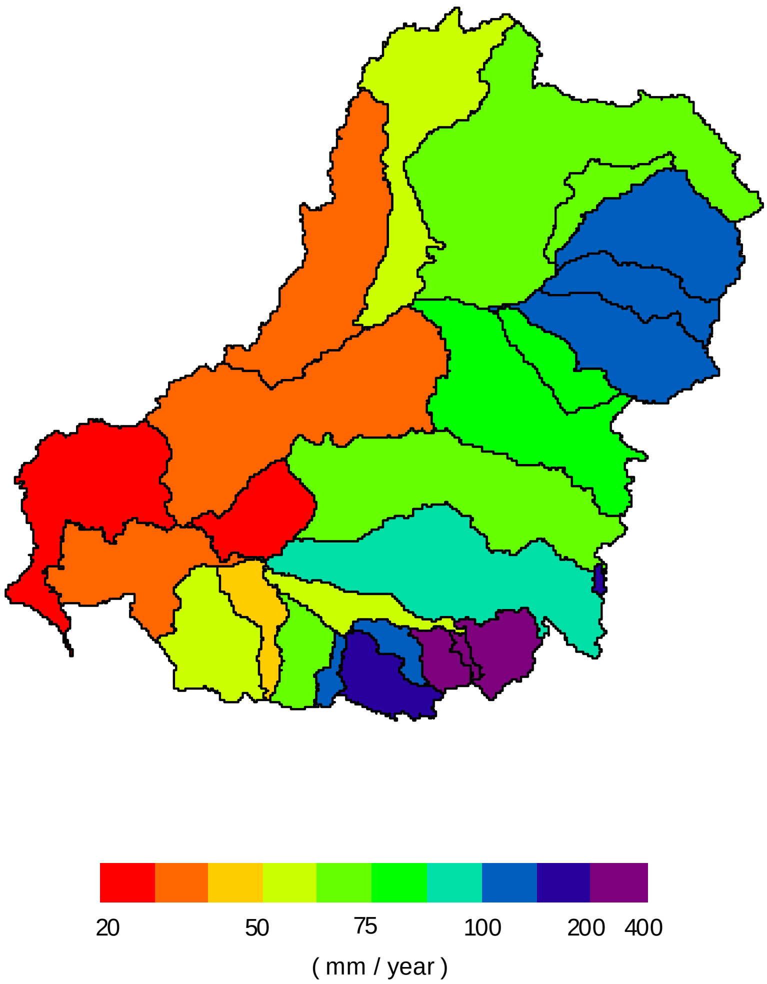

Figure 17 Predicted mean annual water yield distribution across the Murray-Darling Basin under current vegetation cover

These results are indicative only as streamflow data for uncleared land in much of the Basin (especially the lowland regions of the west) is not available. However, they provide some estimates of likely changes in catchment water yields resulting from the clearing of native vegetation. Figure 18 shows many catchments yield significantly less water at this time. There is no gauged stream flow data under pre-European vegetation conditions and the only descriptive information available is written records left by explorers, travellers, and settlers. Their view of streams was based on their European experience and may be subjective, but it provides a qualitative picture of the streams under pre-European conditions. For example, during a drought in the upper Murrumbidgee, "It seems the small stream of the catchment were swampy at the time of European exploration, and many were chains-of-ponds." (Starr et al, 1999). This information suggests that stream flow under pre-European vegetation conditions would be less than the current stream flow.

Table 4 Current forest cover compared to pre-European forest cover for the 26 catchments of the Murray-Darling Basin

Catchment	Current Forest (%)	pre-European Forest (%)	Decrease (%)
Warrego River	21	21	0
Condamine-Culgoa	25	40	15
Paroo River	4	4	0
Moonie River	31	34	2
Border Rivers	29	64	35
Gwydir	14	75	61
Namoi	24	78	54
Macquarie	16	88	72
Darling River	13	23	10
Castlereagh	16	72	56
Lower Murray	28	39	12
Lachlan River	14	71	57
Benanee	27	48	21
Murrumbidgee	16	70	54
Mallee	23	80	57
Avoca River	8	76	69
Lake George	17	76	59
Wimmera-Avon	13	66	53
Murray-Riverina	10	92	83
Loddon River	16	84	68
Upper Murray	69	99	30
Broken River	18	100	82
Ovens River	54	99	45
Goulburn	36	100	64
Campaspe	15	86	71
Kiewa	56	89	33

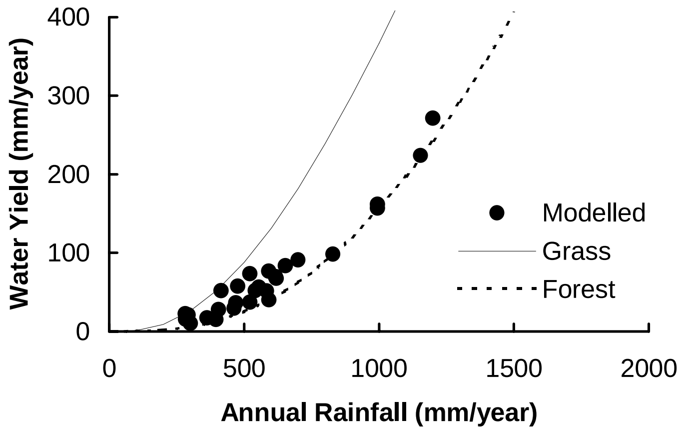

Figure 18 Catchment water yield under pre-European vegetation condition

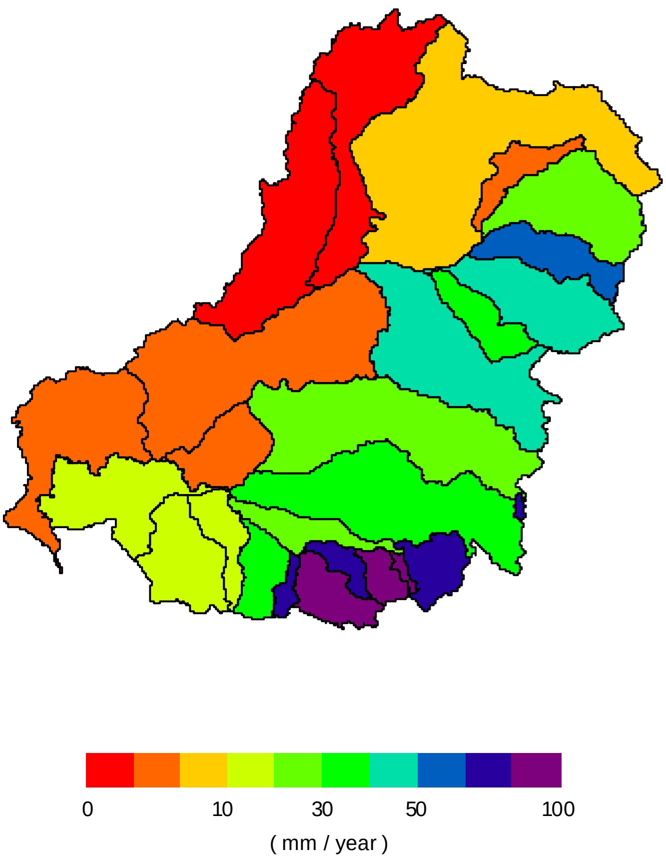

Figure 19 Increase in water yield from pre-European vegetation cover to current vegetation cover

4.3 Impact of Potential Afforestation on Catchment Water Yield

Increased groundwater recharge has been identified as a major factor causing dryland salinity in the Basin (MDBMC, 1999). A number of land management options have been considered to reduce groundwater recharge, one of these being forest plantations. Forest can use more water than pasture and hence reduce recharge to groundwater systems. Afforestation can also affect water yield (Vertessy and Bessard, 1999). A forest plantation capability scenario was mapped for the purpose of investigating potential commercially viable plantation areas (Booth and Jovanovic, 1991). Plantation areas in the Murray-Darling Basin were calculated using numerous factors, one of that was the absence of existing forests. This meant that in order to estimate a future scenario of forested areas, it was necessary to combine the potential afforested areas with the 1990 vegetation dataset. The vegetation scenario was based on the potential implementation of Eucalyptus, Acacia and Pine as commercial plantations. Table 5 lists the criteria for which each species was chosen.

Table 5 Criteria for the selection of suitable forest plantation areas by species (Booth and Jovanovic, 1991)

Species	Mean Rainfall (mm/year)	Rainfall Regime	Dry Season Length (months)	Mean Max Temp (^{0}C)	Mean Min Temp (^{0}C)	Mean Annual Temp (^{0}C)	Soil
Eucalyptus globulus	600 - 1500	Winter / uniform	0 - 5	19 - 30	2 - 12	9 - 18	Fertile loams
Eucalyptus grandis	800 - 2500	Summer	0 - 5	25 - 34	3 - 16	14 - 25	Alluvial, volcanic
Eucalyptus nitens	750 - 1500	All	0 - 4	20 - 28	-3 - 5	7 - 14	Granite, basalt
Eucalyptus pilularis	750 - 2000	Summer / uniform	0 - 2	22 - 31	5 - 12	15 - 22	Sandy loams
Eucalyptus regnans	900 - 2000	Winter / uniform	0 - 3	17 - 27	-2 - 6	7 - 14	Deep moist
Eucalyptus saligna	700 - 1800	Uniform / summer	0 - 5	22 - 32	1 - 14	14 - 21	Sandy loams
Acacia mangium	1150 - 3700	Summer	0 - 5	29 - 33	12 - 30	23 - 28	Acid volcanic
Acacia mearnsii	800 - 1600	Uniform				16 - 20	Sands, loams
Acacia melanoxylon	480 - 2950			19 - 34	-3 - 16	9 - 25	Volcanic soils
Pinus elliottii	750 - 1700	Summer	0 - 5	26.5 - 31	5 - 12.5	18 - 23	Phosphorous soils
Pinus radiata	650 - 1600	Winter / uniform	0 - 4	20 - 30	-2 -12	11 - 18	Mixed

Table 6 illustrates the potential rise in forest cover given full adoption of potential plantation areas. It can be noted that there is opportunity for significant increase in plantation areas in some catchments such as Condamine-Culgoa Rivers, Moonie River, Border Rivers, Goulburn River, and Wimmera-Avon Rivers. Such plantations would increase catchment evapotranspiration and hence reduce water yield (Figure 20).

The water yield for all catchments was compared under the current vegetation and the potential plantation. The results are shown in Figure 21. This analysis shows that the south-eastern catchments of the Murray-Darling Basin will have a low to moderate change in water yield as a result of the afforestation, while the catchments at the head waters of the Murray River, where annual rainfall is relatively high, will experience reduction in water yield between 20 to 40 mm per year. Minimal

Table 6 Current forest cover compared to potential plantation forest cover for the catchments of the Murray-Darling Basin

Catchment	Current Forest (%)	Potential Plantation (%)	Increase (%)
Warrego River	21	37	17
Condamine-Culgoa	25	55	30
Paroo River	4	7	3
Moonie River	31	67	36
Border Rivers	29	49	19
Gwydir	14	32	18
Namoi	24	38	14
Macquarie	16	29	13
Darling River	13	13	0
Castlereagh River	16	37	21
Lower Murray	28	29	1
Lachlan River	14	21	7
Benanee	27	27	0
Murrumbidgee River	16	26	10
Mallee	23	24	1
Avoca River	8	46	39
Lake George	17	36	19
Wimmera-Avon	13	53	40
Murray-Riverina	10	14	4
Loddon River	16	46	30
Upper Murray River	69	85	16
Broken River	18	24	7
Ovens River	54	65	11
Goulburn	36	61	25
Campaspe River	15	20	6
Kiewa	56	69	13

change in water yield will occur in other catchments, as they are viewed as catchments not suited to sustainable plantations. Although these changes are not as dramatic as those under the pre-European vegetation conditions, they may have significant impacts on water supply and salinity control. Vertessy and Bessard (1999) applied a similar relationship, developed by Holmes and Sinclair (1986), to the Murrumbidgee catchment and concluded that afforestation in the catchment may significantly reduce mean annual runoff. Water yield reduction not only imposes costs on users downstream but also affects stream salinity dilution. An important issue is the trade-offs between recharge control and water yield reduction, as they are likely to vary with rainfall. Such information can help us to make responsible management decisions about landuse changes in the Murray-Darling Basin.

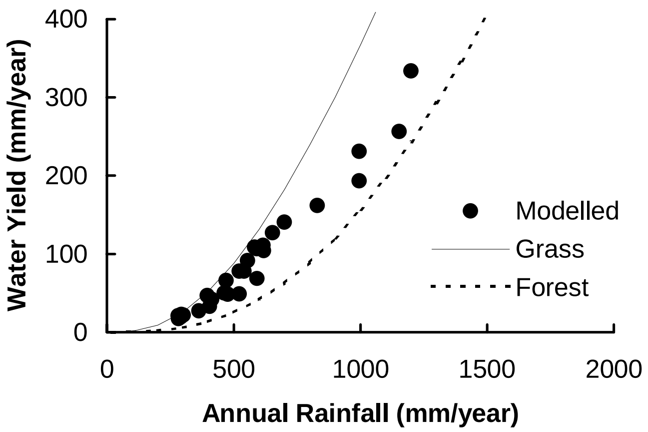

Figure 20 Estimates of water yield under the potential afforestation scenario

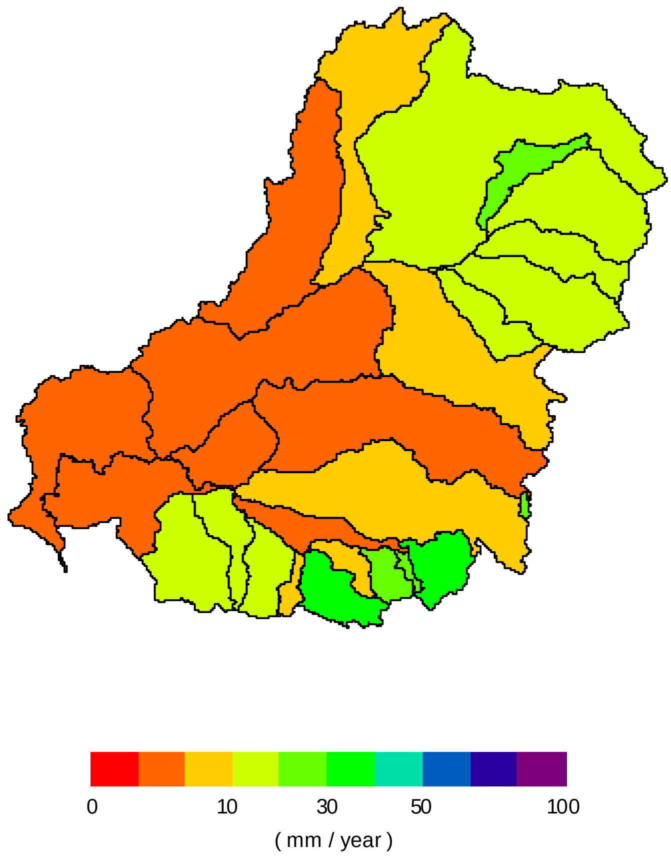

Figure 21 Change in water yield from current vegetation to potential afforested areas

5. Summary

This report demonstrates how the simple water balance model developed by Zhang et al (2001) can be used in a GIS framework to estimate the impacts of vegetation changes on mean average catchment water yield. The model considers the effects of available energy and water on evapotranspiration and requires only mean annual rainfall and vegetation cover. To facilitate practical application to large catchments, the model was implemented in a GIS environment, which enables spatial analysis of rainfall and vegetation data, and eventually catchment water yield. Procedures involved in the spatial data handling are explained in detail (see Appendix B).

Comparison between predicted and measured water yield under current landuse conditions agreed reasonably well for catchments with high rainfall. However, the model tended to overestimate water yield for low rainfall catchments. The model may be improved by introducing a rainfall seasonality index and this will be further investigated. To evaluate the impact of the clearing of native vegetation in the Murray-Darling Basin, water yield under pre-European vegetation conditions was estimated. The results showed significant reduction in water yield from most of the catchments within the Basin. Although there is no direct stream flow data to compare these estimates with, some descriptive information seems to indicate that there would be less runoff under pre-European vegetation conditions. This study also attempted to evaluate the impact of afforestation on future catchment water yields and our analysis suggests that broad-scale afforestation in the basin may reduce mean annual water yield by up to 40 mm per year. This may be desirable for recharge reduction, but its impact on downstream water supply needs to be considered.

Large-scale afforestation not only affects mean annual stream flow, but also flow regime. Results from some paired catchment studies have shown significant changes in flow regime following clearing of forests (Burch et al., 1987; Jones, 2000). Further studies are necessary to model these hydrological responses in large catchments.

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Appendix A: Catchment Evapotranspiration Model (ArcInfo AML)

```
lg
&s inveg [response 'Enter input tree grid']
&s incatch [response 'Enter catchment grid']
&s outtab [response 'Enter the name of the result table']
&s inrain [response 'Enter the rainfall surface']

grid
%inrain%.tab = zonalstats (%incatch%, %inrain%, all)
veg.tab = zonalstats (%incatch%, %inveg%, sum)
q

tables
sel %inrain%.tab
alter MEAN MEAN-rain 12 f 4 mr
sel veg.tab
additem veg.tab percf 4 6 f 4
additem veg.tab percnf 4 6 f 4
calc percf = SUM / COUNT
calc percnf = 1 - percf
q

joinitem veg.tab %inrain%.tab %outtab%.res value

tables
sel %outtab%.res
additem %outtab%.res EVAPOt 8 8 f 2
additem %outtab%.res EVAPOnt 8 8 f 2
additem %outtab%.res EVAPOtot 8 8 f 2
additem %outtab%.res RO_%inveg% 8 8 f 2
calc EVAPOnt = ( MEAN-RAIN * ( ( 1 + 0.5 * ( 1100 / MEAN-RAIN ) ~
) ) / ( ( 1 + 0.5 * ( 1100 / MEAN-RAIN ) + MEAN-RAIN / 1100 ) ) ~
) * PERCNF
calc EVAPOt = ( MEAN-RAIN * ( ( 1 + 2 * ( 1410 / MEAN-RAIN ) ~
) ) / ( ( 1 + 2 * ( 1410 / MEAN-RAIN ) + MEAN-RAIN / 1410 ) ) ~
 ) * percf
calc EVAPOtot = EVAPOnt + EVAPOt
calc RO_%inveg% = MEAN-RAIN - EVAPOtot
kill veg.tab
kill %inrain%.tab
list value MEAN-RAIN EVAPOtot BNAME
&return
```

Appendix B: Resample and Reprojecting of m305 Vegetation Datasets (ArcInfo AML)

```
&do v &list v6626 v6627 v6628 v6630 v6631 v6632 v6726 v6727 v6728 v6729 ~
v6730 v6731 v6732 v6733 v6825 v6826 v6827 v6828 v6829 v6830 v6831 v6832 ~
v6833 v6925 v6926 v6927 v6928 v6929 v6930 v6931 v6932 v6933 v7025 v7026 ~
v7027 v7028 v7029 v7030 v7031 v7032 v7033

re%v% = resample (%v%, 250)
w%v% = re%v%.woody
geo%v% = project (w%v%, amg542geo.prj)
copy geo%v% /earth/mdbcveg/luproject/vic/z54/geo%v%
kill re%v%
kill w%v%
kill geo%v%
&end
```