Generating water yield curves for forest stands in the Thomson catchment for inclusion in the Integrated Forest Planning System

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Executive Summary

The relationship between vegetation age and water yield has been extensively researched in the forested Maroondah group and Thomson catchments, east of Melbourne, Victoria. In 1999/2000 the spatially distributed hydrologic model Macaque was applied to the Thomson catchment in order to predict the water yield impact of forest disturbance (Peel et al., 2000). The application of Macaque to the Thomson catchment was a joint project conducted by the Cooperative Research Centre for Catchment Hydrology, The Department of Natural Resources and Environment (NRE) and Melbourne Water.

The results of the Macaque application to the Thomson presented in Peel et al. (2000) were largely in map form, with some examples of water yield curves for specific forest types. The aim of this project was to convert the spatial information contained in the results of Peel et al. (2000) into time series of water yield that could be inserted directly into the Integrated Forest Planning System (IFPS) run by NRE.

Equations describing the relationship between annual water yield, vegetation type, vegetation age and mean annual precipitation were developed for the following vegetation types.

- E. regnans and E. nitens,
- E. delegatensis,
- E. pauciflora,
- E. obliqua and mixed species,
- E. sieberi and
- heath.

Extra topographic variables were added to the equation for E. pauciflora (slope) and E. obliqua and mixed species (aspect) in order to improve the fit of the equation.

The performance of the equations in predicting the annual water yield was assessed for the different vegetation types and in the case of E. regnans, E. nitens and E. delegatensis the equations are very reliable. The equations for E. pauciflora, E. obliqua and mixed species are generally reliable and for E. sieberi and heath they are less reliable and should be used with caution.

The equations developed in this report are only applicable to the Thomson catchment above the Dam Wall. Other limitations of the equations are also noted in this report.

1. Introduction

The Department of Natural Resources and Environment (NRE) are responsible for the management of public native forests in the state of Victoria. One of their responsibilities is to ensure that the harvesting of these forests does not adversely impact on water resource values. To assist them in the planning of forest utilization, NRE use a software tool called the Integrated Forest Planning System (IFPS). This is a linear programming environment that determines the relative benefits of varying forest management strategies. Amongst other things, the IFPS considers changes in catchment water yield that might ensue from harvesting and subsequent regeneration of native forest stands.

To date, the water yield relationship embedded in the IFPS has been based on an empirical model developed by Kuczera (1987). The so-called ‘Kuczera curve’ describes how mean annual water yield from a mountain ash (E. regnans) forest would vary over the lifecycle of that forest type. The Kuczera curve is founded on a statistical analysis of flow records gathered in the Maroondah catchments by Melbourne Water during the period 1910 to 1975. By virtue of the way it is derived, it is a ‘regional’ curve that gives an average catchment response for forest stands distributed over a wide area with a mean annual rainfall of about 1900 mm.

In managing the Thomson catchment for wood and water supply, NRE expressed a desire to know how logging in different parts of the catchment might affect mean annual water yield. The Kuczera curve was overly general in this regard as the catchment contains several types of Eucalypt stands (not just mountain ash) and is characterized by considerable variation in mean annual rainfall.

Through the 1990’s, the CRC for Catchment Hydrology conducted a significant amount of field experimentation in Eucalypt forest catchments (including the Maroondah catchments) to elucidate the factors controlling annual water yield changes associated with forest harvesting and ageing (see Vertessy et al. 2001 and Roberts et al. 2001). This process knowledge was incorporated into a distributed parameter catchment model called Macaque. Early descriptions and limited testing of the Macaque model were provided by Watson (1999) and Watson et al. (1999a).

Recently, NRE and Melbourne Water (partners in the CRC for Catchment Hydrology) co-funded a project to apply and test the Macaque model on the Maroondah and Thomson catchments. That study was completed in late 2000 and the results were reported in a CRC Technical Report by Peel et al. (2000). That project demonstrated that Macaque could provide credible estimates of annual water yield across a large and diverse mountainous landscape characterized by a variety of forest species and a broad isohyetal range.

In 2001, NRE approached the CRC for Catchment Hydrology to undertake the present study, the main objective of which was to use Macaque to distill some simple generalizations about the effects of species, stand age and mean annual rainfall on annual water yield.

The main outcome of this work is a set of equations that can be used to estimate annual water yield, requiring only knowledge of the species, stand age and mean annual rainfall. These equations are suitable for direct inclusion in the IFPS and will result in far more credible predictions of forest harvesting impacts on water yield than previous versions of the model that were based on the Kuczera curve.

2. Data extraction and selection

The synthetic climate analysis of Peel et al. (2000, Section7) was conducted in order to observe the impact of vegetation disturbance on water yield over a long period. A climatically average year (in this case 1962) was repeated for 250 years, so as to create a synthetic climate with no inter-annual rainfall variability. This synthetic climate was then used as an input to the Macaque model. Under the synthetic climate the entire vegetation was disturbed and allowed to regrow over a 250-year period. Macaque produced a map of water yield for each year of this synthetic scenario. These maps describe the impact on water yield of the vegetation regrowth across the catchment. In Macaque, vegetation regrowth has an impact on water yield due to changes in leaf area index (LAI) with forest age and maximum leaf conductance with forest age. The curves used in Macaque to describe these changes in LAI and maximum leaf conductance with forest age are found in Watson (1999) and Watson et al. (1999a).

The LAI versus forest age curves of Watson (1999) were developed from data collected in the Maroondah catchments. The curves were used in Peel et al. (2000) to estimate LAI for a particular forest type for a given forest age. Maps of forest type and age were provided by NRE for Peel et al. (2000) and were based on pre-State Forest Resource Inventory (SFRI) data. No field observations of LAI were collected in Peel et al. (2000) due to time constraints, so the validity of the assumption that the LAI versus forest age curves of Watson (1999) are appropriate for the Thomson catchment was not tested. Satellite imagery was not used to define LAI due to the lack of field observations of LAI, however, it was used to check for spatial bias in LAI prediction based on the curves of Watson (1999).

Since Peel et al. (2000) the SFRI data for forest type and age has become available for the Thomson catchment. The relationships developed later in this report are expected to be valid if applied to the SFRI data. However, if the work of Peel et al. (2000) were repeated with the new SFRI data as an input to Macaque then the following results would be expected to improve due to the improved spatial resolution of the SFRI data.

A total of 250 maps of water yield were created in the synthetic climate analysis of the Thomson catchment upstream of the dam wall. The maps consist of values of water yield for each elementary spatial unit (ESU). The Thomson catchment above the dam wall was represented in Macaque by 337 hillslopes that consisted of 2276 ESU’s.

An Excel macro was written to open the Macaque files and extract the water yield values for each year for each ESU into an Excel spreadsheet.

Whether the times series of water yield at a particular ESU would be used further in this analysis was assessed by visual inspection of a chart of water yield versus time for each ESU. Figure 2.1 is an example of an acceptable time series, while Figure 2.2 is an example of an unacceptable time series.

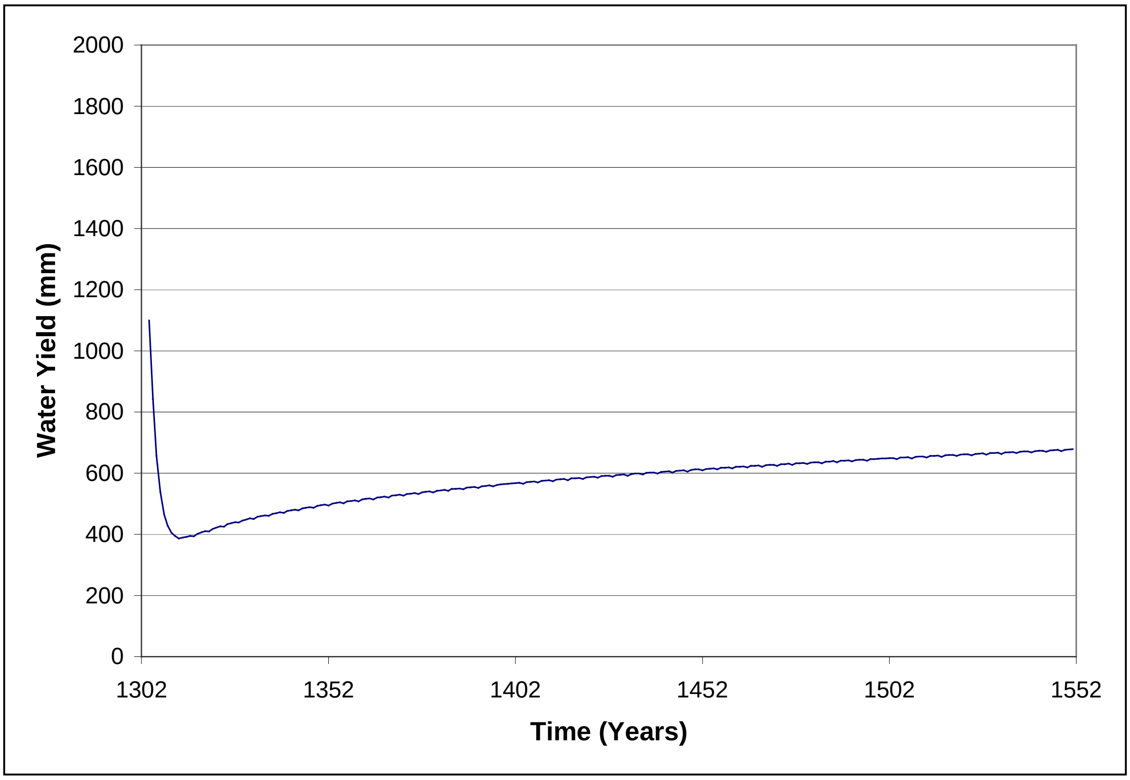

Figure 2.1 An acceptable time series of annual water yield.

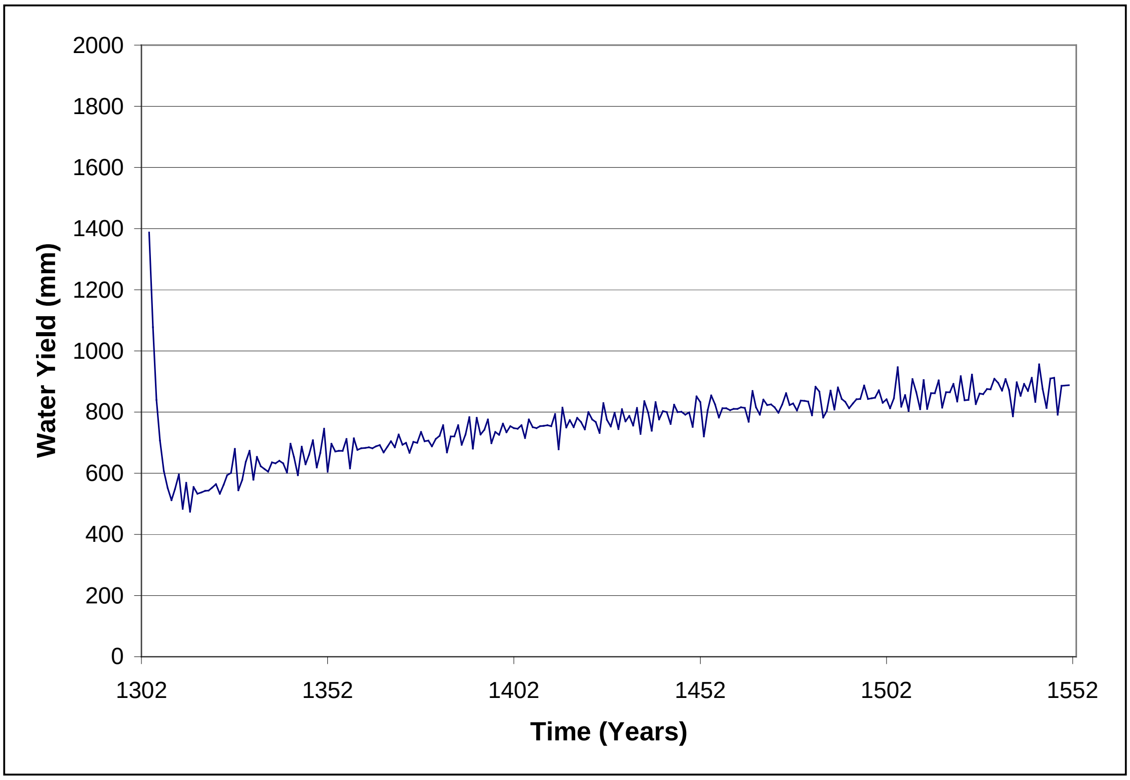

Figure 2.2 An unacceptable time series of annual water yield.

The small 4-year oscillations observed in Figure 2.1 are due to an error in handling leap years made in Peel et al. (2000) when creating the synthetic climate. These small oscillations are minor and will not significantly affect the results of any further analysis.

The cause of the large random oscillations observed in Figure 2.2 is unknown at present. However, they are likely to be due to a numerical instability in the Macaque model. Although the oscillations in the water yield curve are large the average long term shape of the curve remains similar to that observed in Figure 2.1, thus catchment wide conclusions based on the summation of water yield from many ESU's are still likely to be valid. However, the water yield data from ESU's like that shown in Figure 2.2 cannot be used in any further analysis.

Table 2.1 shows the number of ESU's that contain a particular vegetation type. The vegetation classes of water, rock and unknown vegetation type were not used in any further analysis. The number of useable ESU's, determined after visual inspection of time series charts, is also shown in Table 2.1. The remaining sample of useable ESU's contains all the major vegetation types in the Thomson and is sufficient for analysis to continue.

Table 2.1 Frequency of ESU's covered by particular species types for the whole catchment and the frequency of useable ESU's after visual inspection of the time series charts.

Species	Species Code	Number of ESU's	% of ESU's	Number of acceptable ESU's	% of acceptable ESU's
E. regnans	1314	326	17.1%	54	7.93%
E. nitens	1302	43	2.26%	27	3.96%
E. delegatensis	1270	291	15.27%	133	19.53%
E. pauciflora	1308	69	3.62%	42	6.17%
E. sieberi	1318	22	1.15%	5	0.73%
E. obliqua	1304	13	0.68%	4	0.59%
Mixed species	9008	1091	57.24%	404	59.32%
Heath	9021	21	1.1%	12	1.76%
Acacia dealbata	25	17	0.89%		
Wet sclerophyll	9003	9	0.47%		
Rainforest	9012	1	0.05%		
Leptospermum	9004	3	0.16%		
Water	9903	132			
Rocky	9997	3			
Unknown	9999	225			
Zero species	0	10			
Total		2276			
Total (Veg. Only)		1906		681	

Another Excel macro was written to extract values of aspect, slope, elevation and mean annual precipitation (MAP) from the Macaque files for each ESU. The values of aspect, slope and elevation were derived from a digital elevation model of the Thomson catchment Peel et al. (2000), while the mean annual precipitation values were derived from a multiple linear regression (MLR) analysis of monthly precipitation data conducted in Peel et al. (2000).

3. Model development

The form of the model for describing the annual water yield at a given ESU for a given vegetation type is given below.

$$\text{Annual water yield} = \text{MAP} - \text{AET} \qquad (1)$$

Where MAP is the mean annual precipitation and AET is the annual actual evapotranspiration at that given ESU. The MAP was extracted from the Macaque files in the previous section, so the only unknown variable is the AET. The synthetic climate mean annual precipitation (in mm) map is presented in Figure 3.1. If using equation 1 annual water yield is estimated to be a negative value then the annual water yield is set to be equal to zero.

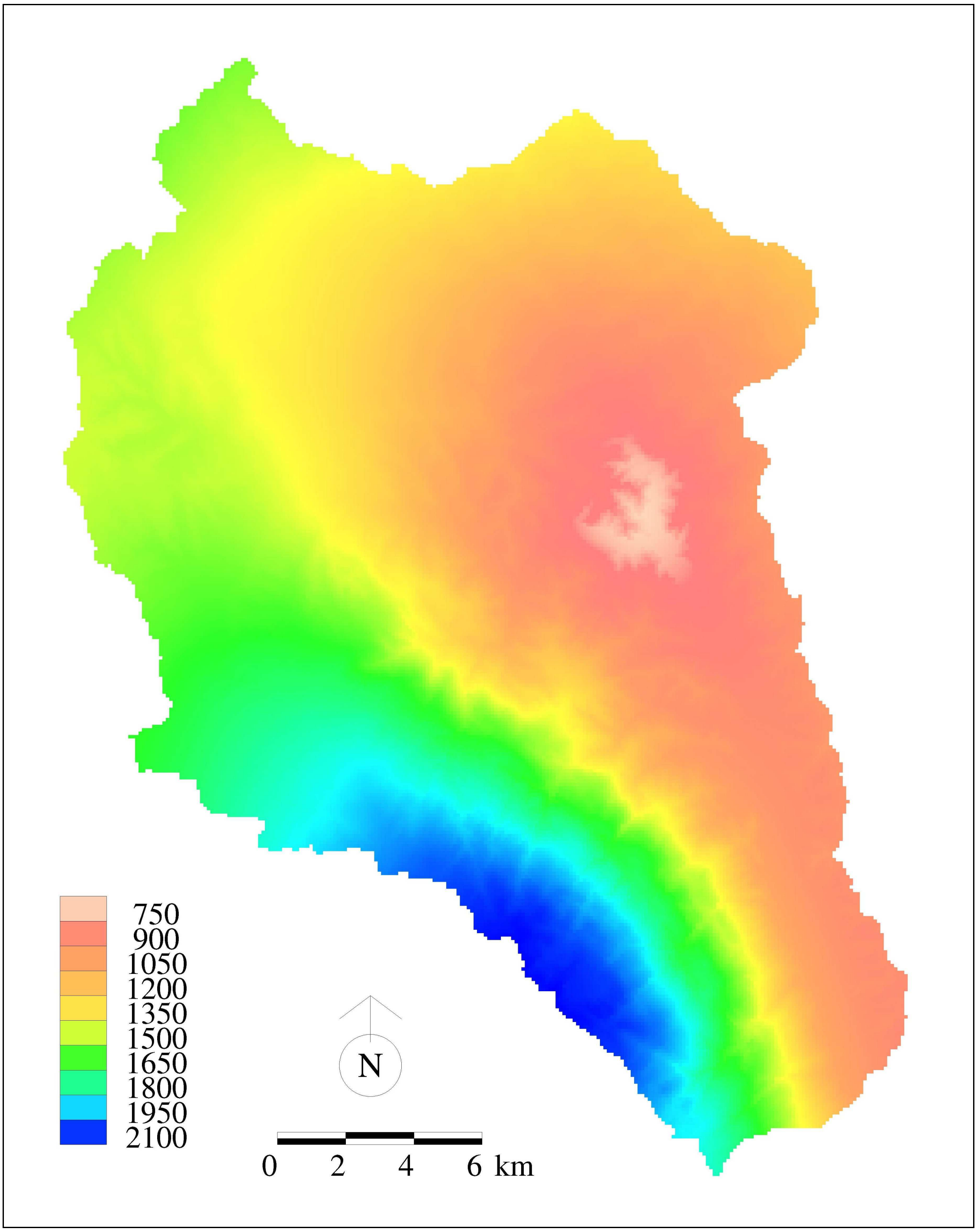

Figure 3.1 Map of mean annual precipitation (synthetic) (in mm) for the Thomson catchment, based on 1962 precipitation data (from Peel et al., 2000).

Watson et al. (1999b) developed a general forest evapotranspiration curve to describe the relationship between forest age and annual evapotranspiration for forests in the Maroondah group of catchments. The form of the Watson et al. (1999b) equation is:

$$
\begin{aligned}
AET = {} & (P1 - P2 - P3) * (e/P5) * AGE * e^{(-AGE/P5)} \\
& + (P2 + P3 - P4)\,(2/(1+e^{(-AGE/P6)}) - 1) \\
& + P3\,(e^{(-AGE/P7)} - 1) + P4
\end{aligned}
\qquad (2)
$$

where P1, P2, P3, P4, P5, P6, P7 are parameters and AGE is the age of the forest.

Equation 2 is a very flexible relationship and is used in this analysis to describe the relationship between forest age and annual actual evapotranspiration. The flexibility of Equation 2 is sufficient to be able to incorporate the relationships between LAI and maximum leaf conductance and forest age.

The version of Macaque used in Peel et al. (2000) is capable of handling many different species of vegetation. However, in that application of the model, Macaque could only discriminate (hydrologically speaking) between four types of vegetation. The four types are determined by whether there are known forest age versus LAI or forest age versus maximum leaf conductance relationships for a particular species as summarised in Table 3.1.

Table 3.1 Summary of the hydrologic differences between vegetation types modeled in Macaque.

Species	Forest Age vs LAI	Forest Age vs Maximum Leaf Conductance
E. regnans & E. nitens	Known	Known
E. delegatensis	Known	Known
Other Eucalypts	Unknown	Known
Non Eucalypts	Unknown	Unknown

Relationships between forest age and LAI and maximum leaf conductance for E. regnans are well known (Watson, 1999, Watson et al., 1999a and Vertessy et al., 2000). These same relationships are assumed to hold for E. nitens. The maximum LAI for E. delegatensis is assumed to be 0.3 lower than that of E. regnans and E. nitens. Following the work of Roberts et al. (2000) a relationship between forest age and maximum leaf conductance is assumed to hold for all eucalypt species. For non-ash eucalypts and non-eucalypts the long-term LAI patterns are unknown, but were assumed to rise from 0 after disturbance to a constant value 5 to 10 year after disturbance (Peel et al., 2000). For non-eucalypts the long-term maximum leaf conductance is also unknown and was assumed to be a constant value (Peel et al., 2000).

Parameter values of Equation 2 were determined by fitting the estimate of annual water yield from Equation 1 (using AET values from Equation 2) to the Macaque annual water yield curve (Macaque output from section 2) by eye. Figure 3.2 is an example of the Macaque water yield and the modeled water yield from Equations 1 and 2 for an ESU covered in E. regnans vegetation. The ESU has elevation of 1056m, MAP of 2122mm, aspect of 159° (0° = North) and slope of 14.7°.

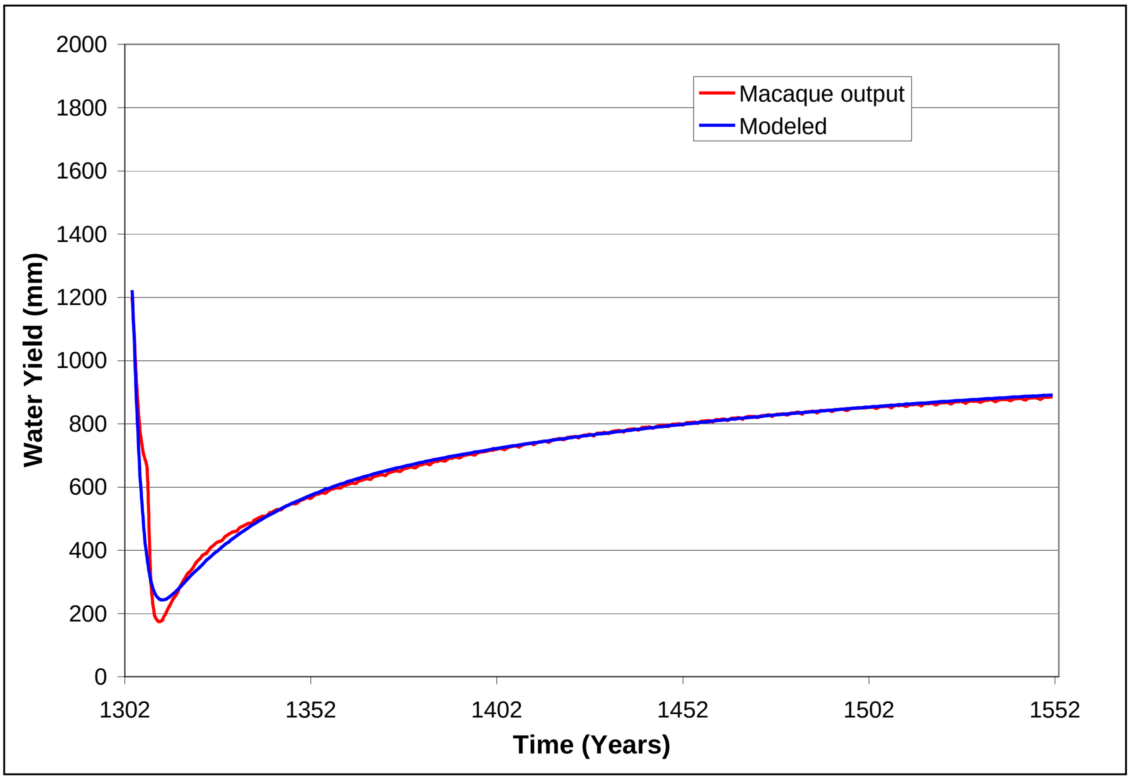

Figure 3.2 Modeled versus Macaque annual water yield for an E. regnans covered ESU.

The shape of the water yield curve in Figure 3.2 is largely similar to the water yield curves for other ESU's of the same vegetation type. This indicates that the shape of the water yield curve is largely determined by the LAI and maximum leaf conductance relationships with forest age, which are jointly described by Equation 2. Differences in elevation, aspect and slope between ESU's are largely expected to shift the water yield curve vertically or modify the shape of the water yield curve.

The 250-year period used to model the synthetic climate in Peel et al. (2000) and shown in Figure 3.2 and all subsequent time series figures was from 1302 to 1552. This period was arbitrarily chosen for the synthetic climate analysis and does not represent the true climate or forest disturbance history for this period. A period prior to the collection of any climate or forest data was chosen for the synthetic analysis so as to avoid any confusion of the model results with observed conditions.

Parameter values of Equation 2 were determined for each vegetation type at a single ESU. The water yield curve of the ESU chosen was compared to the water curves of other ESU's with the same vegetation type in order to assess whether the ESU chosen was representative of ESU's with that vegetation type. The parameter values were then used for the same vegetation type at different ESU's in order to check if the model was performing well. If the model was not performing well then the inclusion of extra variables into the model, for example elevation, aspect and slope, were considered in order improve model performance.

4. Model performance

The model performance was assessed for each of the four different vegetation types modeled in Peel et al. (2000).

4.1. E. regnans & E. nitens

Topographic and climate details of the ESU used for estimating the parameters of equation 2 for E. regnans and E. nitens are presented in Table 4.1.

Table 4.1 Details of ESU used for estimating parameters for E. regnans & E. nitens.

Hillslope	ESU	Species	MAP (mm)	Elevation (m)	Aspect	Slope
3	1	E. regnans	2122	1056	159°	14.7°

Figure 4.1 shows the fit between the Macaque annual water yield and the modeled annual water yield for the ESU using Equation 1 (E = 0.97).

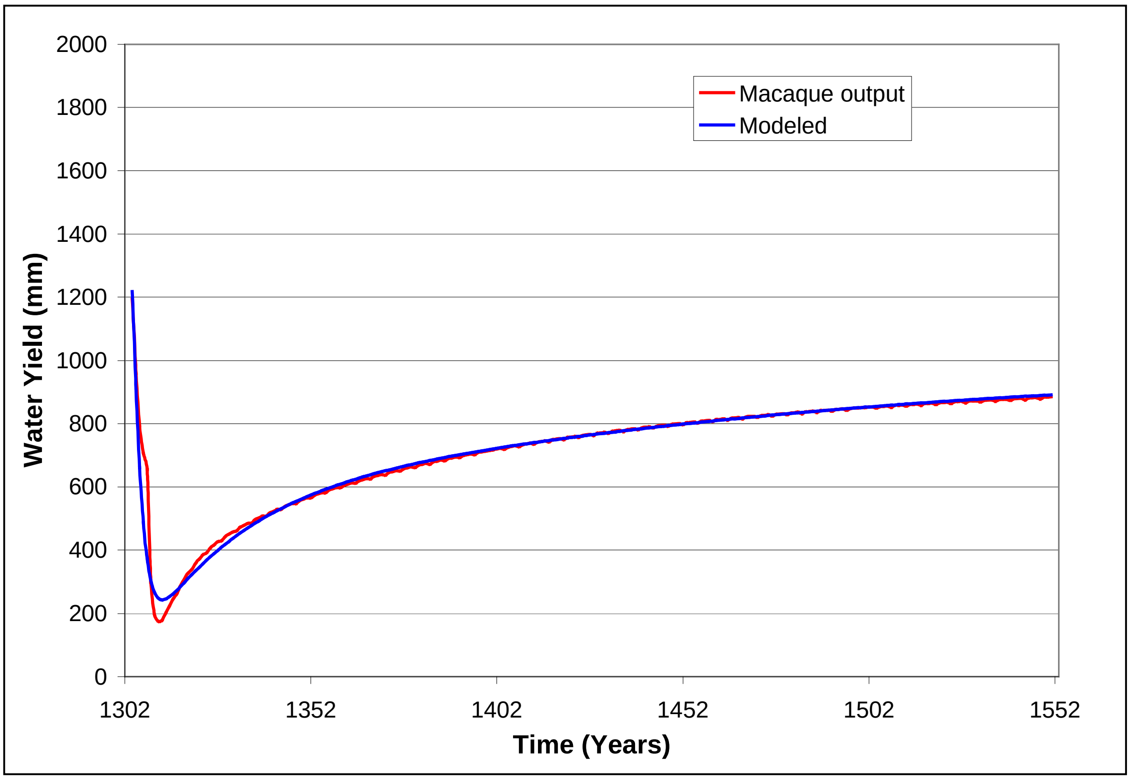

Figure 4.1 Modeled versus Macaque annual water yield for an E. regnans covered ESU.

The parameter values of Equation 2 for E. regnans and E. nitens are given in Table 4.2

Table 4.2 Equation 2 parameter values for E. regnans & E. nitens.

Parameter	Value
P1	1900
P2	1160
P3	920
P4	550
P5	40
P6	2
P7	100

The coefficient of efficiency (E) introduced by Nash and Sutcliffe (1970) is an objective measure of model performance. The equation for E is

$$E = \frac{\left(\sum_{i=1}^{n} \left(REC_i - \overline{REC}\right)^2 - \sum_{i=1}^{n} \left(SIM_i - REC_i\right)^2 \right)}{\sum_{i=1}^{n} \left(REC_i - \overline{REC}\right)^2} \tag{3}$$

where REC_i is a Macaque annual water yield, SIM_i is a modeled annual water yield (from Equations 1 and 2) and $\overline{REC}$ is the Macaque mean annual water yield. An E value of 1.0 indicates a perfect reproduction of the Macaque data by the model. Chiew et al. (1993) noted that E values greater than 0.6 can be considered satisfactory and E values greater than 0.8 can be considered to be acceptable. The E value represents the proportion of variation in the Macaque data that the model is able to reproduce. For example if E = 0.8, then the model is able to reproduce 80% of the variation in the Macaque data.

Examples of how close the model is to reproducing the Macaque annual water yield for a given E value are provided in Section 4.7, for a range of vegetation types, as a visual indication of the model error associated with different E values.

When the fitted model is applied to the other ESU's with E. regnans and E. nitens vegetation the model performs well. The distribution of E values from ESU's with E. regnans and E. nitens vegetation is presented in Table 4.3.

Table 4.3 Distribution of E values for model fit for E. regnans and E. nitens.

E	Number	Percentage
≥ 0.95	36	44%
0.9 < 0.95	27	33%
0.8 < 0.9	10	12%
0.6 < 0.8	4	5%
<0.6	4	5%
Total	81	

The model is acceptable for 90% of the ESU's tested. In 77% of the ESU's the model E values where 0.9 or higher, which is considered an extremely good fit. The model results were poor (E < 0.6) in only 5% of the ESU's. Since the model results are so good, the addition of topographic variables to the model (Equation 1) in order to improve the model further was not necessary. Visual inspection of poor model fit ESU's did not indicate an obvious topographic variable to add in order to improve the model fit.

4.2. E. delegatensis

Topographic and climate details of the ESU used for estimating the parameters of equation 2 for E. delegatensis are presented in Table 4.4.

Table 4.4 Details of ESU used for estimating parameters for E. delegatensis.

Hillslope	ESU	Species	MAP (mm)	Elevation (m)	Aspect	Slope
8	1	E. delegatensis	2330	1190	-56°	14.9°

Figure 4.2 shows the fit between the Macaque annual water yield and the modeled annual water yield for the ESU using Equation 1 (E = 0.96).

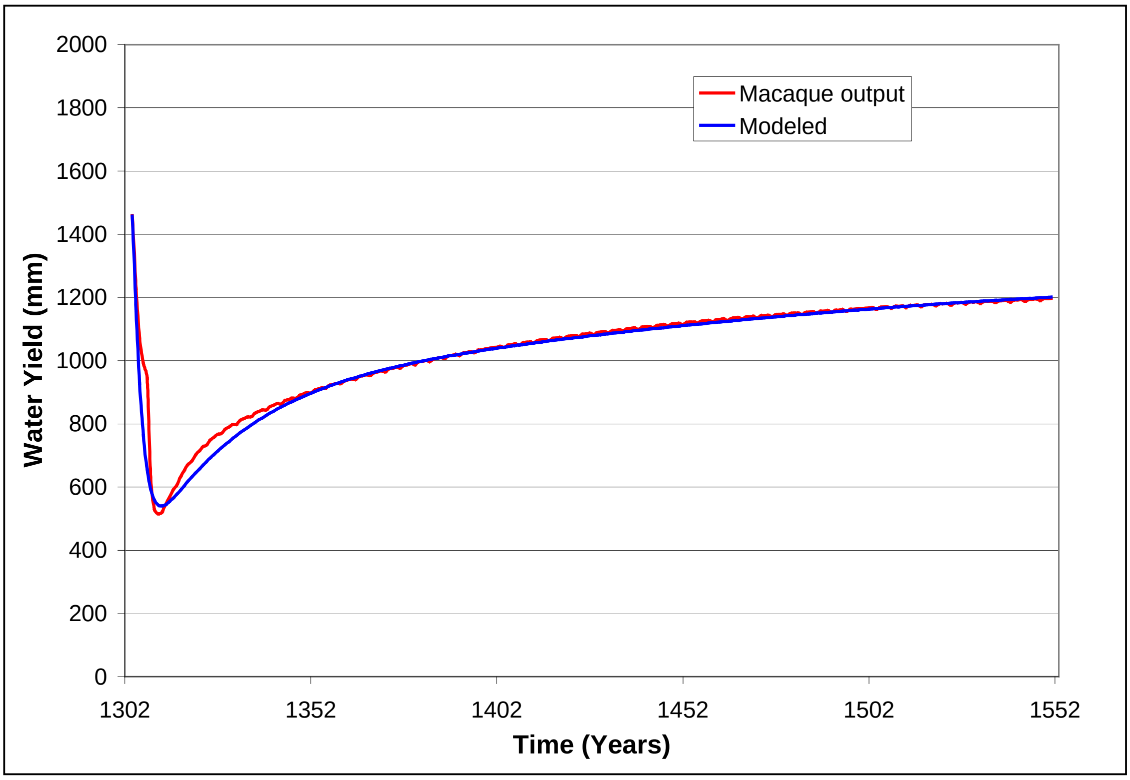

Figure 4.2 Modeled versus Macaque annual water yield for an E. delegatensis covered ESU.

The parameter values of Equation 2 for E. delegatensis are given in Table 4.5

Table 4.5 Equation 2 parameter values for E. delegatensis.

Parameter	Value
P1	1800
P2	1060
P3	950
P4	540
P5	40
P6	2
P7	100

When the fitted model is applied to the other ESU's with E. delegatensis vegetation the model performs well. The distribution of E values from ESU's with E. delegatensis vegetation is presented in Table 4.6.

Table 4.6 Distribution of E values for model fit for E. delegatensis.

E	Number	Percentage
≥ 0.95	65	49%
0.9 < 0.95	37	28%
0.8 < 0.9	22	17%
0.6 < 0.8	6	5%
<0.6	3	2%
Total	133	

The model is acceptable for 93% of the ESU's tested. In 77% of the ESU's the model E values where 0.9 or higher, which is considered an extremely good fit. The model results were poor ($E < 0.6$) in only 2% of the ESU's. Since the model results are so good, the addition of topographic variables to the model (Equation 1) in order to improve the model further was not necessary. Visual inspection of poor model fit ESU's did not indicate an obvious topographic variable to add in order to improve the model fit.

4.3. E. sieberi

Initially all of the non-ash eucalypts were modeled as one group, however, the results did not prove satisfactory. In particular E. sieberi and E. pauciflora covered ESU's had different water yield curves when compared to E. obliqua and mixed species ESU's. Thus the E. sieberi and E. pauciflora ESU's are considered separately and the E. obliqua and mixed species ESU's are considered together.

Topographic and climate details of the ESU used for estimating the parameters of equation 2 for E. sieberi are presented in Table 4.7.

Table 4.7 Details of ESU used for estimating parameters for E. sieberi.

Hillslope	ESU	Species	MAP (mm)	Elevation (m)	Aspect	Slope
337	0	E. sieberi	1400	610	21^o	19.7^o

Figure 4.3 shows the fit between the Macaque annual water yield and the modeled annual water yield for the ESU using Equation 1 (E = 0.99).

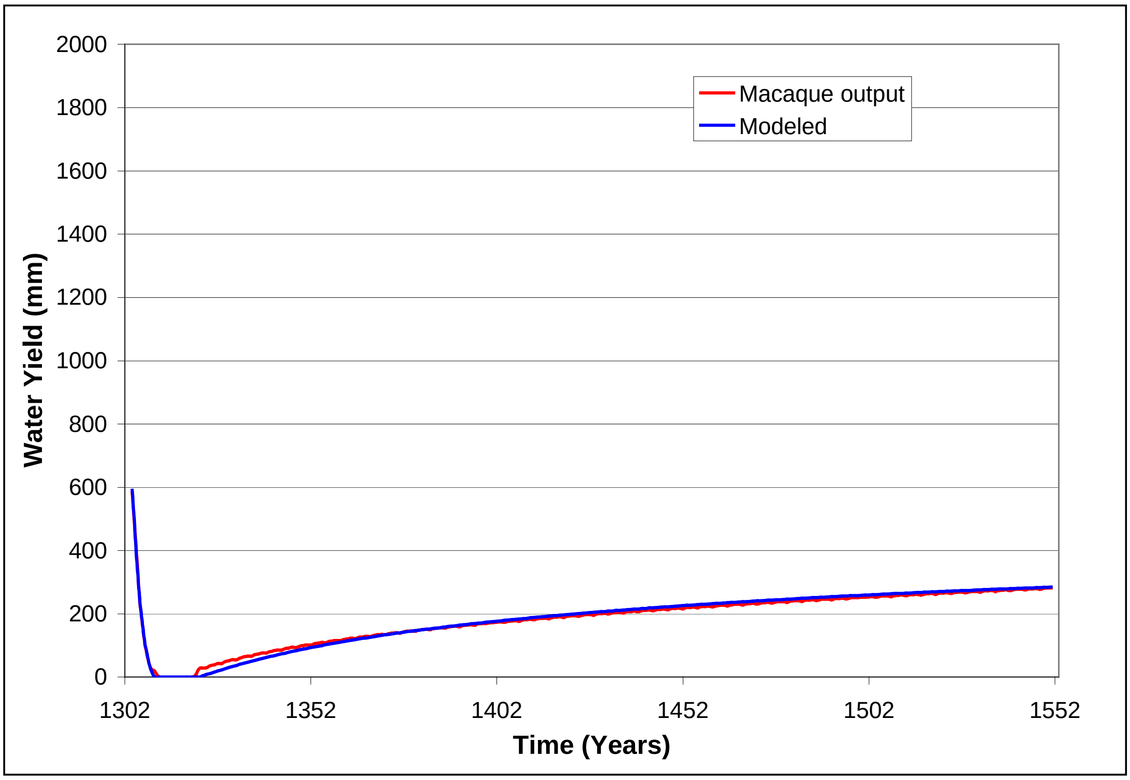

Figure 4.3 Modeled versus Macaque annual water yield for an E. sieberi covered ESU.

The parameter values of Equation 2 for E. sieberi are given in Table 4.8

Table 4.8 Equation 2 parameter values for E. sieberi.

Parameter	Value
P1	1450
P2	1060
P3	440
P4	610
P5	40
P6	2
P7	130

When the fitted model is applied to the other ESU's with E. sieberi vegetation the model performs satisfactorily. The distribution of E values from ESU's with E. sieberi vegetation is presented in Table 4.9.

Table 4.9 Distribution of E values for model fit for E. sieberi.

E	Number	Percentage
≥ 0.95	3	60%
0.9 < 0.95	0	0%
0.8 < 0.9	0	0%
0.6 < 0.8	1	20%
<0.6	1	20%
Total	5	

Due to the small number of ESU's available for testing the model only very general comments about the model performance are appropriate. The model appears to be performing satisfactorily and no further topographic variables where added to the model in order to improve the model fit.

4.4. E. pauciflora

Topographic and climate details of the ESU used for estimating the parameters of equation 2 for E. pauciflora are presented in Table 4.10.

Table 4.10 Details of ESU used for estimating parameters for E. pauciflora.

Hillslope	ESU	Species	MAP (mm)	Elevation (m)	Aspect	Slope
49	2	E. pauciflora	2300	1360	-36^o	10.1^o

Figure 4.4 shows the fit between the Macaque annual water yield and the revised modeled annual water yield for the ESU using Equation 1 (E = 0.99).

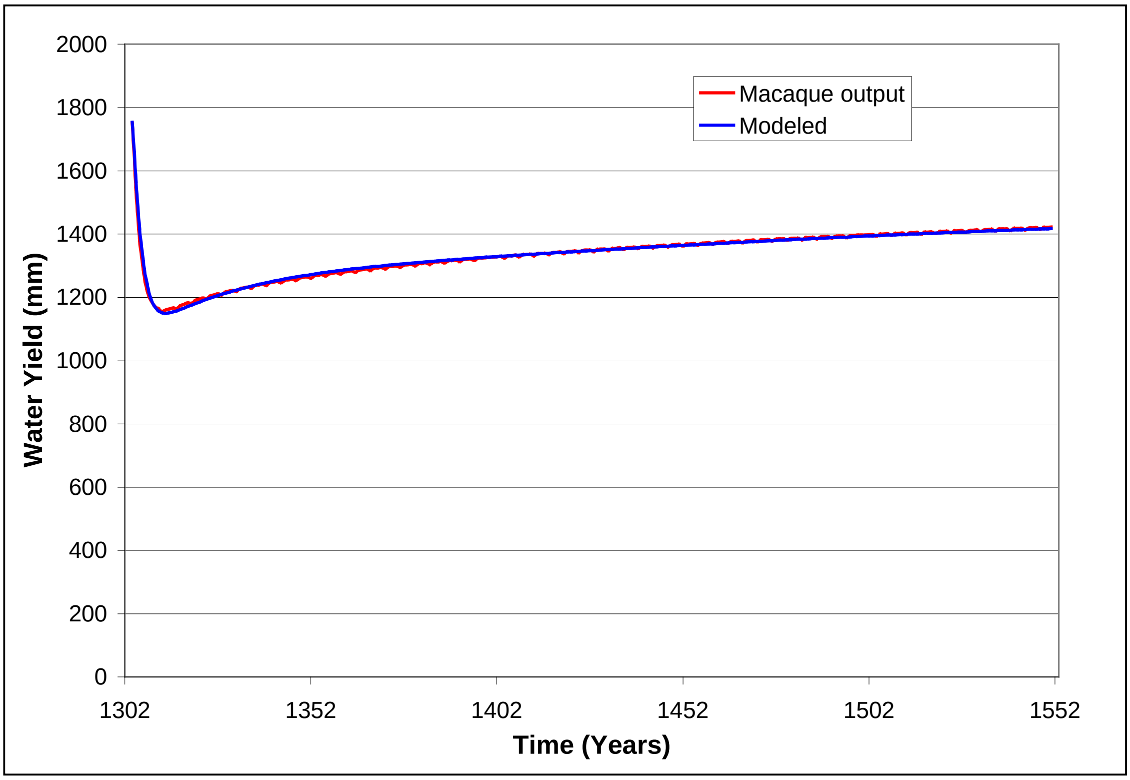

Figure 4.4 Modeled versus Macaque annual water yield for an E. pauciflora covered ESU.

The parameter values of Equation 2 for E. pauciflora are given in Table 4.11

Table 4.11 Equation 2 parameter values for E. pauciflora.

Parameter	Value
P1	1160
P2	830
P3	410
P4	340
P5	40
P6	2
P7	130

When the fitted model is applied to the other ESU's with E. pauciflora vegetation the model performs satisfactorily. The distribution of E values from ESU's with E. pauciflora vegetation is presented in Table 4.12.

Table 4.12 Distribution of E values for model fit for E. pauciflora.

E	Number	Percentage
≥ 0.95	11	26%
0.9 < 0.95	3	7%
0.8 < 0.9	9	21%
0.6 < 0.8	6	14%
<0.6	13	31%
Total	42	

The model is acceptable for 54% of the ESU's tested. In 33% of the ESU's the model E values where 0.9 or higher, which is considered an extremely good fit. The model results were poor (E < 0.6) in 31% of the ESU's. The model results are satisfactory. However, visual inspection of poor model fit ESU's indicated that the addition of a slope variable may improve the model fit.

The revised model with a slope term is given below.

$$\text{Annual water yield} = \text{MAP} - \text{AET} * (\text{Slope} / 10)^{0.1} \tag{5}$$

The revised model parameter values of Equation 2 for E. pauciflora are given in Table 4.13

Table 4.13 Revised model Equation 2 parameter values for E. pauciflora.

Parameter	Value
P1	1160
P2	830
P3	410
P4	340
P5	40
P6	2
P7	130

The distribution of E values from the revised model for ESU's with E. pauciflora vegetation is presented in Table 4.14.

Table 4.14 Distribution of E values from revised model for E. pauciflora.

E	Number	Percentage
≥ 0.95	16	38%
0.9 < 0.95	8	19%
0.8 < 0.9	5	12%
0.6 < 0.8	5	12%
<0.6	8	19%
Total	42	

The revised model is acceptable for 69% of the ESU's tested. In 57% of the ESU's the revised model E values where 0.9 or higher, which is considered an extremely good fit.

The revised model results were poor (E < 0.6) in 19% of the ESU's. The addition of a slope term to the model has improved the results, however they remain only satisfactory. Visual inspection of poor revised model fit ESU's did not indicate another obvious topographic variable that could be added to improve the revised model further.

4.5. E. obliqua and mixed species

Topographic and climate details of the ESU used for estimating the parameters of equation 2 for E. obliqua and mixed species are presented in Table 4.15.

Table 4.15 Details of ESU used for estimating parameters for E. obliqua and mixed species.

Hillslope	ESU	Species	MAP (mm)	Elevation (m)	Aspect	Slope
47	0	Mixed species	1615	820	-119°	20.2°

Figure 4.5 shows the fit between the Macaque annual water yield and the revised modeled annual water yield for the ESU using Equation 1 (E = 0.998).

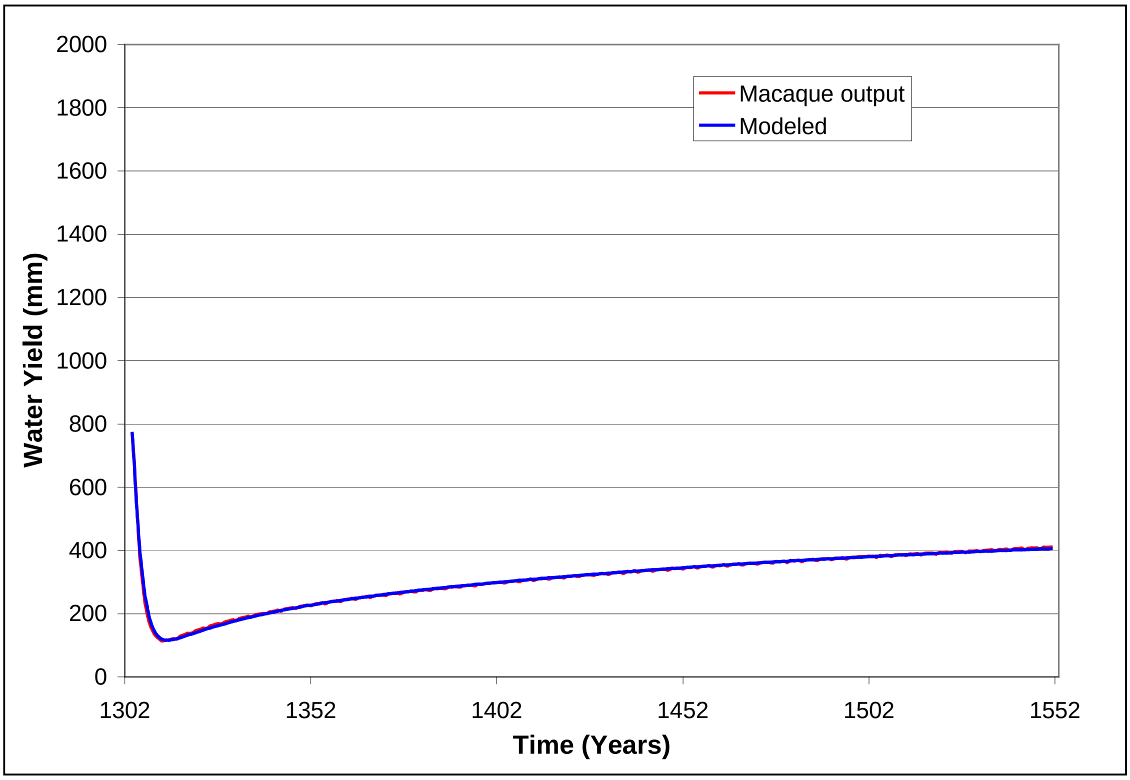

Figure 4.5 Modeled versus Macaque annual water yield for a mixed species covered ESU.

The parameter values of Equation 2 for E. obliqua and mixed species are given in Table 4.16

Table 4.16 Equation 2 parameters values for E. obliqua and mixed species.

Parameter	Value
P1	1520
P2	1150
P3	410
P4	620
P5	40
P6	2
P7	130

When the fitted model is applied to the other ESU's with E. obliqua and mixed species vegetation the model performs satisfactorily. Initially 408 ESU's were modeled, however, 138 of these ESU's had Macaque annual water yield of zero for the complete 250 years of record. Thus the calculation of an E value was not possible for these ESU's. The distribution of E values from the remaining 270 ESU's with E. obliqua and mixed species vegetation is presented in Table 4.17.

Table 4.17 Distribution of E values for model fit for E. obliqua and mixed species.

E	Number	Percentage
≥ 0.95	85	31%
0.9 < 0.95	45	17%
0.8 < 0.9	43	16%
0.6 < 0.8	32	12%
<0.6	65	24%
Total	270	

The model is acceptable for 64% of the ESU's tested. In 48% of the ESU's the model E values where 0.9 or higher, which is considered an extremely good fit. The model results were poor ($E < 0.6$) in 24% of the ESU's. The model results are satisfactory. Visual inspection of poor model fit ESU's indicated that the addition of an aspect variable may improve the model fit.

The revised model with an aspect term is given below.

$$\text{Annual water yield} = \text{MAP} - \text{AET} - 25 \times \cos(2 \times \text{Aspect}) \qquad (6)$$

The revised model parameter values of Equation 2 for E. obliqua and mixed species are given in Table 4.18

Table 4.18 Revised model Equation 2 parameter values for E. obliqua and mixed species.

Parameter	Value
P1	1530
P2	1160
P3	420
P4	640
P5	40
P6	2
P7	130

The distribution of E values from the revised model for the remaining 270 ESU's with E. obliqua and mixed species vegetation is presented in Table 4.19.

Table 4.19 Distribution of E values from revised model for E. obliqua and mixed species.

E	Number	Percentage
≥ 0.95	100	37%
$0.9 < 0.95$	40	15%
$0.8 < 0.9$	49	18%
$0.6 < 0.8$	37	14%
<0.6	44	16%
Total	270	

The revised model is acceptable for 70% of the ESU's tested. In 52% of the ESU's the revised model E values where 0.9 or higher, which is considered an extremely good fit. The revised model results were poor ($E < 0.6$) in 16% of the ESU's. The addition of an aspect term to the model has improved the results, however they remain only satisfactory. Visual inspection of poor revised model fit ESU's did not indicate another obvious topographic variable that could be added to improve the revised model further.

4.6. Heath

Heath is the only non-eucalypt species that had sufficient number of useable ESU's for this analysis. Topographic and climate details of the ESU used for estimating the parameters of equation 2 for heath are presented in Table 4.20.

Table 4.20 Details of ESU used for estimating parameters for heath.

Hillslope	ESU	Species	MAP (mm)	Elevation (m)	Aspect	Slope
49	5	Heath	2280	1300	-54^{o}	7.6^{o}

Figure 4.6 shows the fit between the Macaque annual water yield and the modeled annual water yield for the ESU using Equation 1 ($E = 0.99$).

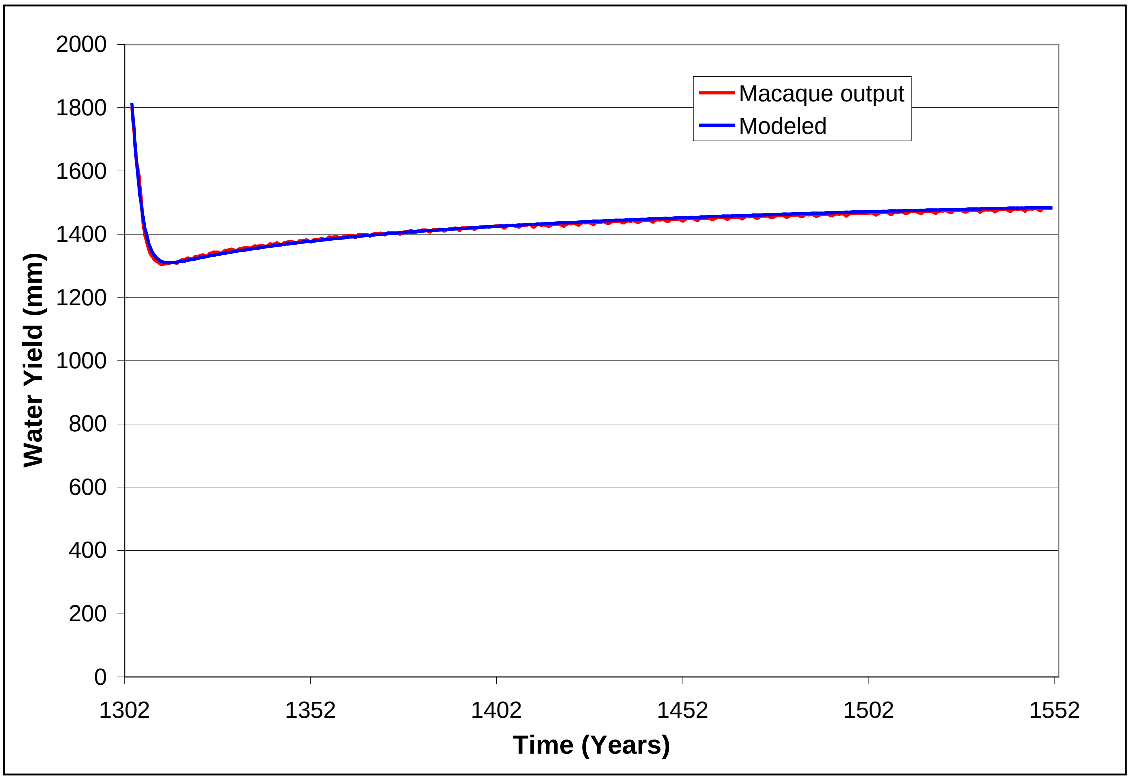

Figure 4.6 Modeled versus Macaque annual water yield for a heath covered ESU.

The parameter values of Equation 2 for heath are given in Table 4.21

Table 4.21 Equation 2 parameters values for heath.

Parameter	Value
P1	980
P2	760
P3	250
P4	300
P5	50
P6	2
P7	130

When the fitted model is applied to the other ESU’s with heath vegetation the model performs satisfactorily. The distribution of E values from ESU’s with heath vegetation is presented in Table 4.22.

Table 4.22 Distribution of E values for model fit for heath.

E	Number	Percentage
≥ 0.95	4	33%
0.9 < 0.95	0	0%
0.8 < 0.9	3	25%
0.6 < 0.8	1	8%
<0.6	4	33%
Total	12	

Due to the small number of ESU's available for testing the model only very general comments about the model performance are appropriate. The model appears to be performing satisfactorily and no further topographic variables where added to the model in order to improve the model fit.

4.7. Examples of times series for different E values

The following figures are provided in order to give a visual assessment of the model error associated with a given E value. The figures presented in the previous sections for each vegetation type were examples of very good model performance (E ≥ 0.95). Four figures are presented for each of the three E values ranges (0.8 > 0.9, 0.6 > 0.8 and below 0.6). The examples are also chosen to represent the full range of vegetation types where possible.

Topographic and climate details for 4 ESU's where the E values range from 0.8 > 0.9 are presented in Table 4.23.

Table 4.23 Details of the 4 example ESU's with E values between 0.8 and 0.9.

Hillslope	ESU	Species	MAP (mm)	Elevation (m)	Aspect	Slope	E
7	2	E. regnans	2252	1096	59.8	14.5	0.84
48	2	E. delegatensis	2226	1259	-100.4	9.9	0.89
139	2	Mixed species	1877	750	165.7	20.3	0.82
104	0	E. pauciflora	2252	1311	88.0	10.9	0.89

Figures 4.7 – 4.10 shows the fit between the Macaque annual water yield and the modeled annual water yield for the 4 example ESU's.

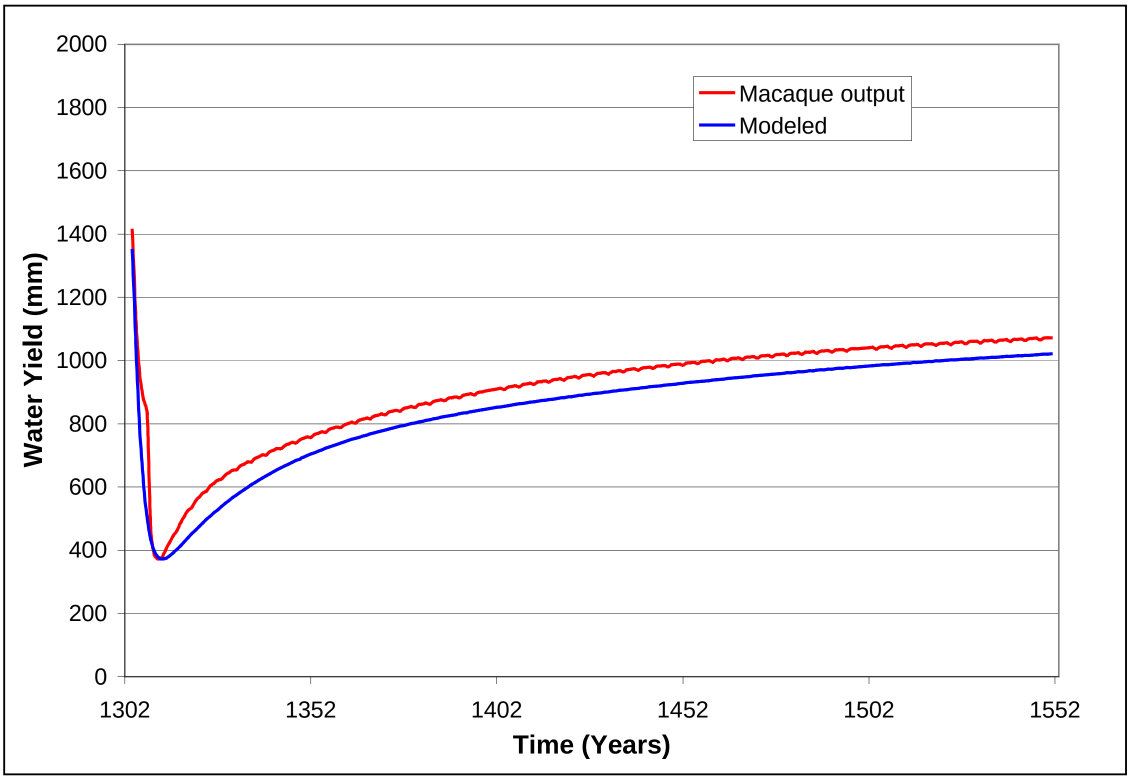

Figure 4.7 Modeled versus Macaque annual water yield for an E. regnans covered ESU (E = 0.84).

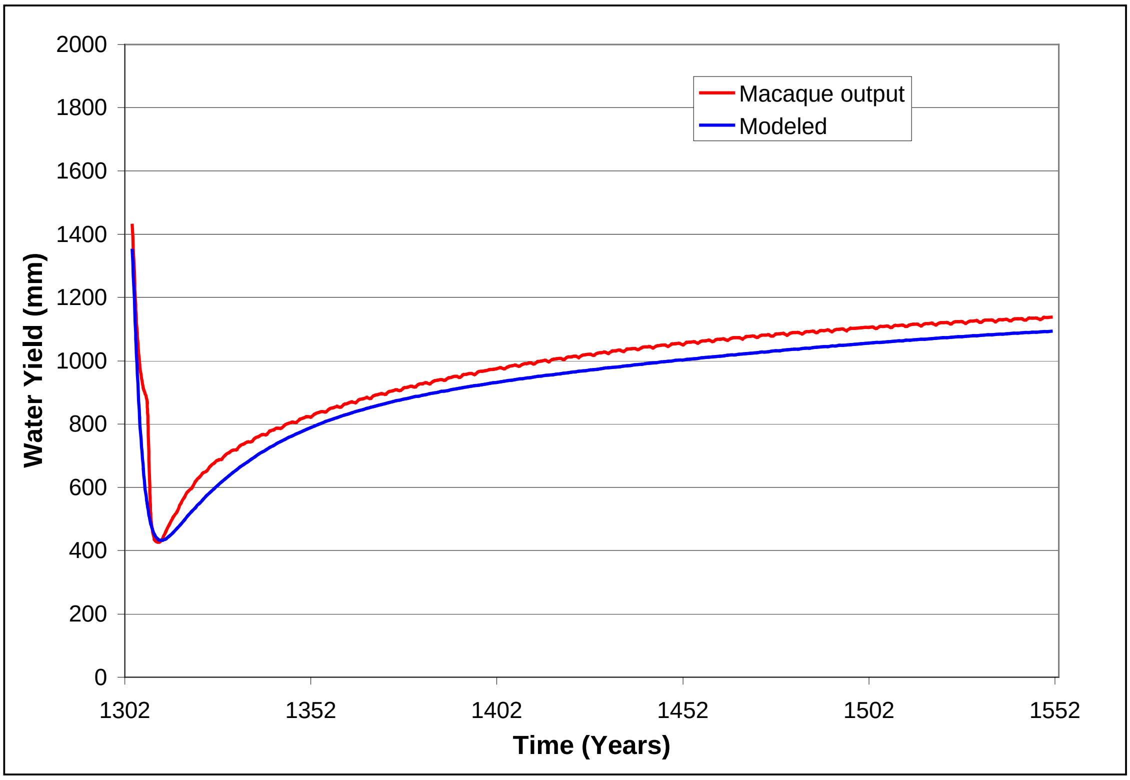

Figure 4.8 Modeled versus Macaque annual water yield for an E. delegatensis covered ESU (E = 0.89).

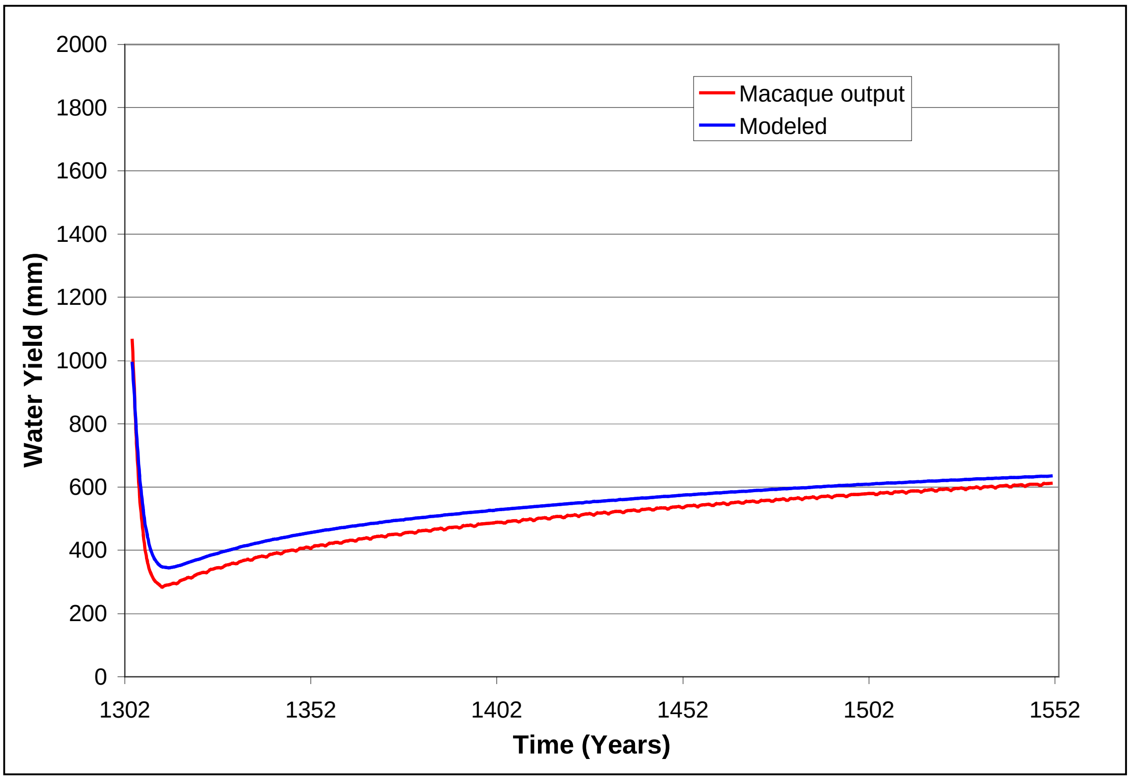

Figure 4.9 Modeled versus Macaque annual water yield for a mixed species covered ESU (E = 0.82).

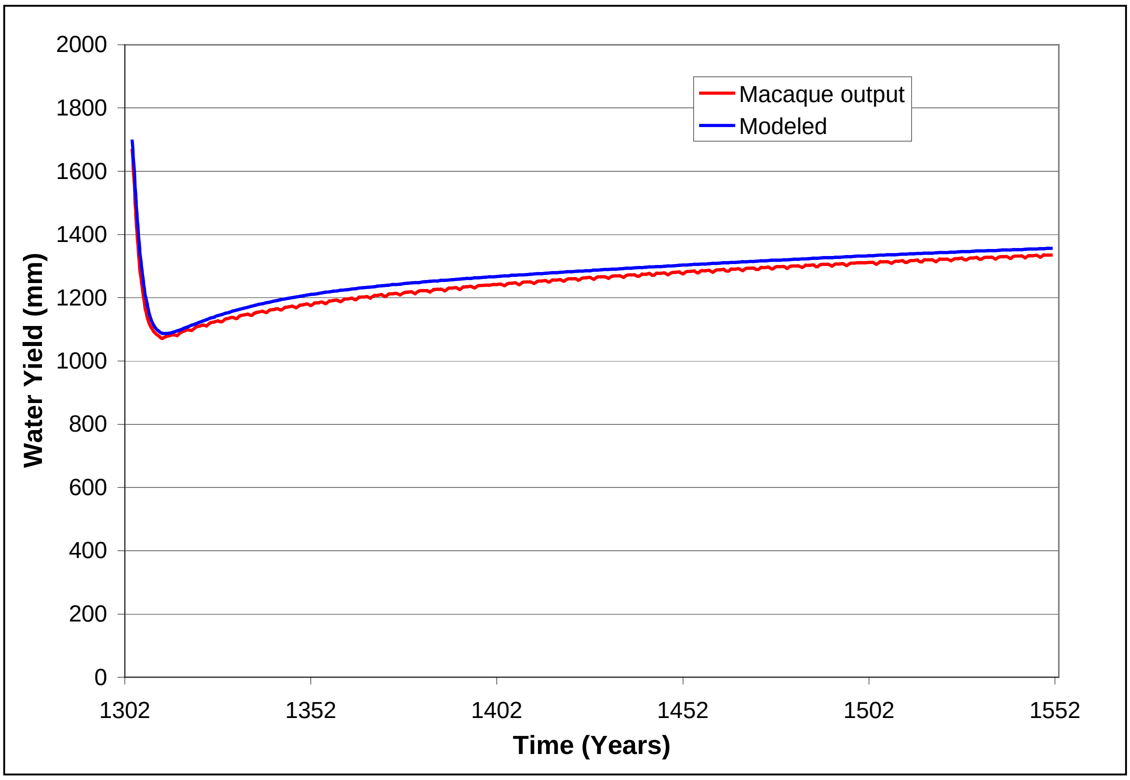

Figure 4.10 Modeled versus Macaque annual water yield for an E. pauciflora covered ESU (E = 0.89).

Topographic and climate details for 4 ESU's where the E values range from 0.6 > 0.8 are presented in Table 4.24.

Table 4.24 Details of the 4 example ESU's with E values between 0.6 and 0.8.

Hillslope	ESU	Species	MAP (mm)	Elevation (m)	Aspect	Slope	E
98	3	E. regnans	1822	835	120.3	16.8	0.77
51	2	E. delegatensis	2176	1253	22.5	8.3	0.74
310	0	Mixed species	1498	929	124.9	20.0	0.69
106	0	E. pauciflora	2191	1280	-144.1	11.6	0.63

Figures 4.11 – 4.14 shows the fit between the Macaque annual water yield and the modeled annual water yield for the 4 example ESU's.

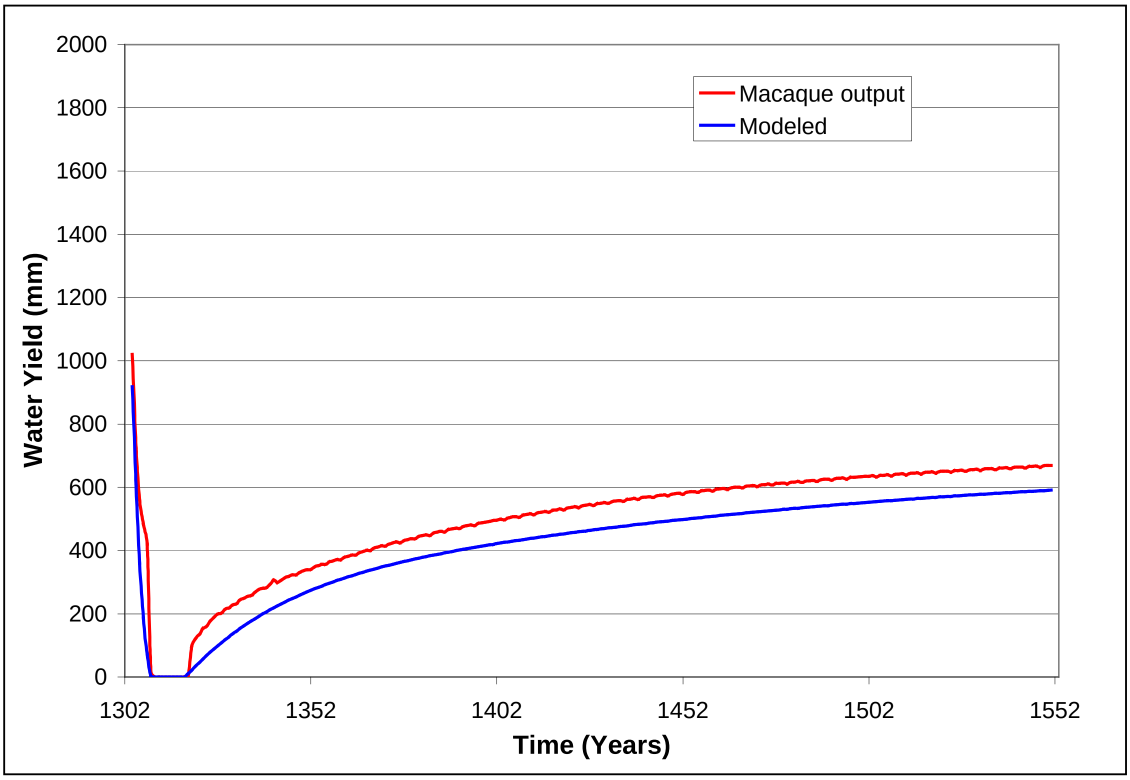

Figure 4.11 Modeled versus Macaque annual water yield for an E. regnans covered ESU (E = 0.77).

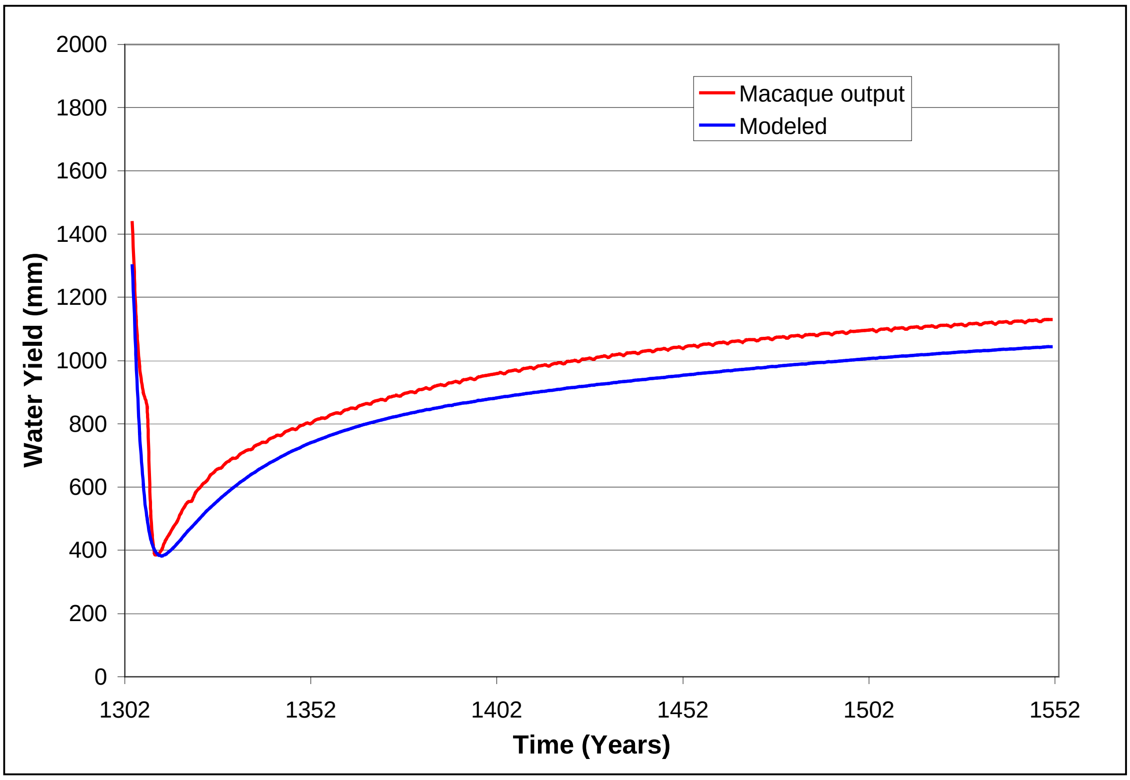

Figure 4.12 Modeled versus Macaque annual water yield for an E. delegatensis covered ESU (E = 0.74).

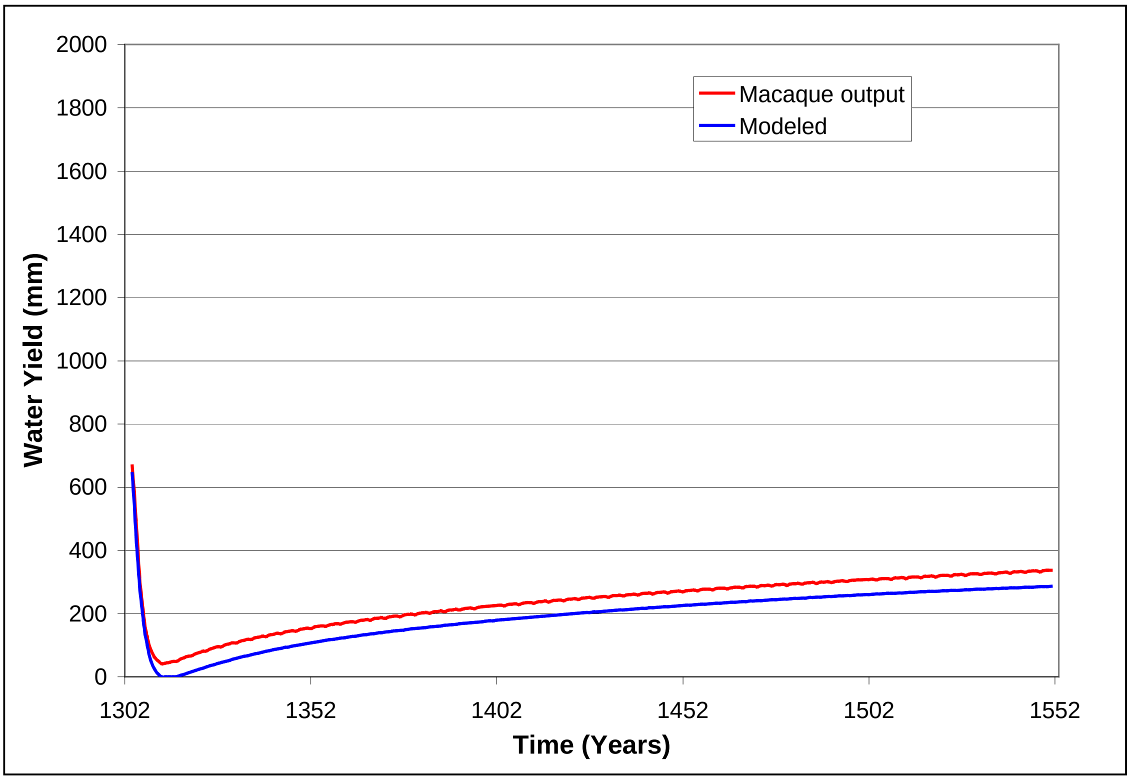

Figure 4.13 Modeled versus Macaque annual water yield for a mixed species covered ESU (E = 0.69).

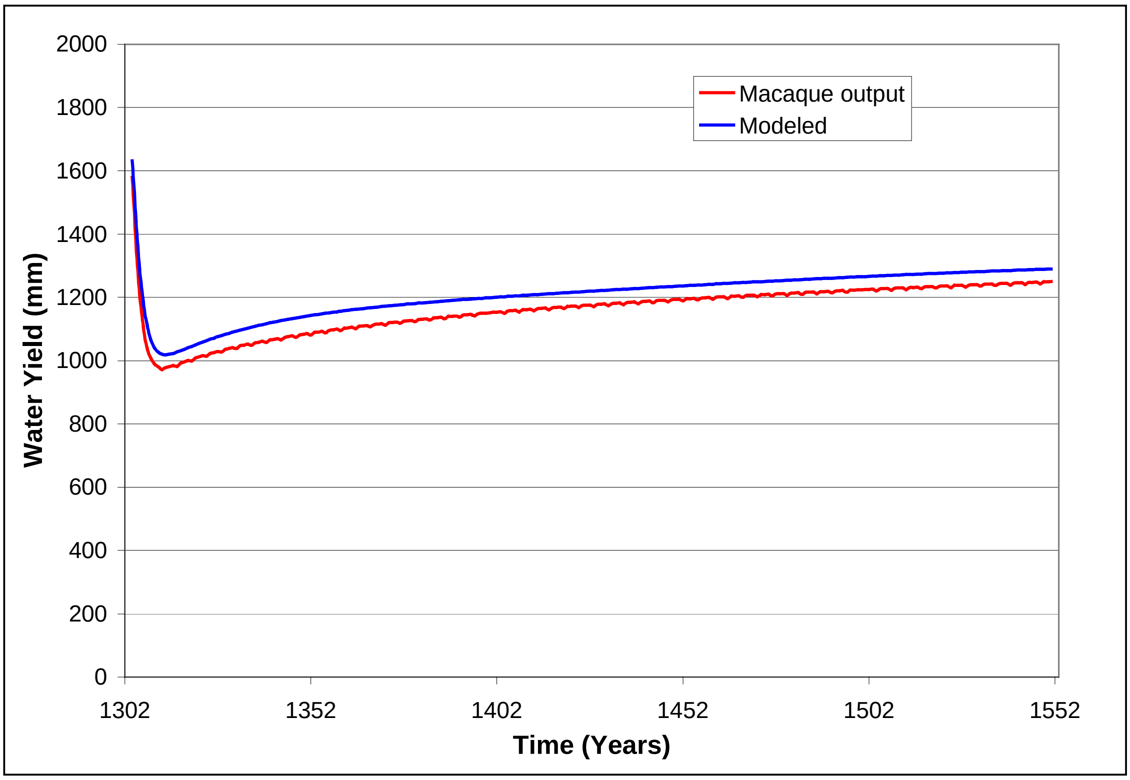

Figure 4.14 Modeled versus Macaque annual water yield for an E. pauciflora covered ESU (E = 0.63).

Topographic and climate details for 4 ESU's where the E values below 0.6 are presented in Table 4.25.

Table 4.25 Details of the 4 example ESU's with E values below 0.6.

Hillslope	ESU	Species	MAP (mm)	Elevation (m)	Aspect	Slope	E
23	7	E. regnans	2052	960	26.3	0.5	0.48
159	3	E. delegatensis	2281	1227	82.6	10.0	0.58
310	1	Mixed species	1504	889	38.4	23.4	0.24
4	1	E. pauciflora	2241	1167	62.9	13.5	-0.08

Figures 4.15 – 4.18 shows the fit between the Macaque annual water yield and the modeled annual water yield for the 4 example ESU's.

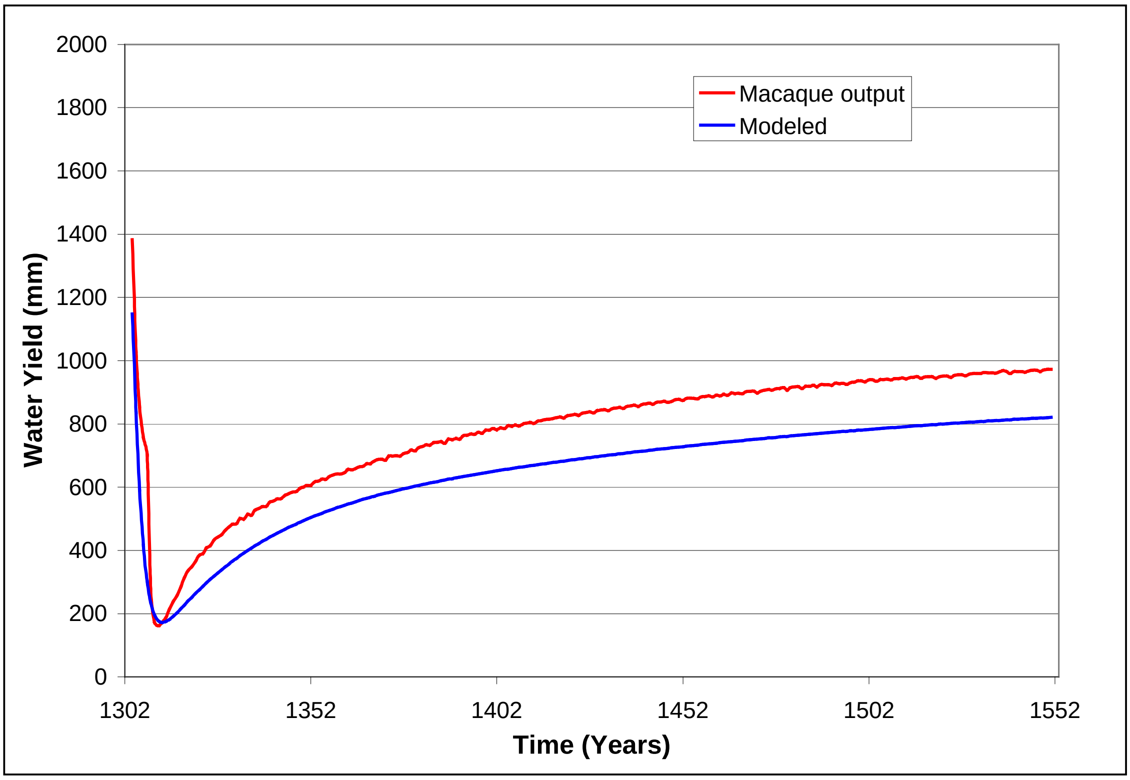

Figure 4.15 Modeled versus Macaque annual water yield for an E. regnans covered ESU (E = 0.48).

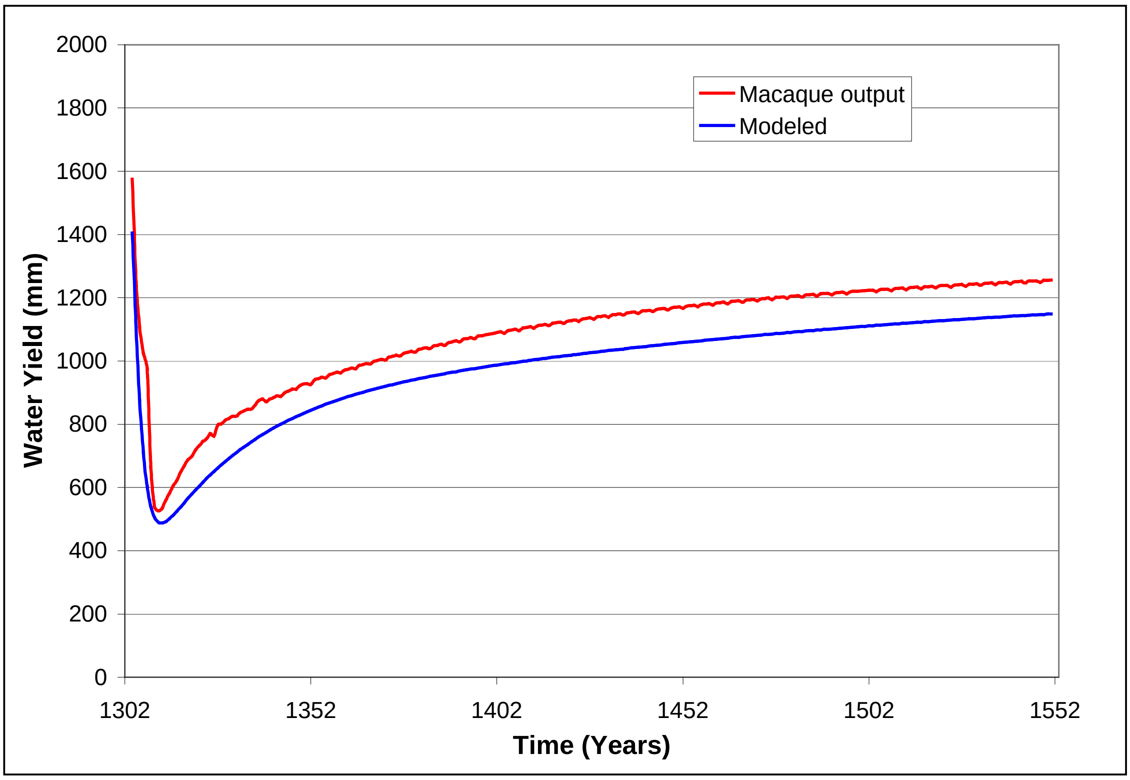

Figure 4.16 Modeled versus Macaque annual water yield for an E. delegatensis covered ESU (E = 0.58).

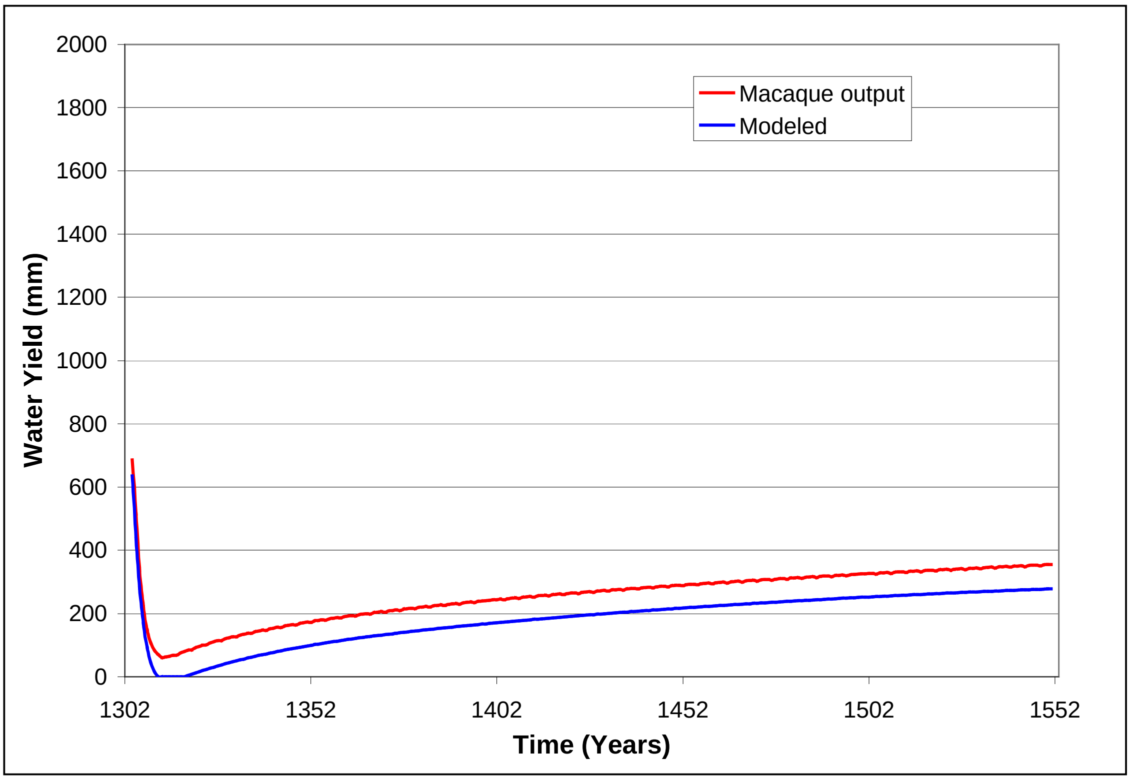

Figure 4.17 Modeled versus Macaque annual water yield for a mixed species covered ESU (E = 0.24).

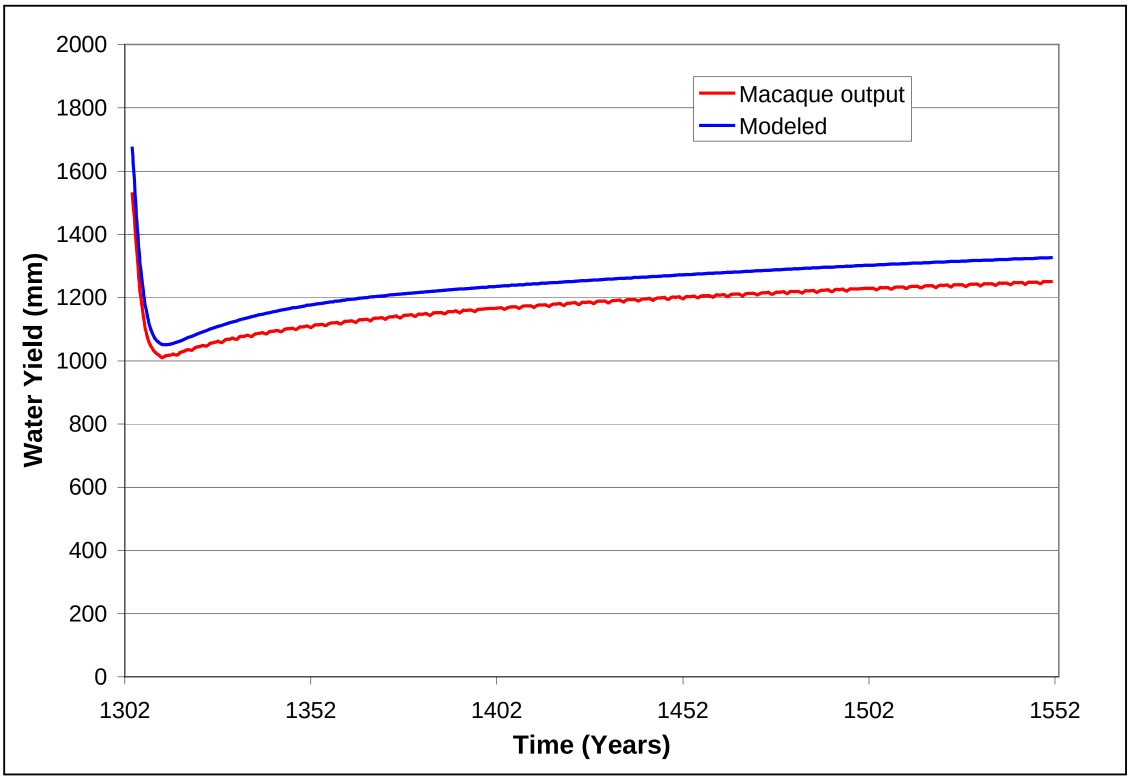

Figure 4.18 Modeled versus Macaque annual water yield for an E. pauciflora covered ESU (E = -0.08).

5. Summary of Models

The basic form of the model for describing the annual water yield at a given ESU for a given vegetation type was given in Equation 1. In the process of fitting the model to the Macaque outputs different values of the parameters for estimating the annual evapotranspiration (Equation 2) have been used for the different vegetation types. In the cases of E. pauciflora and E. obliqua and mixed species an extra topographic variable was added to the basic form of the model in order to improve the models performance. The final form of the model and parameter values for each vegetation type are summarized in Table 5.1.

Table 5.1 Summary of final model form and parameter values for each vegetation type.

Species	Model form	P1	P2	P3	P4	P5	P6	P7
E. regnans & E. nitens	MAP - AET	1900	1160	920	550	40	2	100
E. delegatensis	MAP - AET	1800	1060	950	540	40	2	100
E. sieberi	MAP - AET	1450	1060	440	610	40	2	130
E. pauciflora	MAP - AET x $(\text{Slope}/10)^{0.1}$	1160	830	410	340	40	2	130
E. obliqua & Mixed species	MAP – AET – 25 x Cos(2 x Aspect)	1530	1160	420	640	40	2	130
Heath	MAP - AET	980	760	250	300	50	2	130

6. Limitations

The vegetation type dependant relationships between annual water yield and stand age have been constructed from outputs of the Macaque model application to the Thomson catchment (Peel et al., 2000). Thus the relationships presented in the previous section are subject to the limitations of the Macaque model and its application to the Thomson catchment, which were discussed in detail in Sections 6, 7 and 8 of Peel et al. (2000).

Furthermore, the equations presented in the previous section are only applicable to the Thomson catchment above the Dam Wall, an area of 487 km^2, which is the area that was modeled in the synthetic climate analysis of Peel et al. (2000).

Based on the results of the model performance in the previous section, the relationships for describing long-term water yield from areas covered in E. regnans, E. nitens and E. delegatensis seem very reliable. The relationship for E. pauciflora, E. obliqua and mixed species are generally reliable. The relationships for E. sieberi and heath should be treated with some caution as the percentage of poor model fits is high and or the sample size is small.

The relationship for E. pauciflora includes a slope variable. Values of slope for ESU covered in E. pauciflora ranged from 5.1^{o} to 17.0^{o}. Therefore application of the E. pauciflora relationship for slope values outside of this range should be treated with caution.

The relationship for E. obliqua and mixed species includes aspect as a variable. Values of aspect for ESU covered in E. obliqua and mixed species ranged from -180^o to 180^o. Therefore application of the E. obliqua and mixed species relationship is appropriate for all values of aspect.

7. Conclusion

The two objectives of this study were:

- To collate the results of the synthetic climate water yield analyses conducted on the Thomson catchment (Peel et al., 2000) into Excel spreadsheet form.
- To synthesize the catchment modeling results of Peel et al. (2000) to derive equations between forest age and water yield for the four vegetation classes modeled in Macaque, which can be implemented in IFPS (a DNRE decision support system) for the Thomson catchment.

The results of the synthetic climate analysis have been collated and placed into Excel spreadsheets. These results were then visually inspected to determine their suitability for further analysis in order to achieve the second objective. Using a subset of the entire results the second objective was achieved by creating a model that has been calibrated by eye for the four difference vegetation types modeled in Peel et al. (2000). The performance of the model has been assessed when applied to the four different vegetation types and in the case of E. regnans, E. nitens and E. delegatensis it is very reliable, E. pauciflora, E. obliqua and mixed species it is generally reliable and for E. sieberi and heath it is less reliable and should be used with caution.

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