What contribution can ecohydrology make to forecasting impacts of land use and climate change on water yield and salinity in forested catchments of South-West Australia?

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Motivation

- Need to provide forecasts of climate change impacts on water resources and how forests should be managed to maintain water yield.

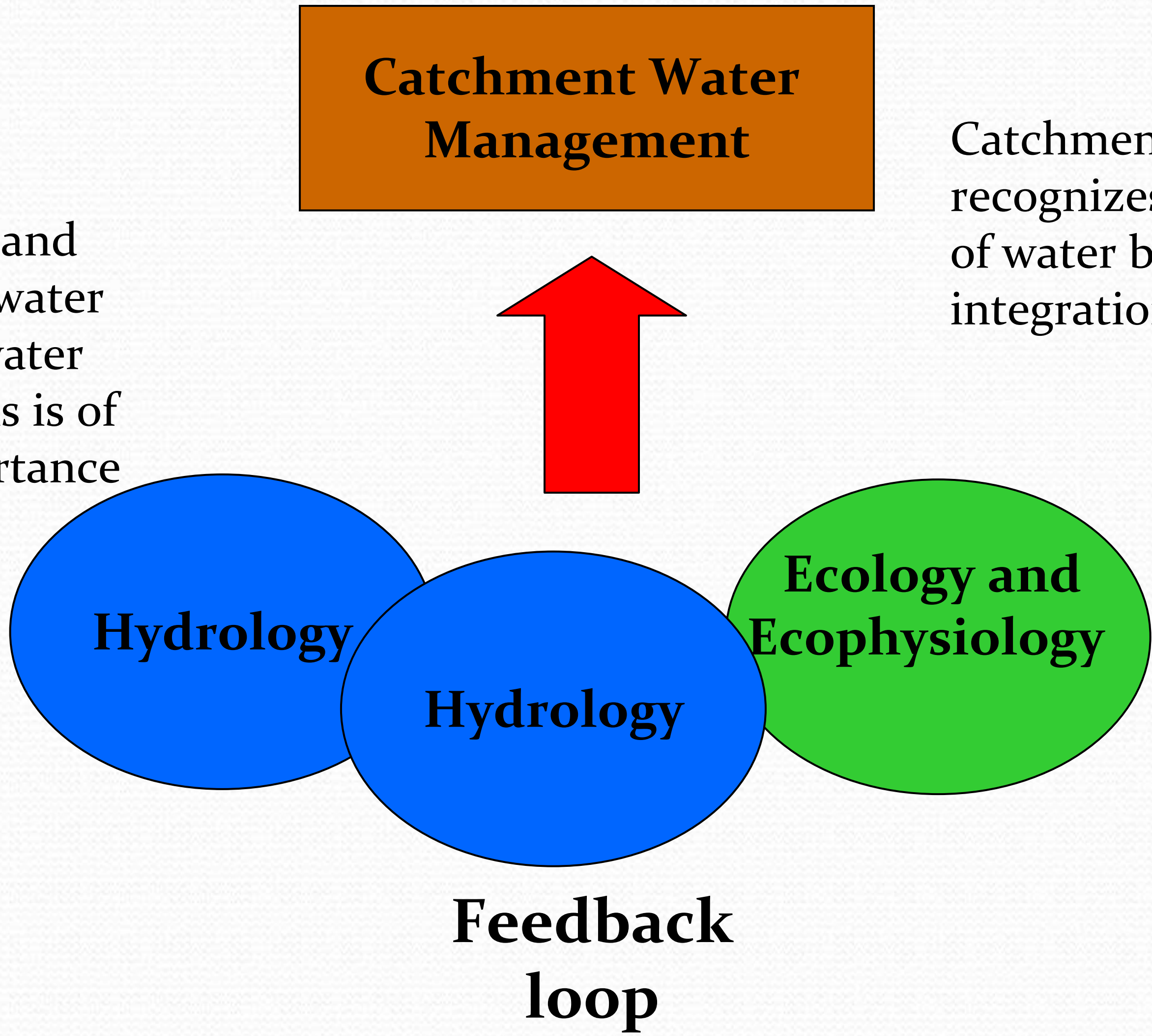
- Need to understand how land use change in catchments impacts on runoff (not just water balance but landscape connectivity).

- How do vegetative feedback loops affect these projections?

- What is the potential impact of climate change on the biomes of southwest Australia?

Ecohydrology for Sustainability

Sustainability and protection of water resources in water limited regions is of primary importance

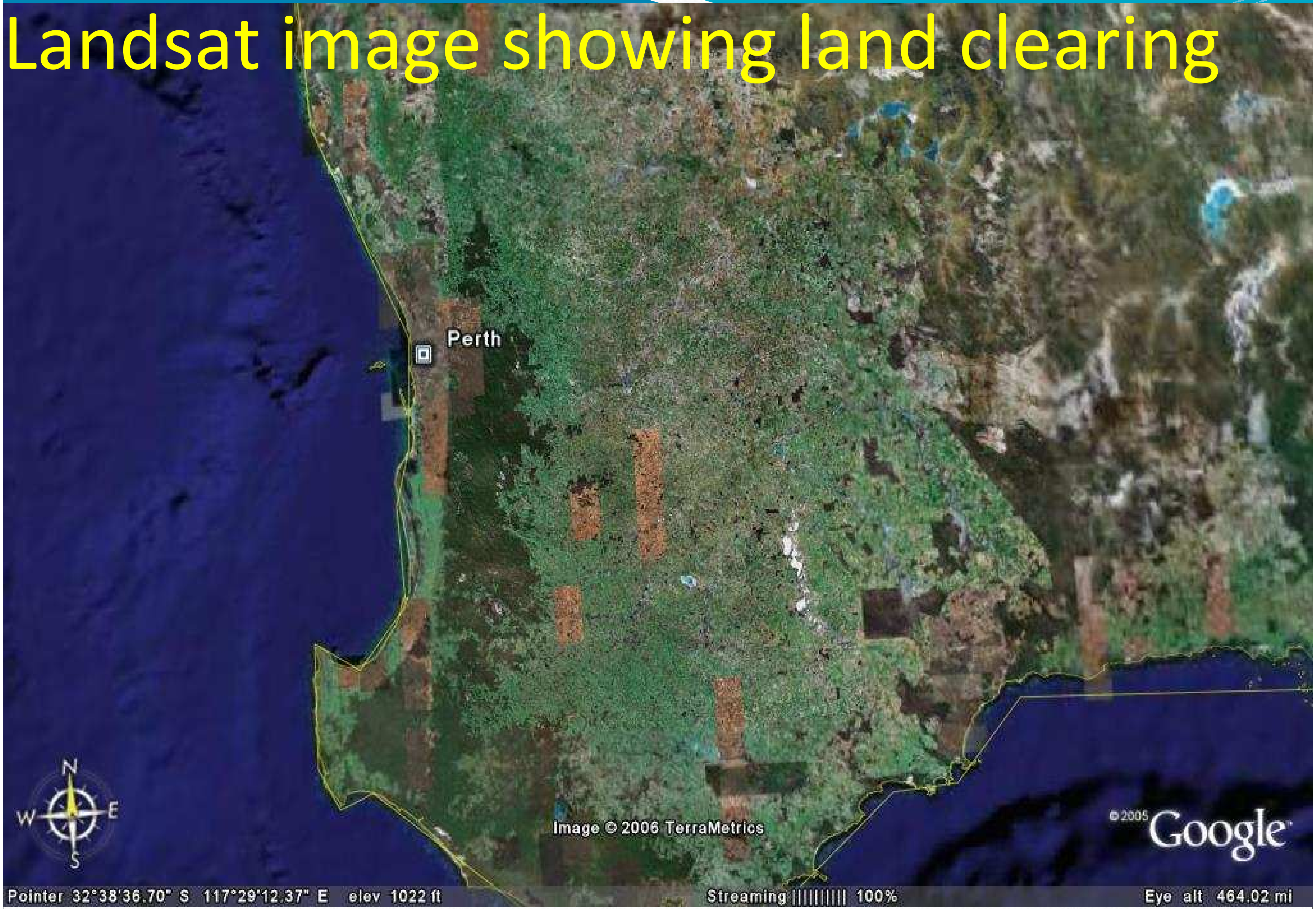


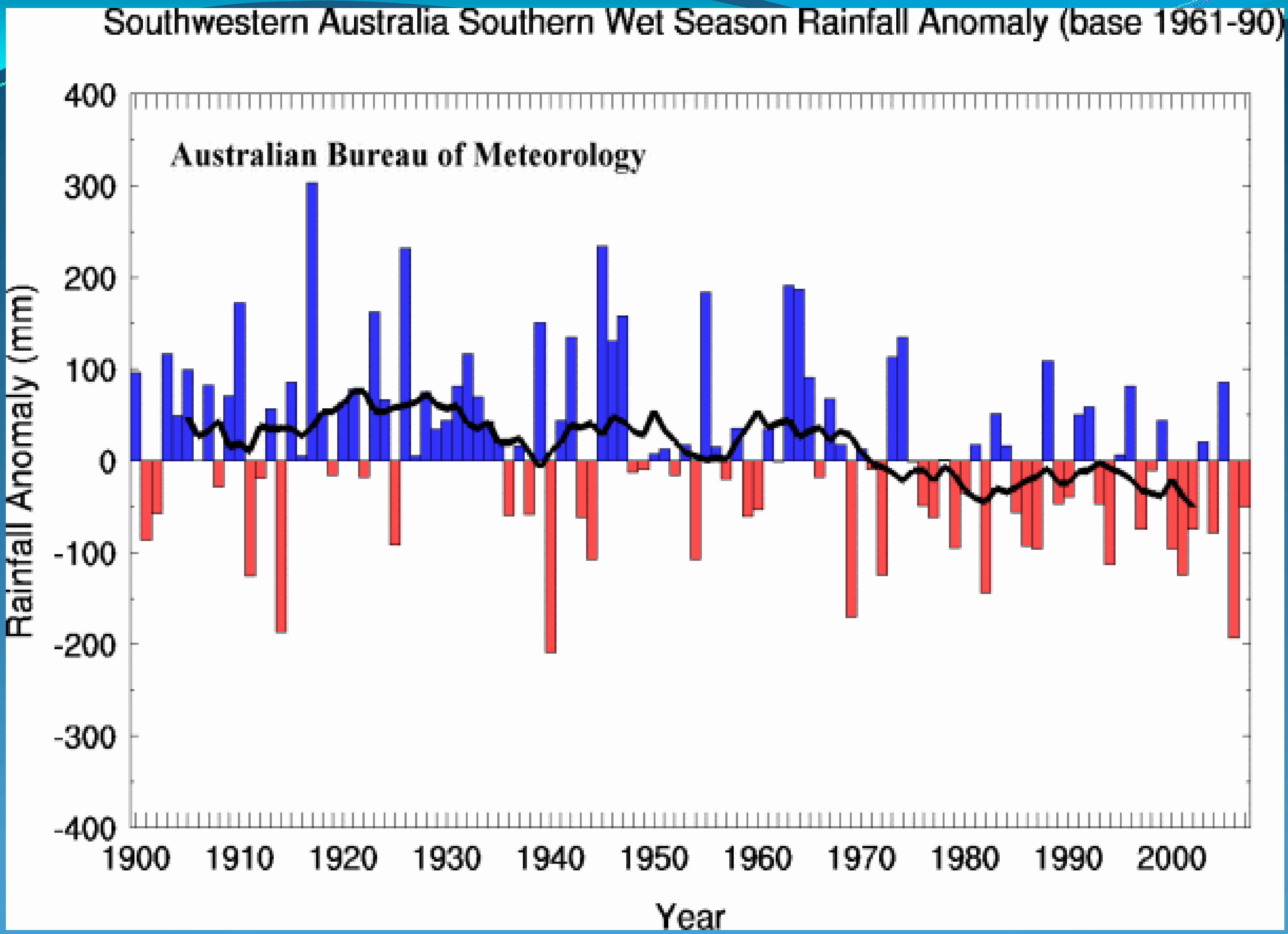
Catchment-based: recognizes importance of water balance and integration of response

Terminology

- Scenario: a possible, plausible, internally consistent, but not necessarily probable, development
- Projection: a potential future evolution of a quantity or set of quantities
- Prediction: the result of an attempt to produce an estimate of the actual evolution of a quantity in the future, for example at seasonal, inter-annual or long-term time scales
- Climate *projections* are distinguished from climate *predictions* in order to emphasize that climate projections depend upon the emission/concentration/radiative forcing scenario used, which are based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realised

Landsat image showing land clearing





Southwestern Australia Southern Wet Season Rainfall Anomaly (base 1961-90)
Australian Bureau of Meteorology
Rainfall Anomaly (mm)
400
300
200
100
0
-100
-200
-300
-400
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Year

Some typical hydrologic objectives

- **How have rainfall patterns changed in the study area in last 100 years?**

- **How have past rainfall changes affected catchment hydrological processes?**

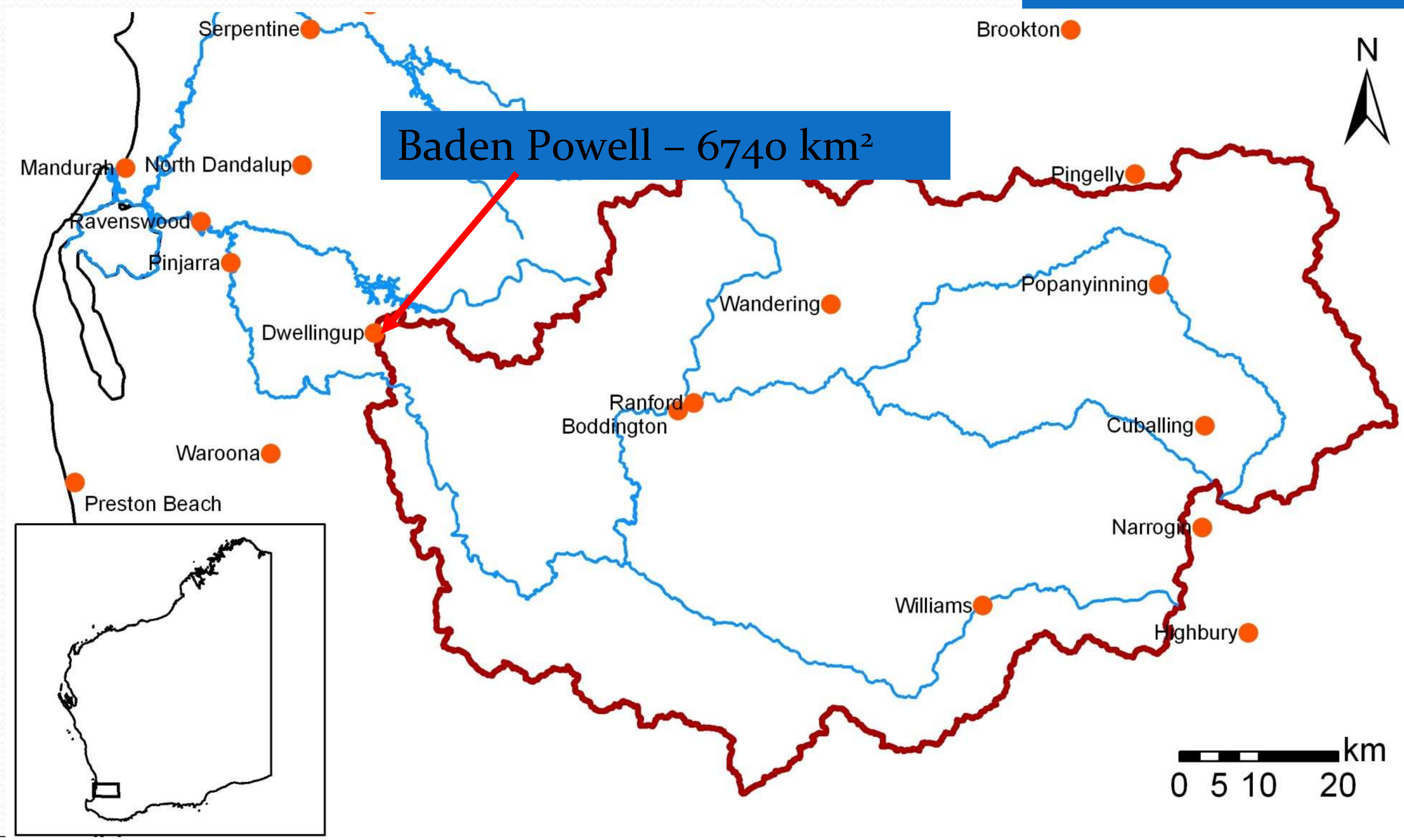
- **How might projected climate change affect catchment hydrological processes?**
  - Flow duration
  - Yield

Murray Hotham catchment

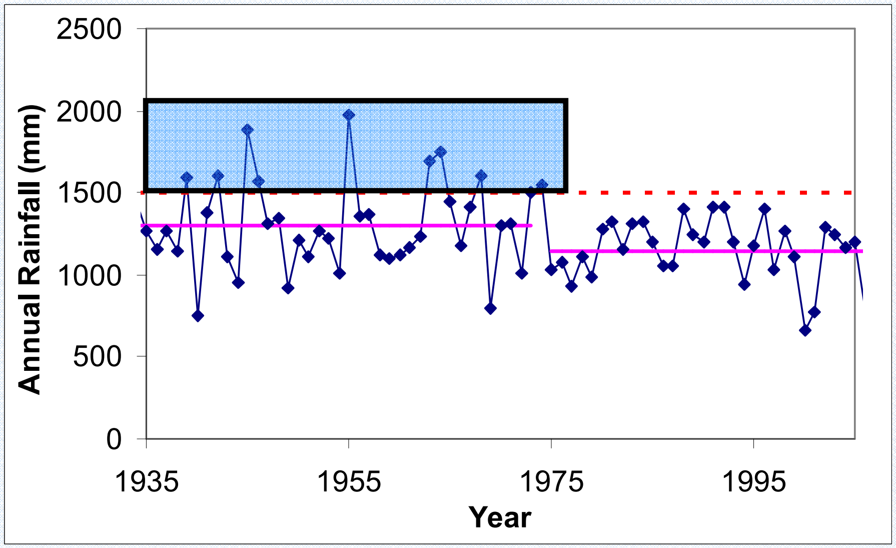
Rainfall -1100 to 400 mm; Streamflow - 275 GL (40 mm); Pan evaporation - 1900 to 1450 mm; Cleared area – more than 50%

Yarragil – 73 km²

Baden Powell – 6740 km²

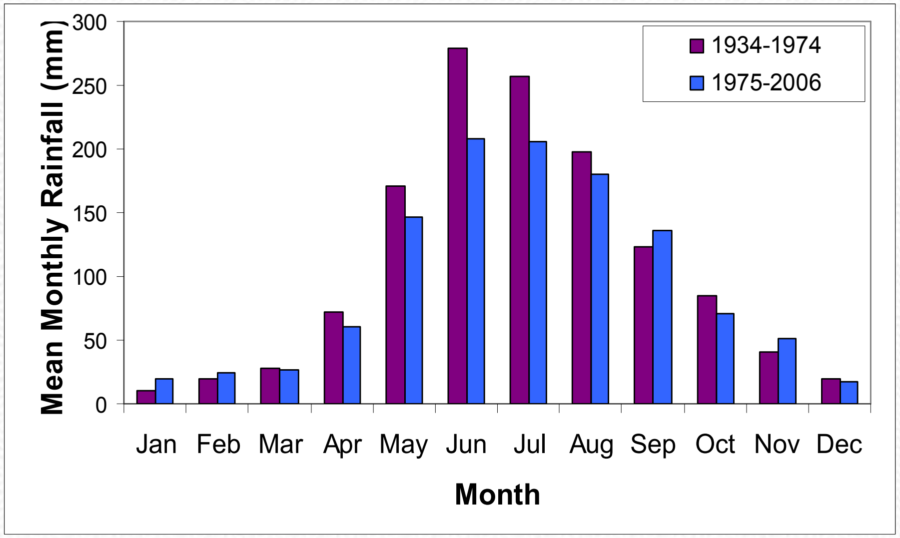


Rainfall change



- Pre-1975 vs post-1975 data
  - 4 long–term weather stations
- 11 - 17% decrease in annual rain
- Fewer wet years post-1975

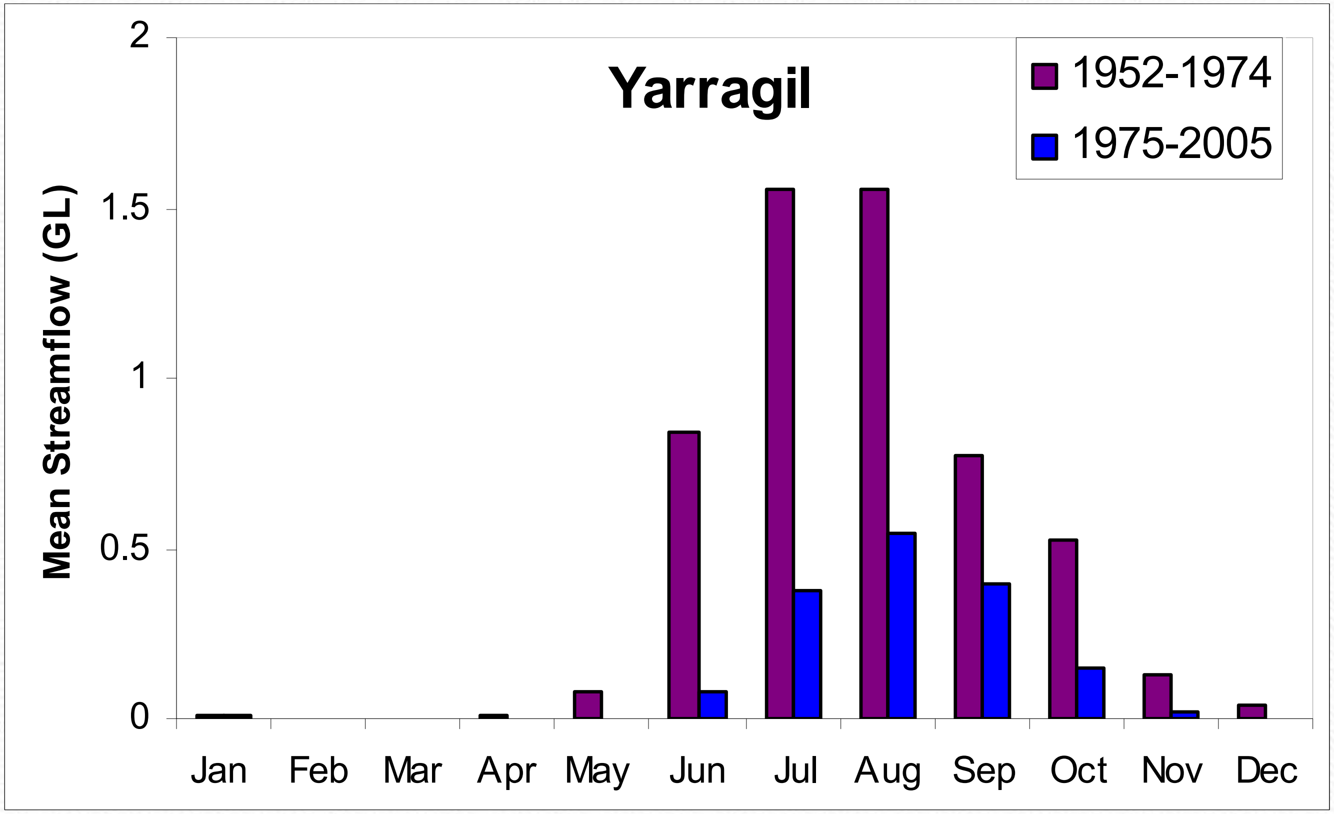
- **Monthly distribution shows seasonal shift**
- **Large (~25%) decrease in autumn & early winter rains**
- **Much smaller increase in spring & summer rains**



Observations are consistent with identified changes of synoptic drivers of rainfall over the region (Indian Ocean Climate Initiative)

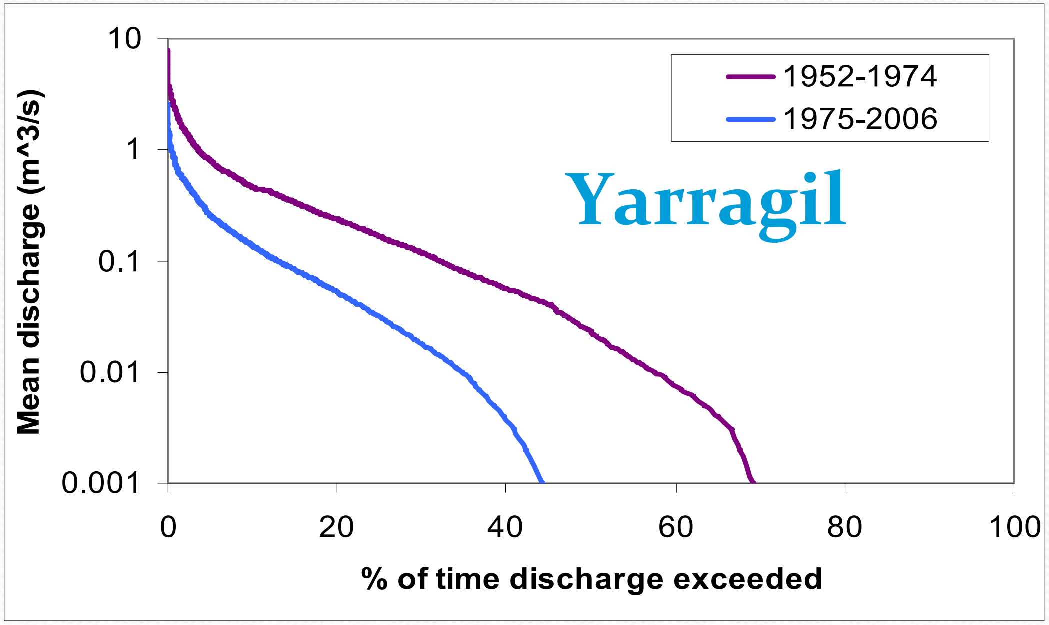
- Reduction in strength of subtropical jet over Australia
- Reduction in the likelihood of synoptic disturbances developing over the region
- Increased frequency of days with high pressure, i.e. more dry days
- These changes consistent with modelled changes due to increased greenhouse gas emissions

Hydrological change



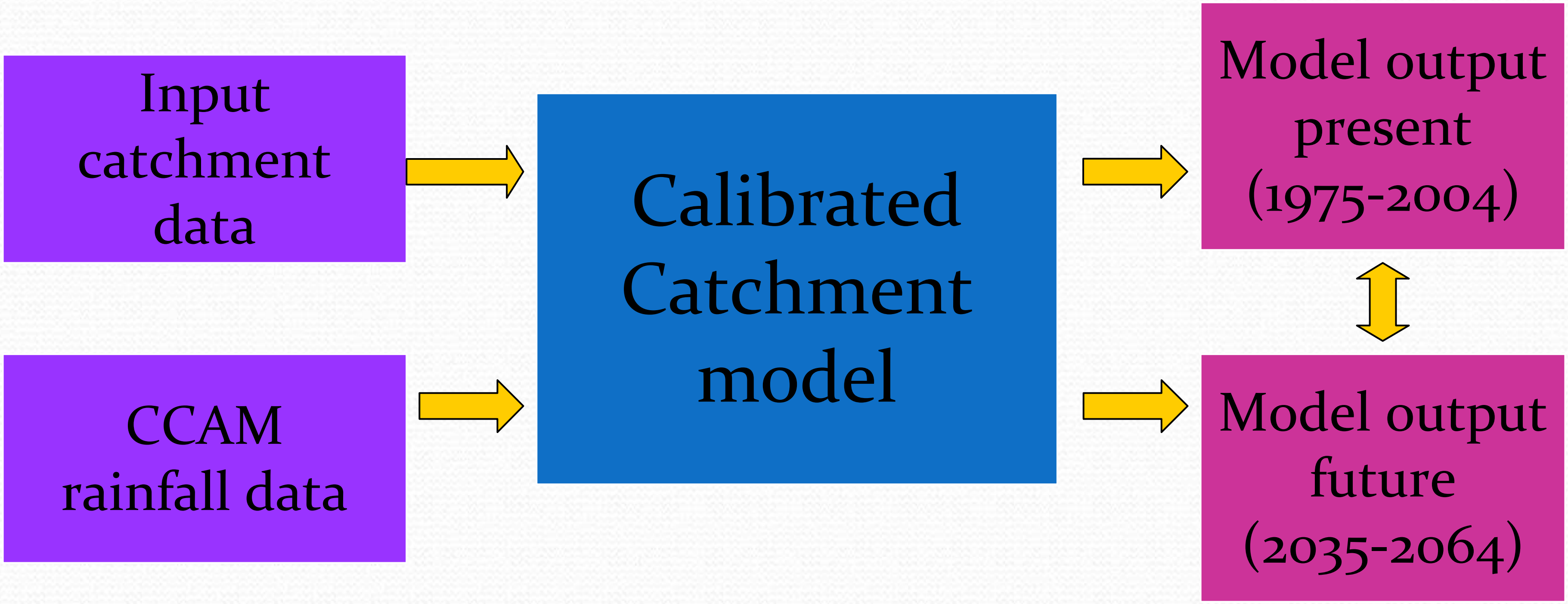
- **Pre-1975 vs post-1975 data**
  - Gauging stations: Baden Powell Water Spout, Yarragil Formation
- **Baden Powell 42%, Yaragill 71% decrease in mean annual flow**
- **Monthly yield delayed & rainfall decrease magnified**

Rainfall change



- Flow duration decreased at both sites
- 22% decrease in flow duration (82 days) at Yararragil.
- Exceedence decreased for all discharge levels at Baden Powel

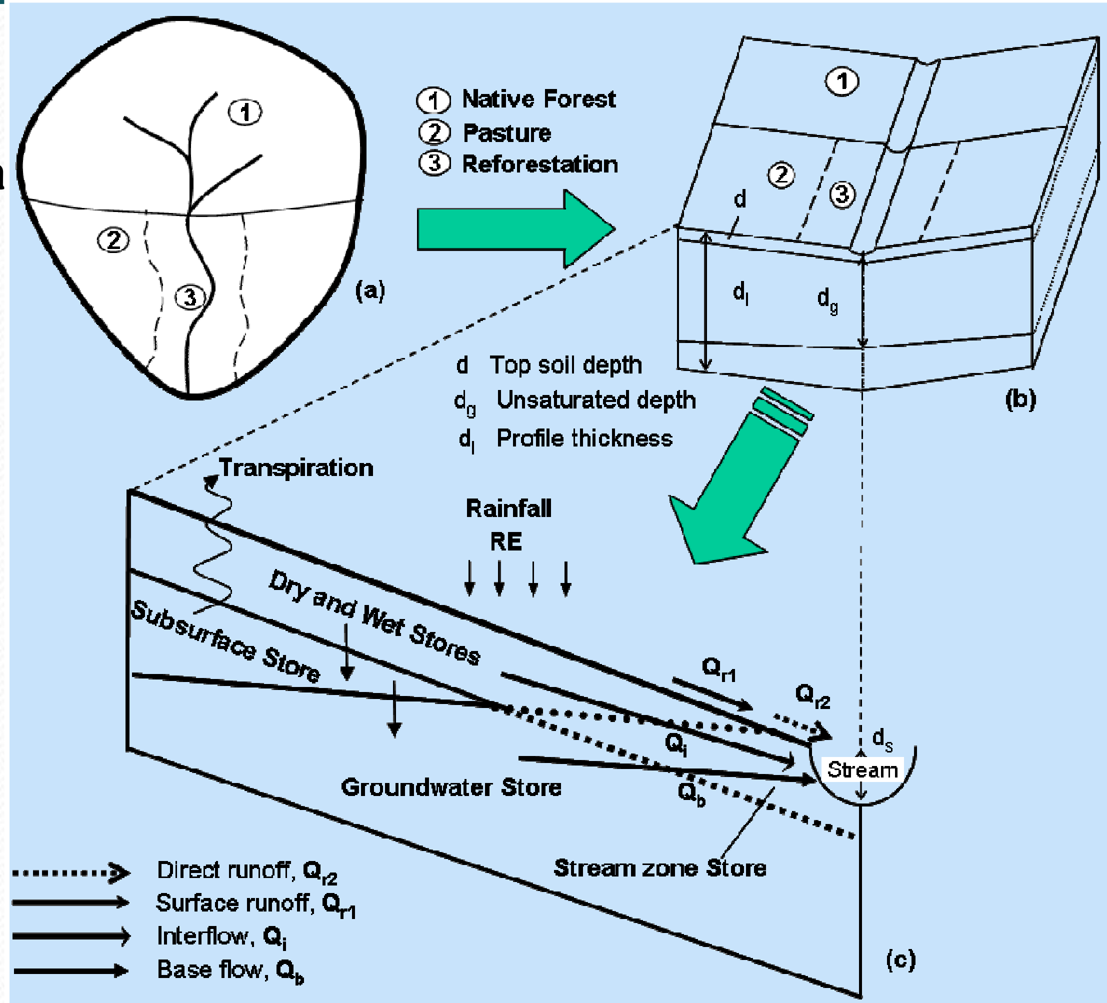
Projections to 2064



Note that in this approach there is no vegetative feedback loop.

Projections to 2064

- Projections made using a distributed conceptual hydrologic model
- Daily water balance
- Large-scale catchments
- "Open book" hill-slope model



(a) depicts a hypothetical catchment,
(b) is an open book representation, and

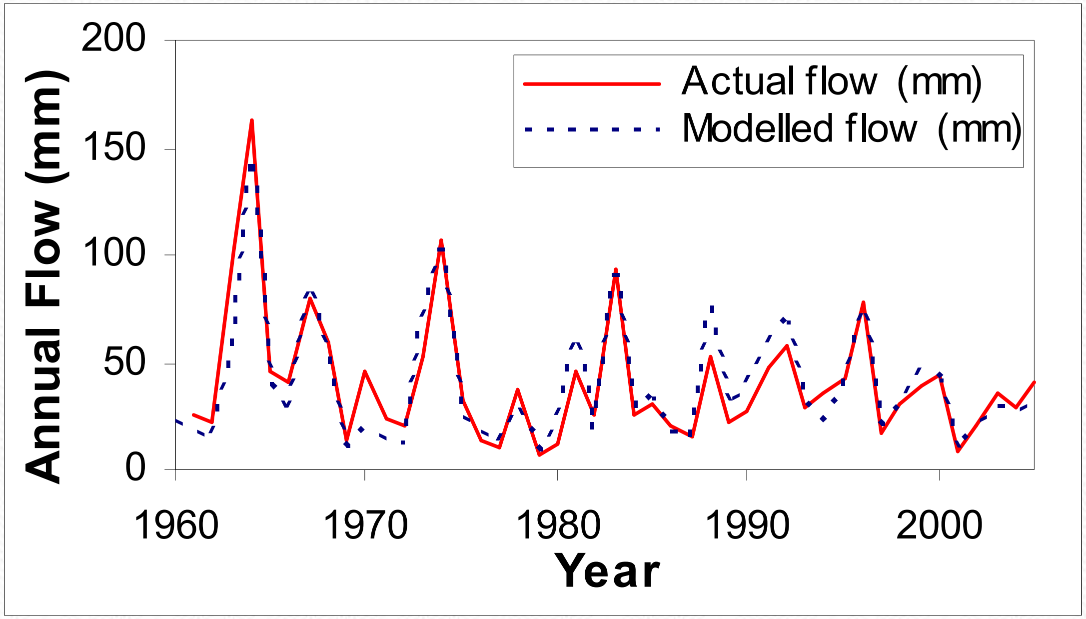
Bari and Smettem (2006 a,b)

Projections to 2064

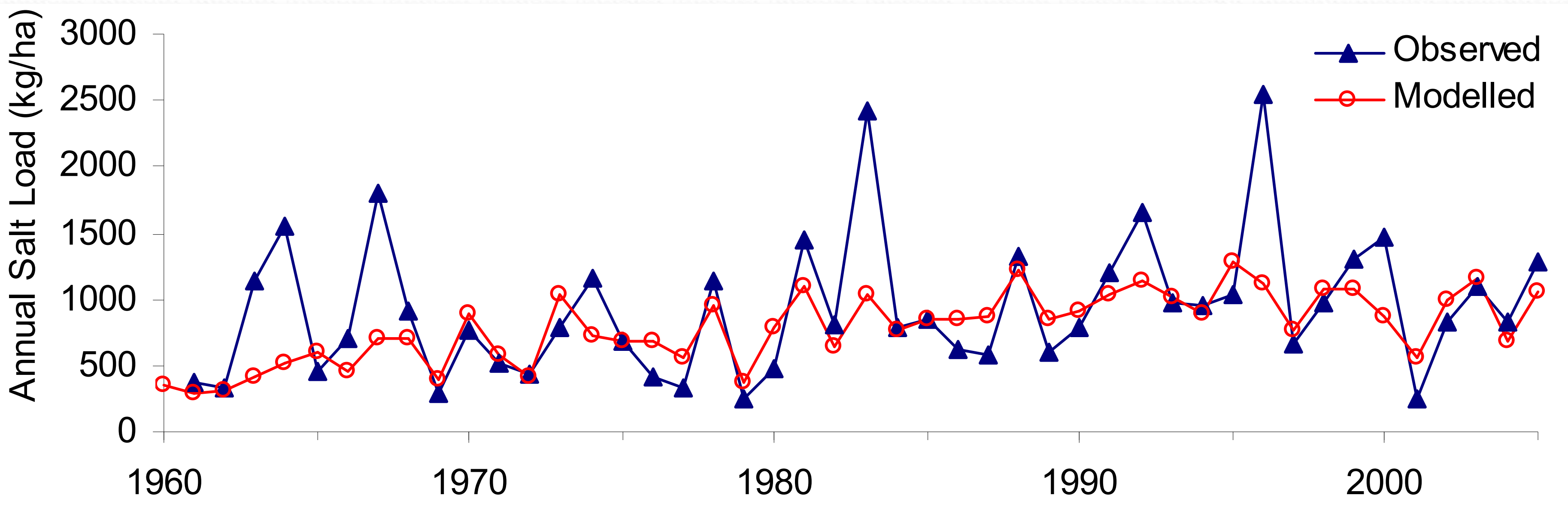
- Digital elevation model – Hydrological Response Units and stream network
- 135 Hydrologic Response Units

- Catchment parameters defined
- One set for the whole catchment

- Calibrated model gives Annual streamflow error: of -0.8 to +2.4% in 1990s



Measured and predicted salt load for the Murray-Hotham Catchment



Summary of observations and model runs

To Now:

- **Annual rainfall has diminished by 10 - 17% since 1975**
- **Stream yields down 40%**
- **Flow duration shortened significantly**
- **Seasonal distribution of rainfall has changed**
- **Probability of extreme rainfall unchanged**

From now to 2064:

- **CCAM (A2): further 13% rainfall decrease by 2064**
- **Hydrologic modelling: projects a 49% decrease in runoff from the present annual mean value by 2064.**
- ***HOWEVER, the hydrologic model does not factor in any future changes to vegetation.***

Ecohydrology and Natural Selection

- **“On the basis of natural selection, then, it may be expected that biological organisms, placed for sufficiently long time within a specific set of environmental circumstances, will tend to assume characteristics which are optimal with respect to these circumstances” Rosen (1967)**

- **Eagleson (2002) demonstrates physical constraints of the vegetation-soil-climate system control natural selection of climax monoculture plant communities.**
  - **Plant geometry (height, diameter, crown, roots, density)**
  - **Plant physiology (stomatal control, nutrient extraction)**
  - **Momentum, heat, light and vapor fluxes**

- **Eagleson. P.S. 2002 Ecohydrology: Darwinian Expression of Vegetation Form and Functi. Cambridge University Press.**

Penman-Monteith (P-M) equation

$\varepsilon = s / \gamma$ $s = \dfrac{de_{sat}}{dT}$ γ = psychrometric constant

A is available energy adsorbed by the surface:
Net radiation –soil heat flux

$\rho =$ Density of air

D_a = VPD of air

c_p = specific heat of air

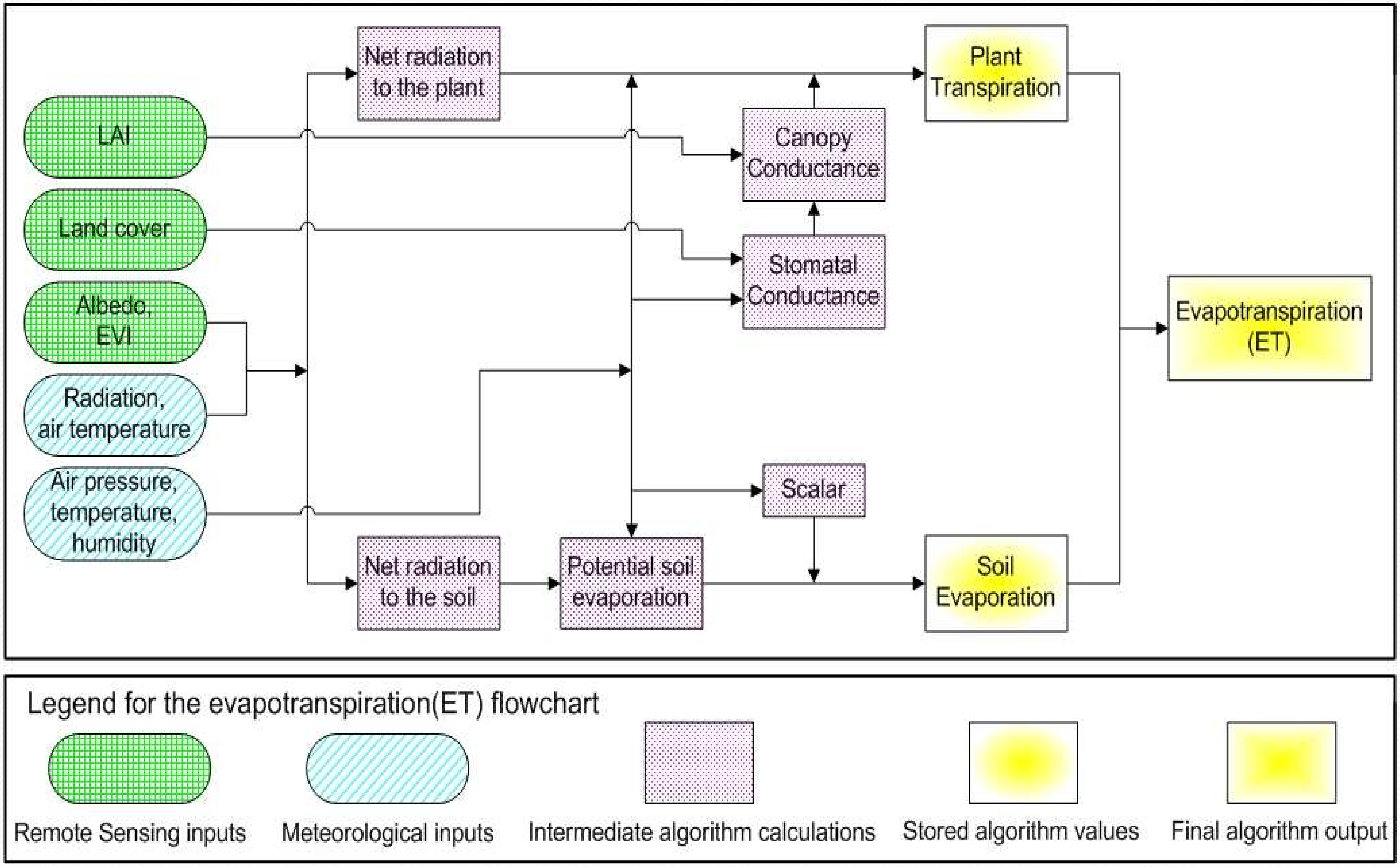
$$\lambda E = \frac{\varepsilon A = (\rho c_p / \gamma) D_a G_a}{\varepsilon + 1 + G_a / G_s}$$

Aerodynamic conductance

$\lambda =$ Latent heat of evaporation

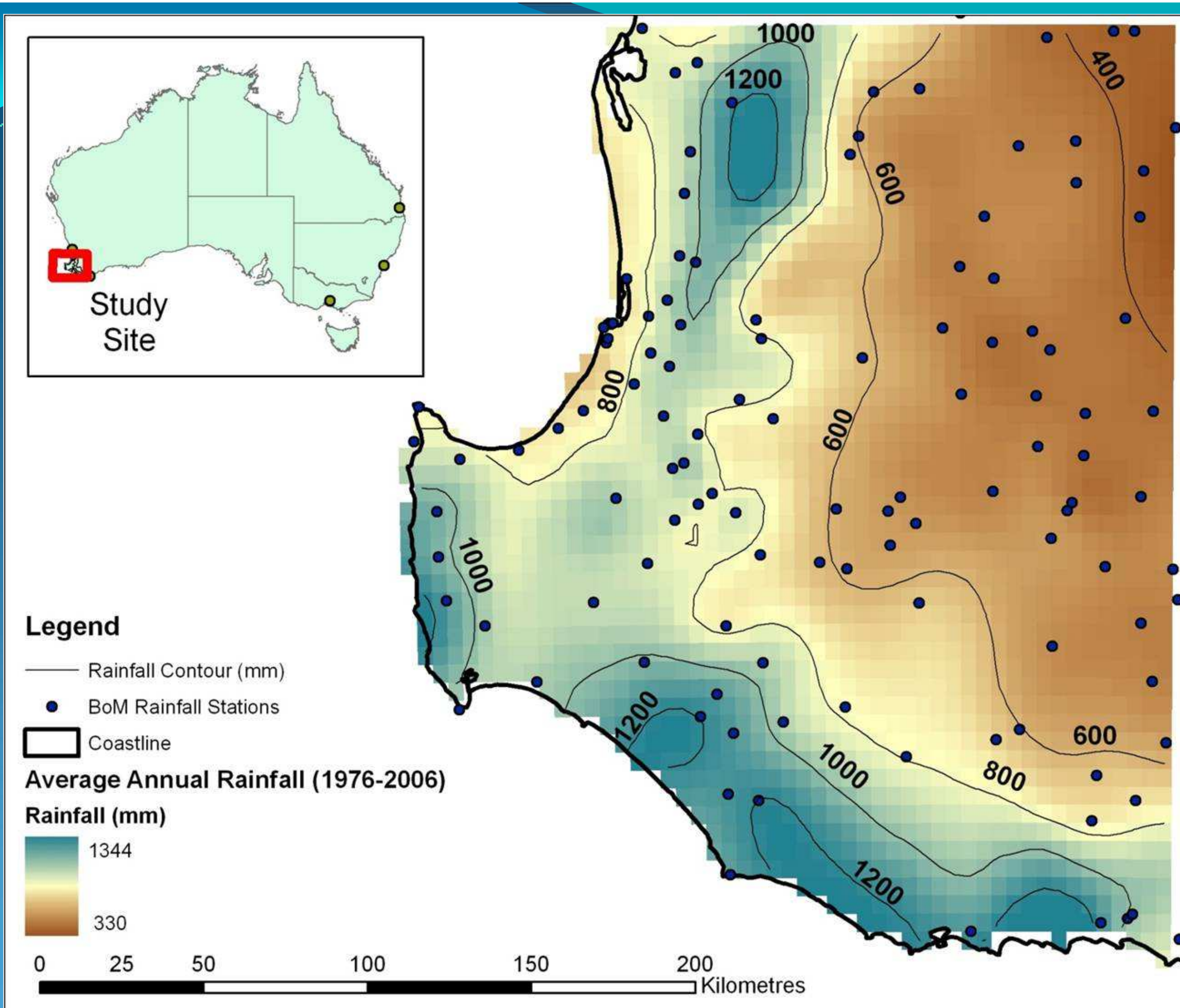
$$G_S = C_L \times LAI \times f\left(VPD, T_{\min}\right)$$

MOD16 ET FLOWCHART

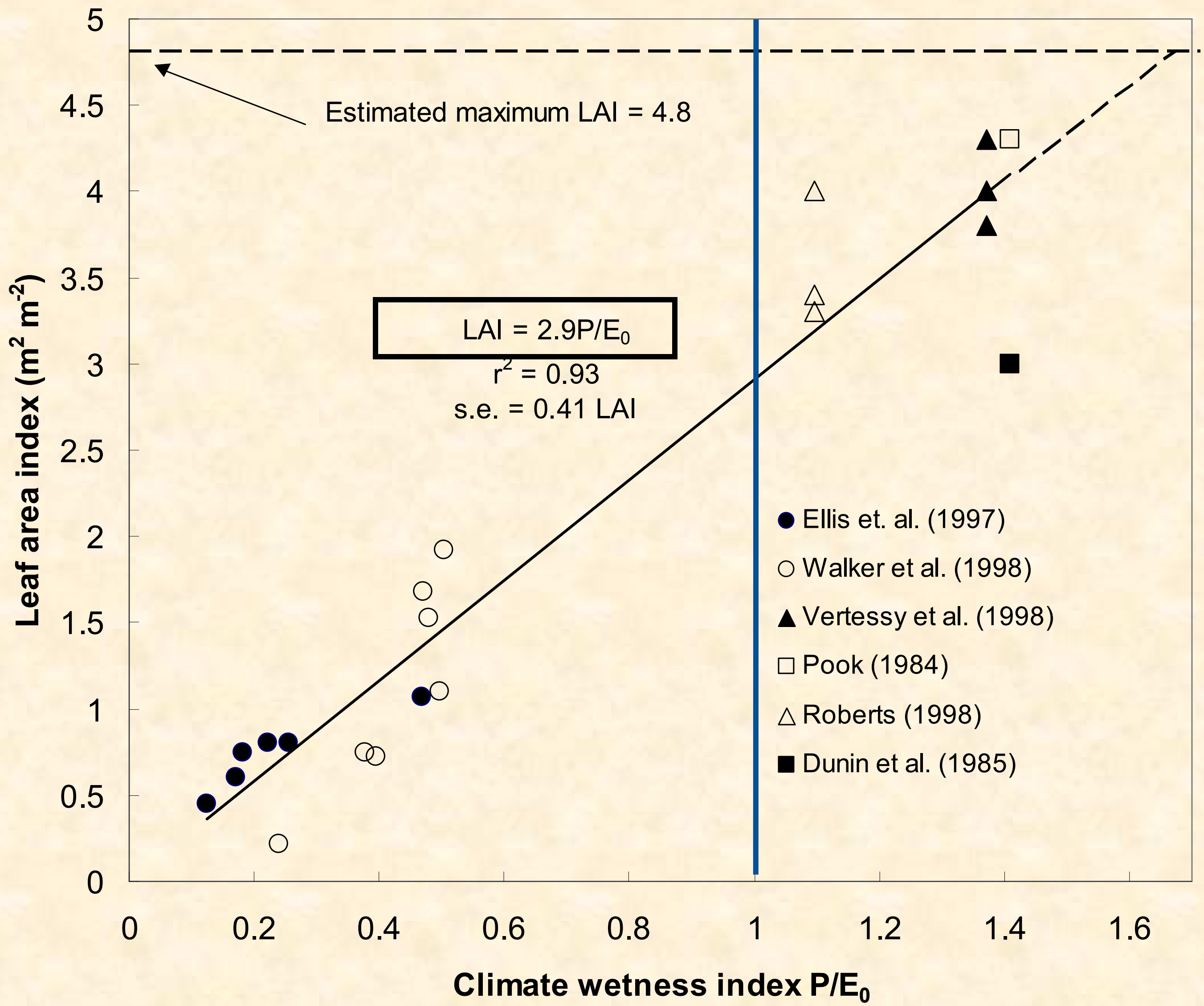


Ecological optimality postulates that in water limited environments the crown cover of perennial vegetation and climate are in dynamic equilibrium and that average annual LAI will decrease at the climate dries.

(However, the rate and nature of native vegetation response to climate change is unknown .)

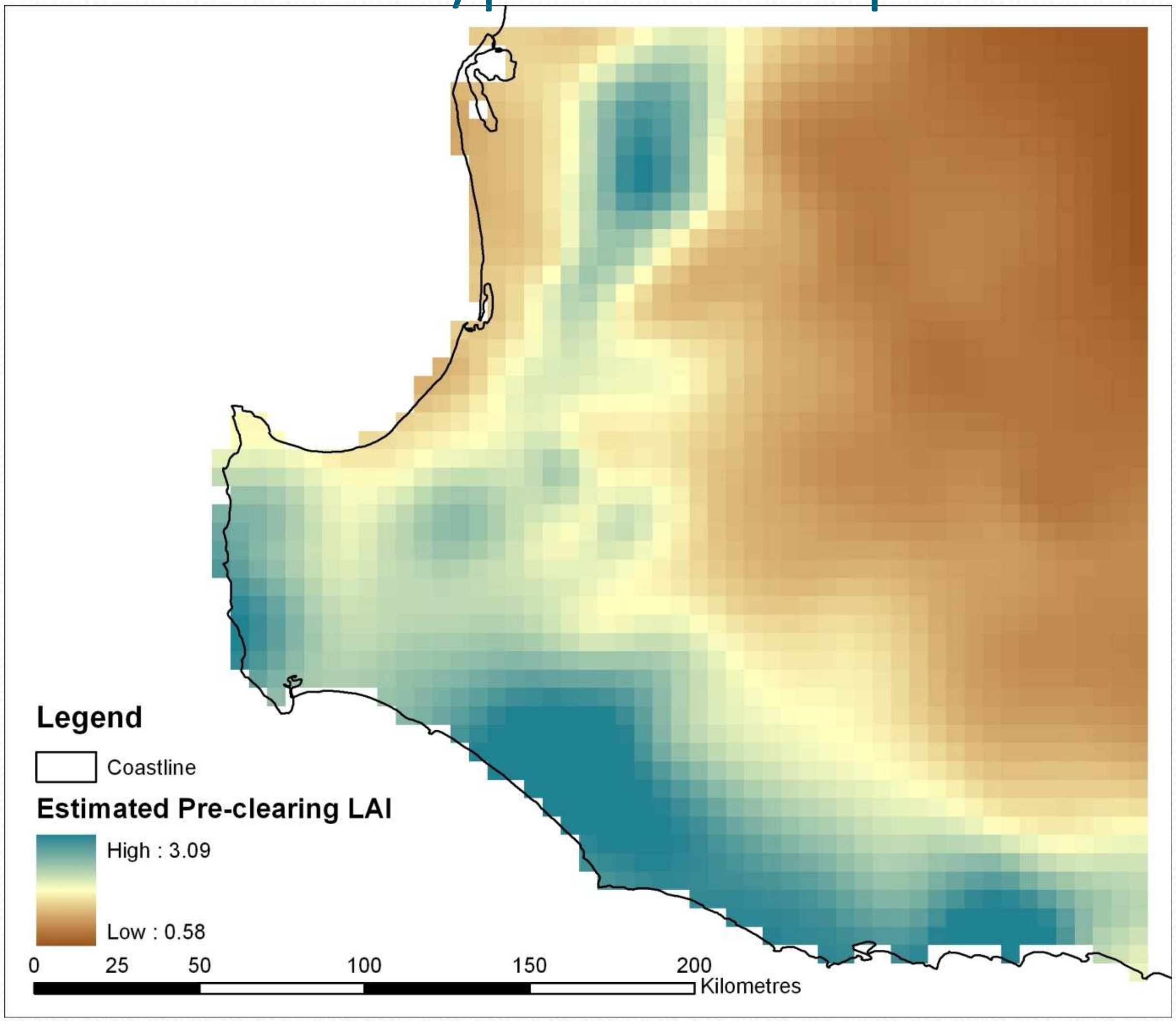

Study Site
Legend
Rainfall Contour (mm)
BoM Rainfall Stations
Coastline
Average Annual Rainfall (1976-2006)
Rainfall (mm)
1344
330
0 25 50 100 150 200
Kilometres
1000
1200
400
600
800

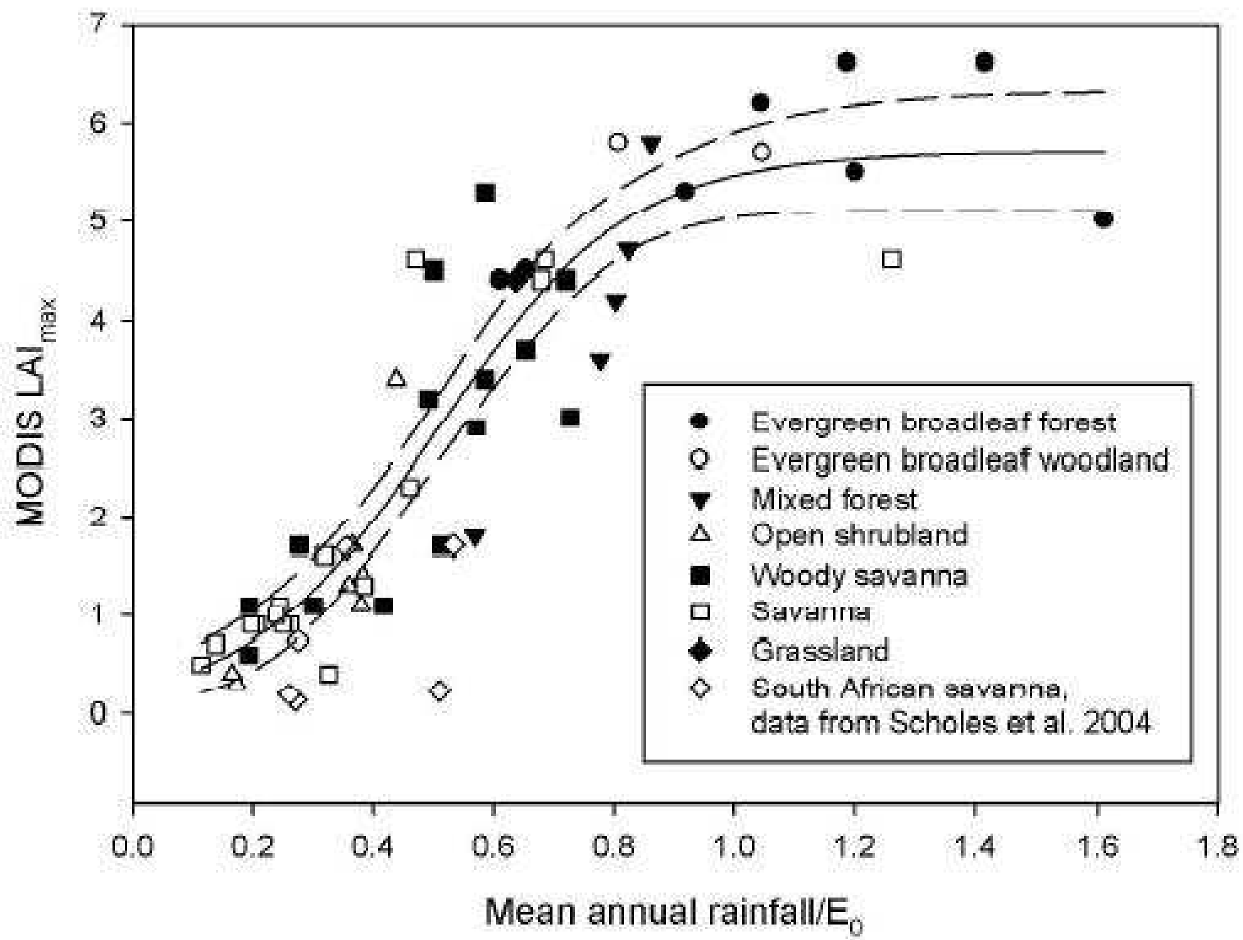
Water limited annually | No annual water limit



Source: Ellis et al (2006)

Modeled Pre-clearing Mean Annual Leaf Area Index LAI=2.9 x rainfall/potential evap'n.





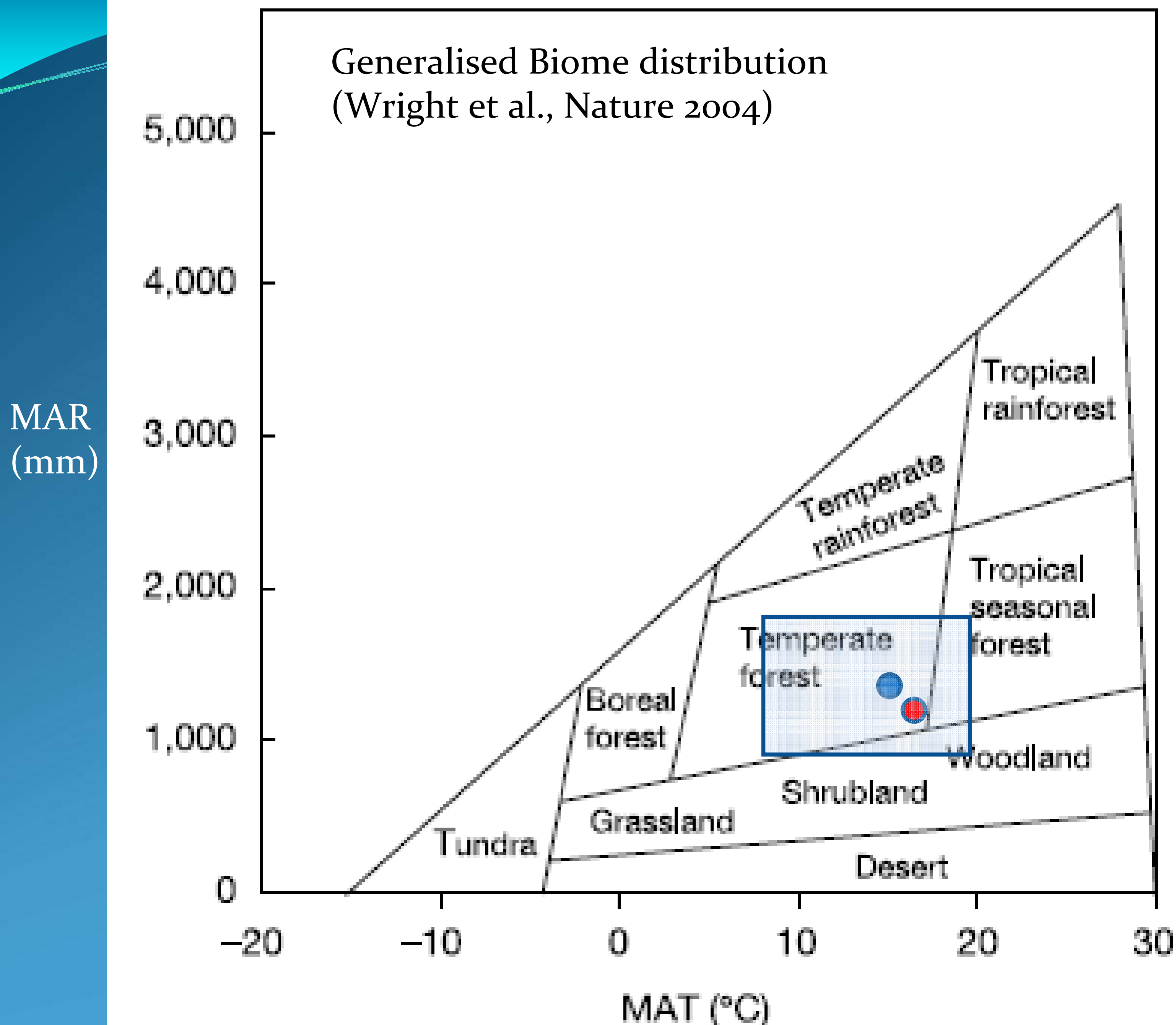
Source: Palmer et al., ECOHYDROOGY 2009

The *Eucalyptus* forest ecosystems of Southwestern Australia are experiencing a drying and warming climate.

Climate change models predict that rainfall will continue to decline across this region leading to enhanced water stress in native ecosystems and reduced runoff from water supply catchments .

Although *Eucalypts* can turn over their entire leaf biomass in a year (Ameida et al., 2007), the deep rooting habit of key overstorey species in southwestern Australia (>30 m has been reported) may buffer against inter-annual variations in rainfall (Silberstein et al., 2001).

To date, the response of Leaf Area to climate variation has not been assessed across this region.



Generalised Biome distribution
(Wright et al., Nature 2004)
MAR
(mm)
5,000
4,000
3,000
2,000
1,000
0
Tropical rainforest
Temperate rainforest
Tropical seasonal forest
Temperate forest
Boreal forest
Woodland
Shrubland
Grassland
Tundra
Desert
–20
–10
0
10
20
30
MAT (°C)

Direct LAI measurement is time consuming, site-specific (small scale) and is rarely repeated to yield time series (for native vegetation)

So, can climate –related variation in leaf area from satellite-derived measurements reveal regional responses to inter-annual climate variation across southwest Western Australia?

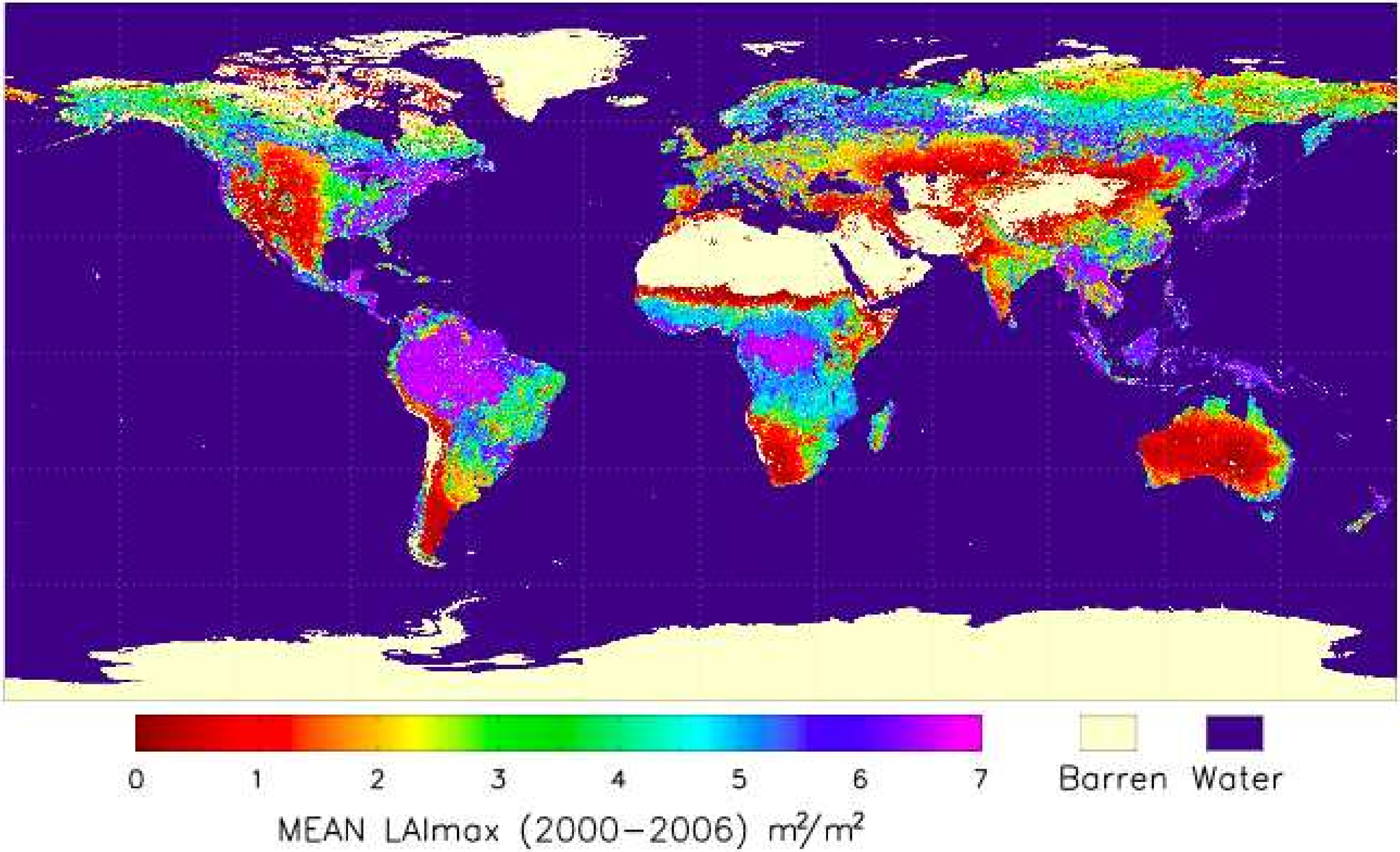
Methods

- We analysed data from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard NASA's TERRA and AQUA satellites to obtain Leaf Area Index (LAI) and Evapotranspiration (ET) (Mu et al., 2007) at a spatial resolution of 3km by 3 km across Southwestern Australia from 2000 to 2006 (MODIS was launched in 2000).

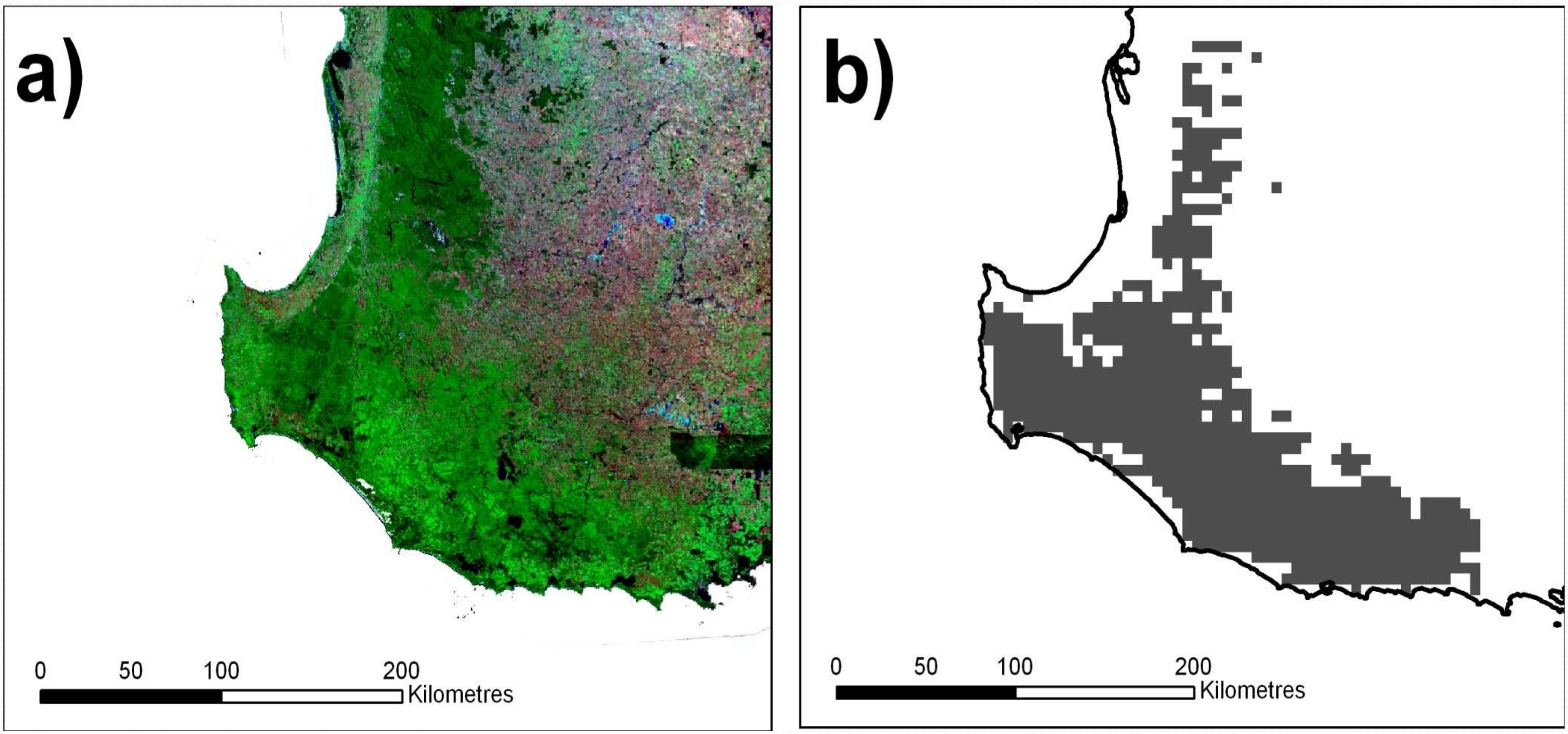
- Forested areas were identified from LANDSAT imagery with a density slicing method.

- Annual rainfall across the region was obtained from the Bureau of Meteorology and monthly values were derived for every MODIS pixel.

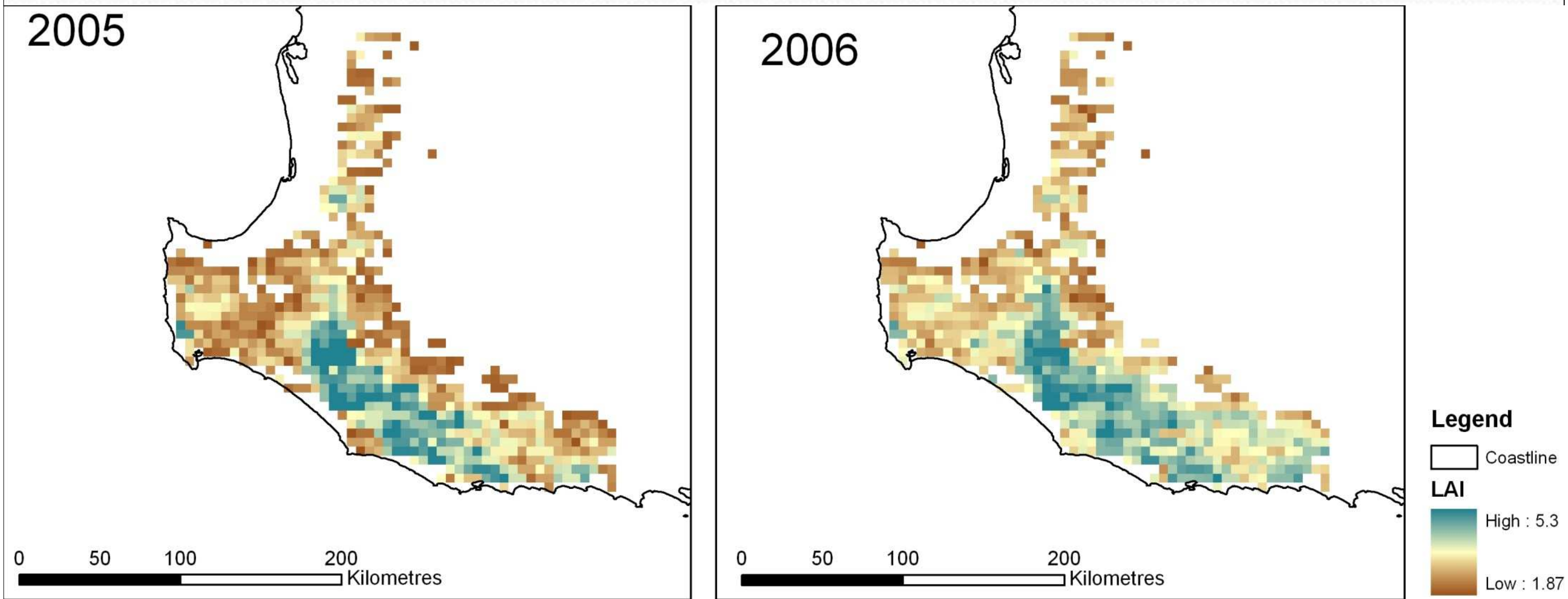
Satellite-derived Global Mean maximum LAI



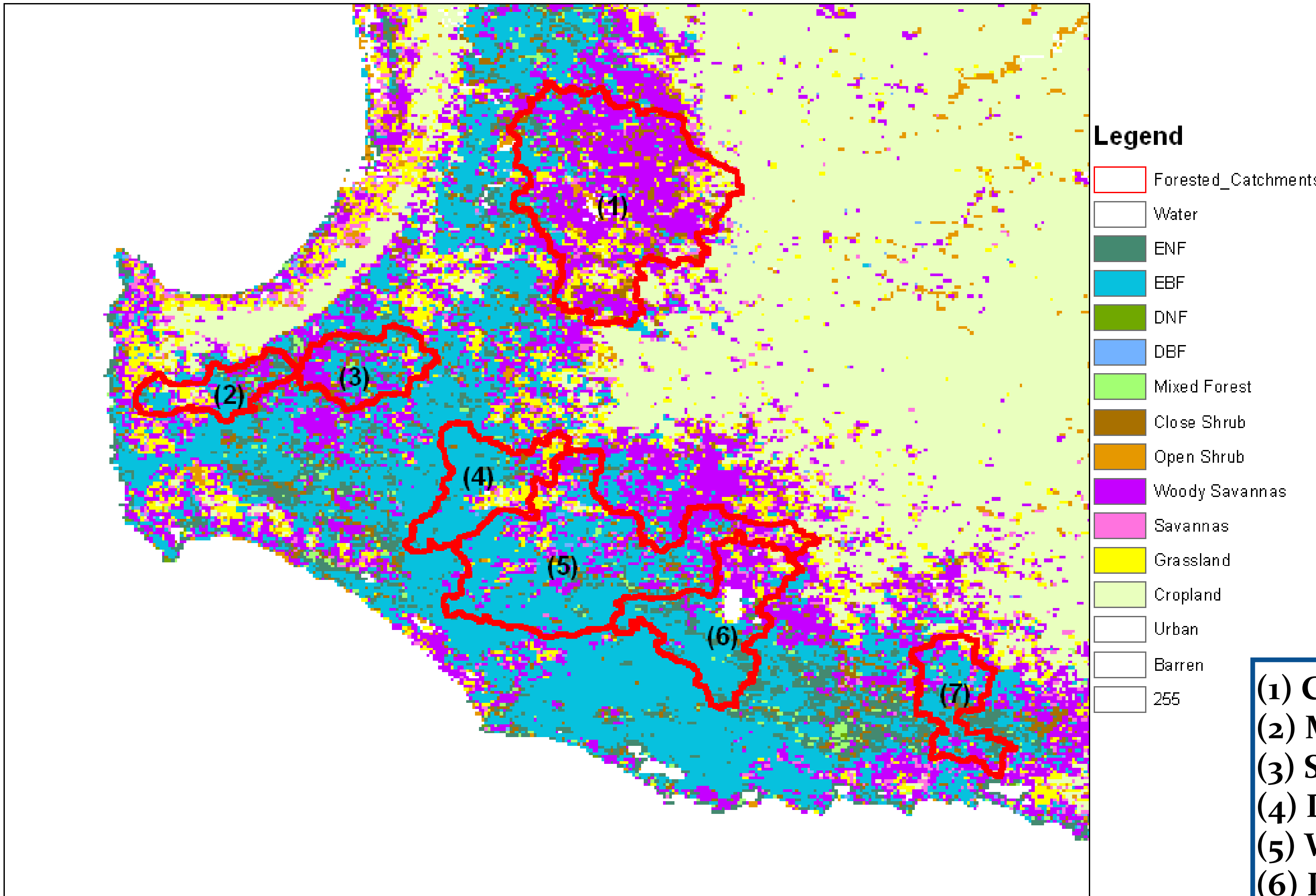
Vegetation and cleared agricultural land over the study region. A landsat image of the study area (a), was classified (using a density slicing method) into areas dominated by forest (a threshold value of 80% forest within each 3km MODIS grid cell was used).



MODIS LAI for 2005 and 2006 over the forested areas of southwest Australia

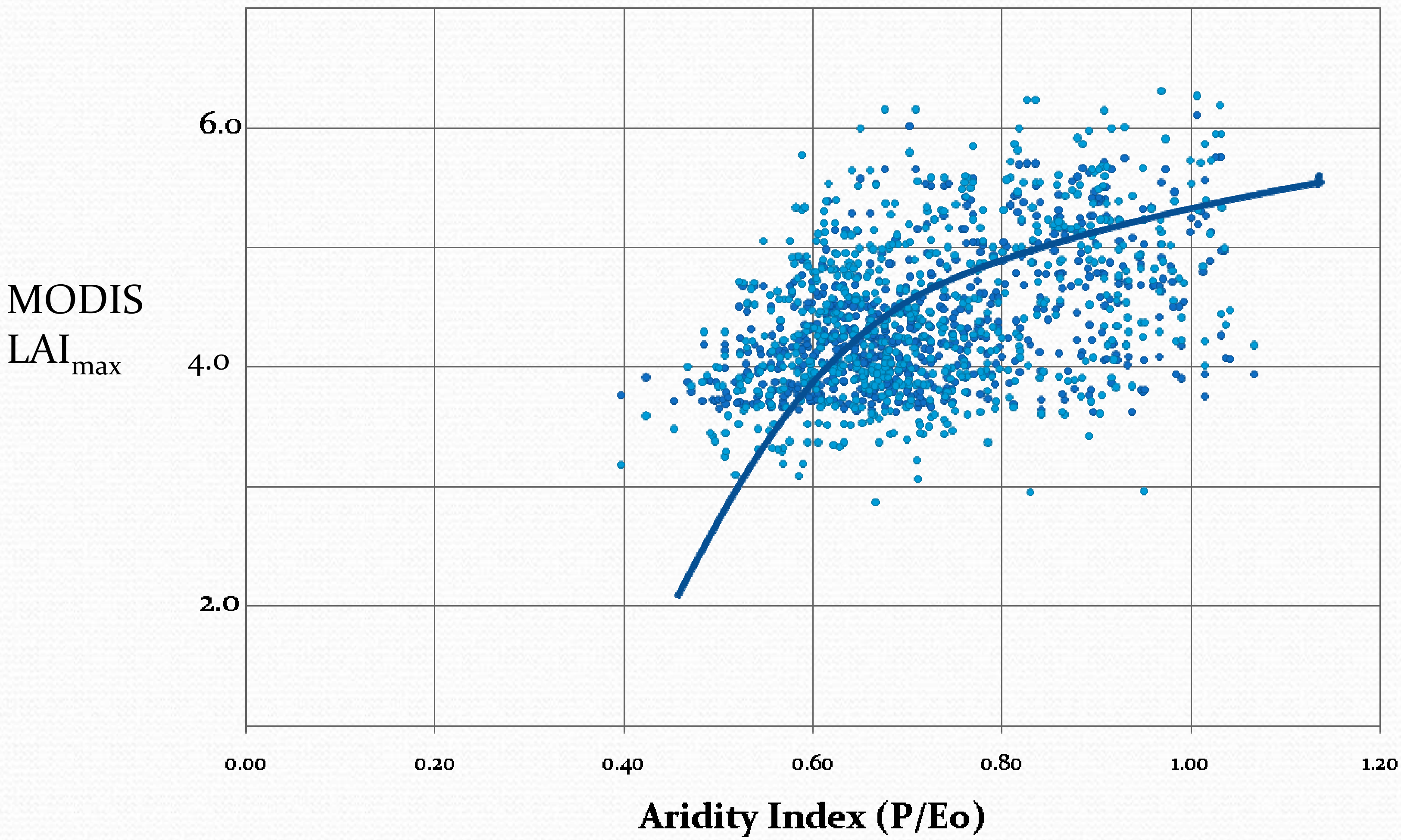


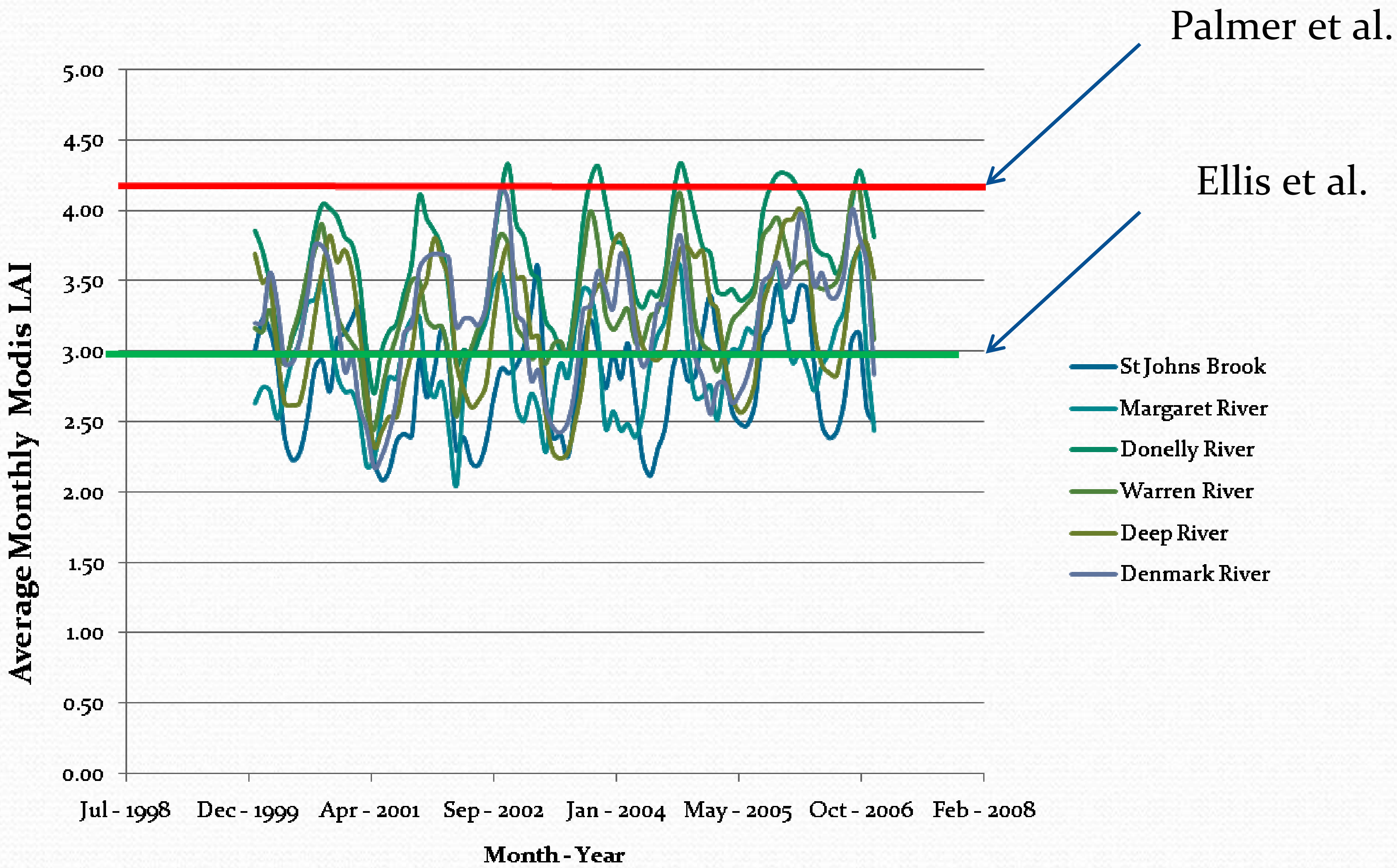
7 Watersheds in Southwest Australia



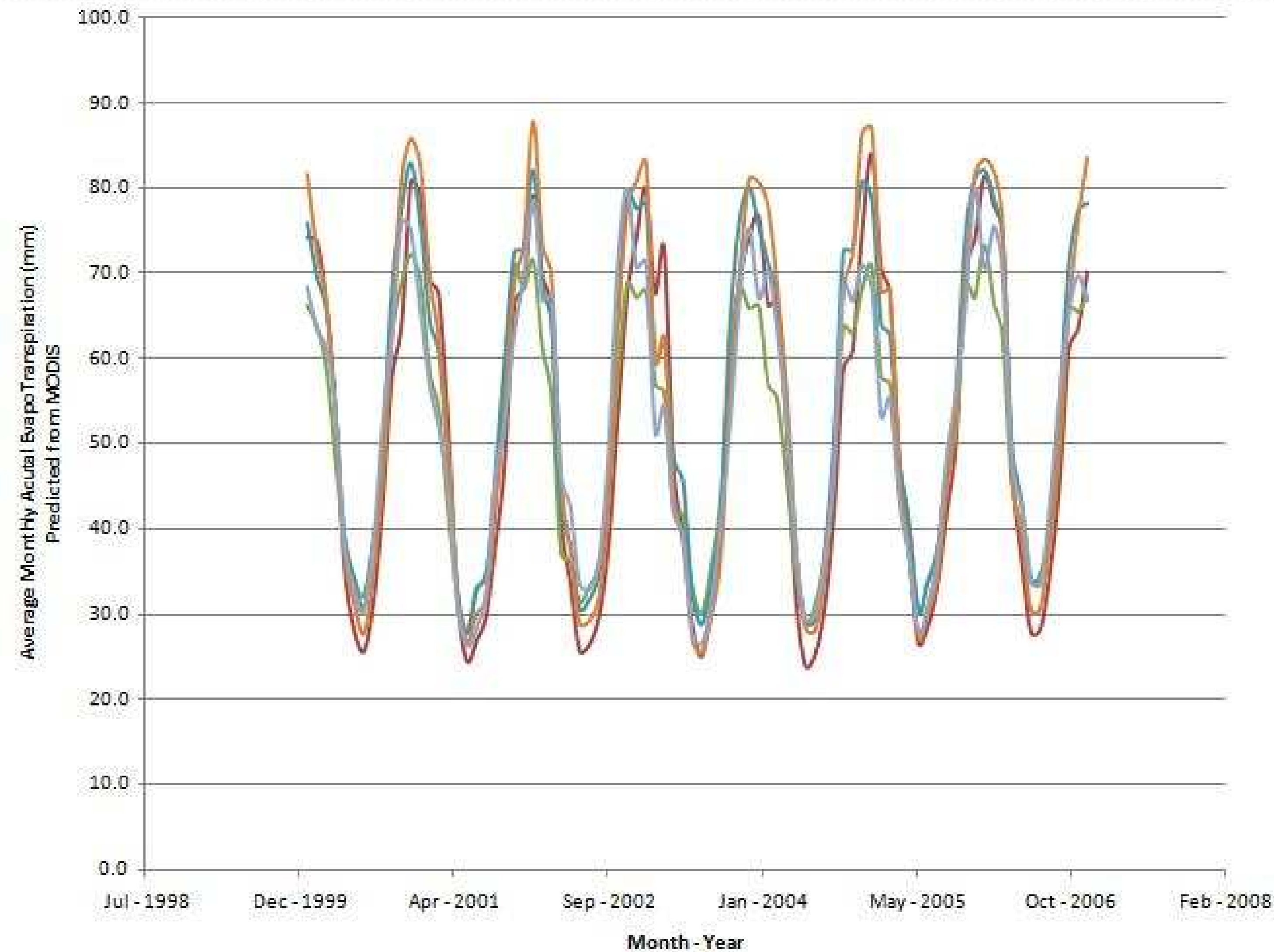
(1) Collie River
(2) Margaret River
(3) St Johns Brook
(4) Donelly River
(5) Warren River
(6) Deep River
(7) Denmark River

Modis Mean Annual LAI_{max} (2000-2006) for forested cells (3km x 3km grid) plotted against an aridity index.

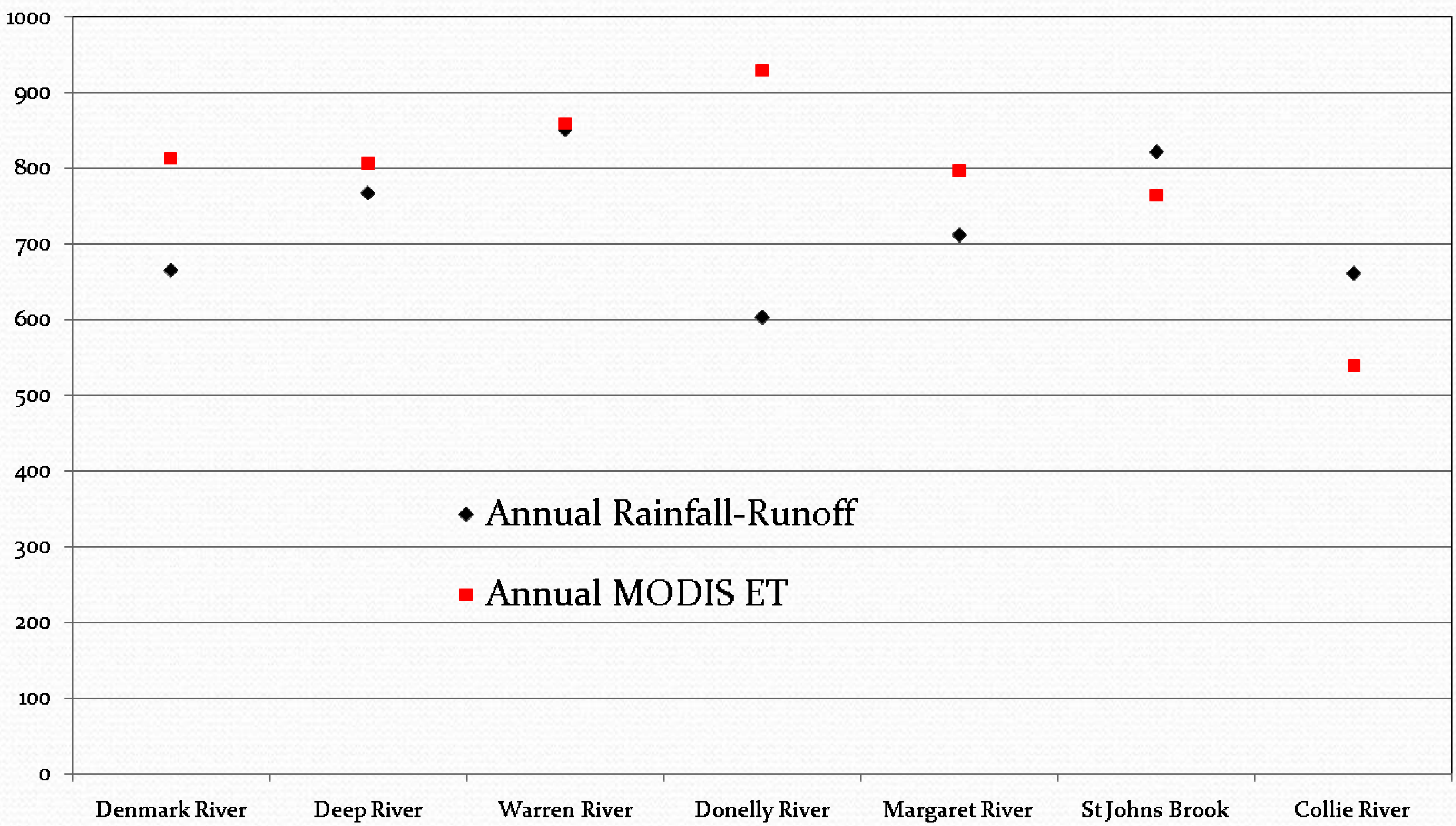


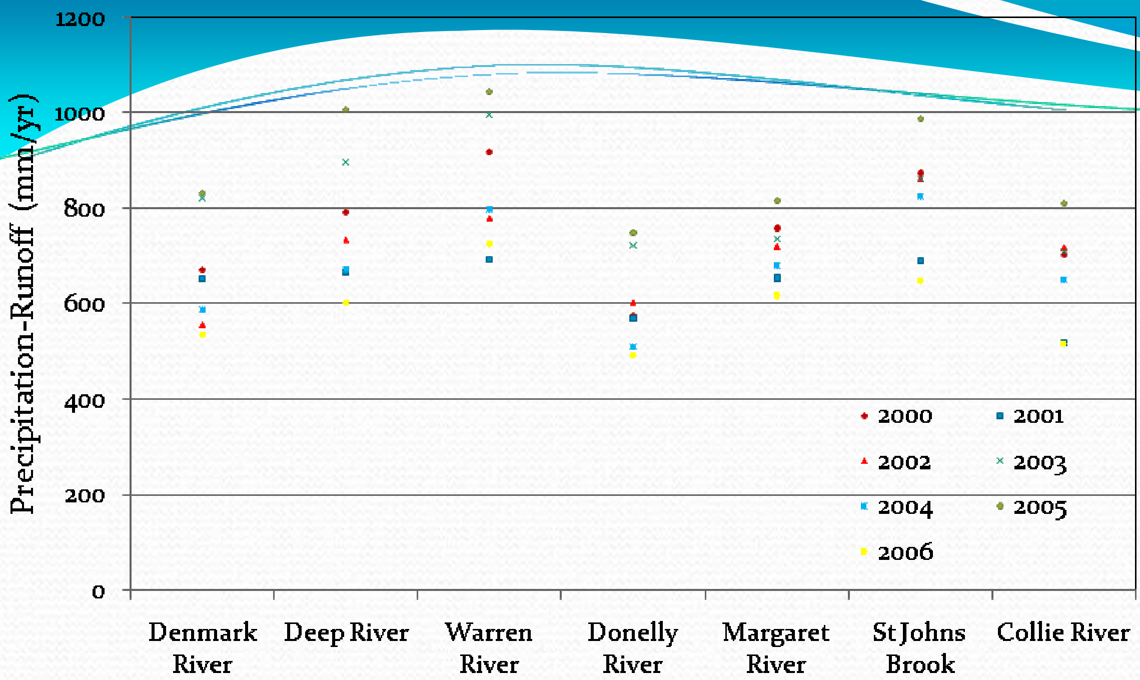

Palmer et al.
Ellis et al.
Average Monthly Modis LAI
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Jul - 1998
Dec - 1999
Apr - 2001
Sep - 2002
Jan - 2004
May - 2005
Oct - 2006
Feb - 2008
Month - Year
St Johns Brook
Margaret River
Donelly River
Warren River
Deep River
Denmark River

MODIS derived monthly ET for forested watersheds in Southwest Australia (LAI monthly max 4.0, min 2.4)



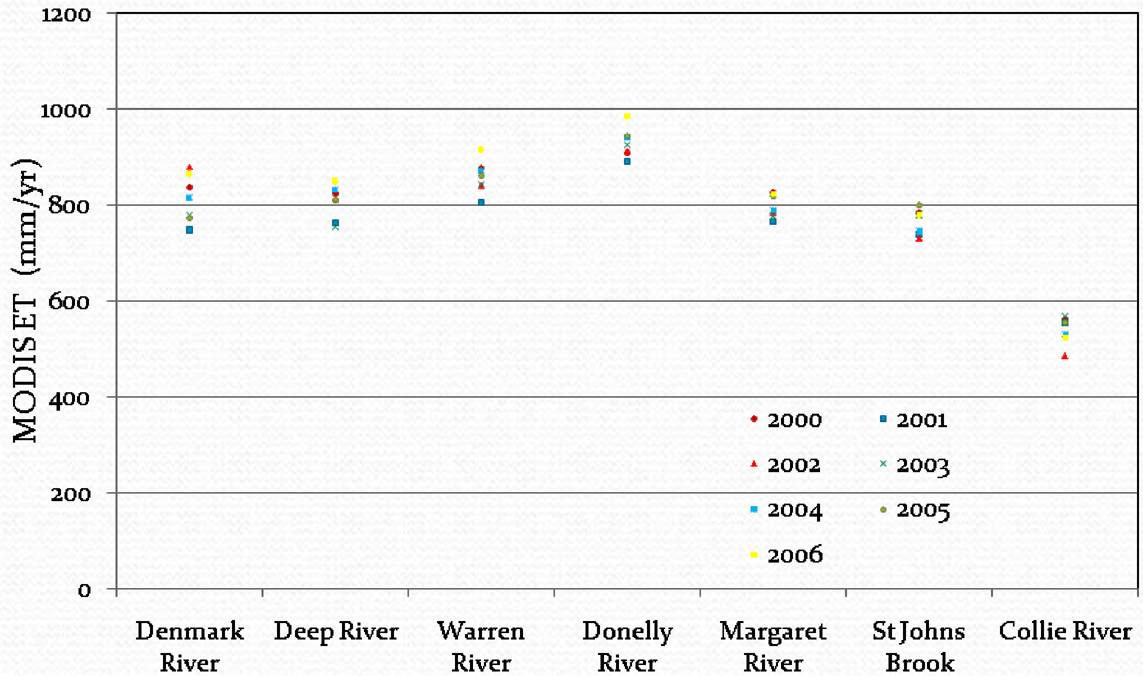
Annual Average MODIS ET, Observed (Precipitation-Runoff) over 2000-2006 for the 7 Watersheds in Southwest Australia





The Inter-Annual Variability of Annual (Precipitation-Runoff) over 2000-2006 for the 7 Watersheds in Southwest Australia

The Inter-Annual Variability of Annual MODIS ET over 2000-2006 for the 7 Watersheds in Southwest Australia



Human response to climate change:

‘Droughtproofing’ farms by increasing farm dams and diverting surface water using banks.

(Callow and Smettem, 2009: Env't Modelling and Software, 24: 959-968)

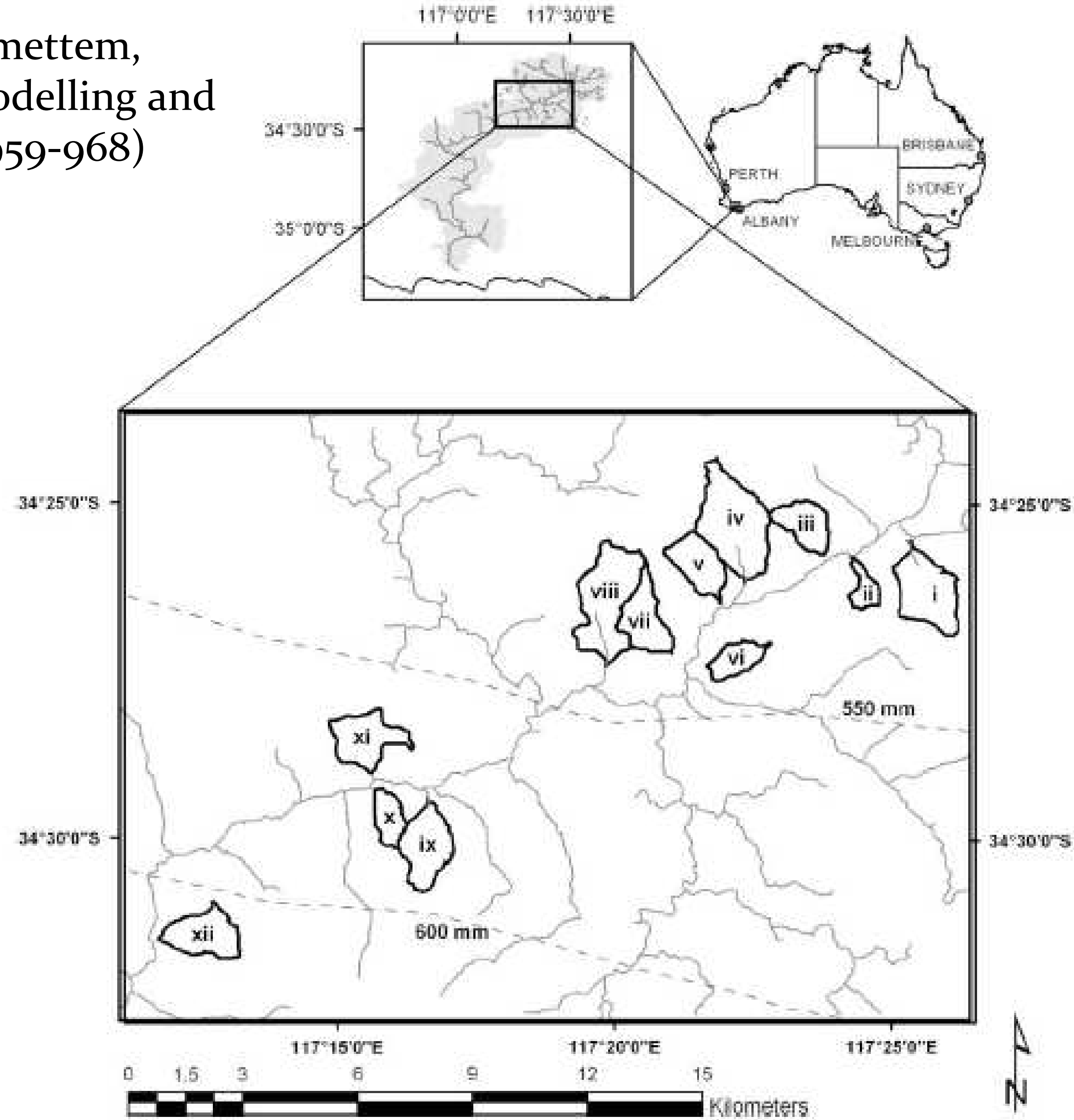


Fig. 1. Location of the twelve basins in the upper Kent River catchment, with annual rainfall isohyets.

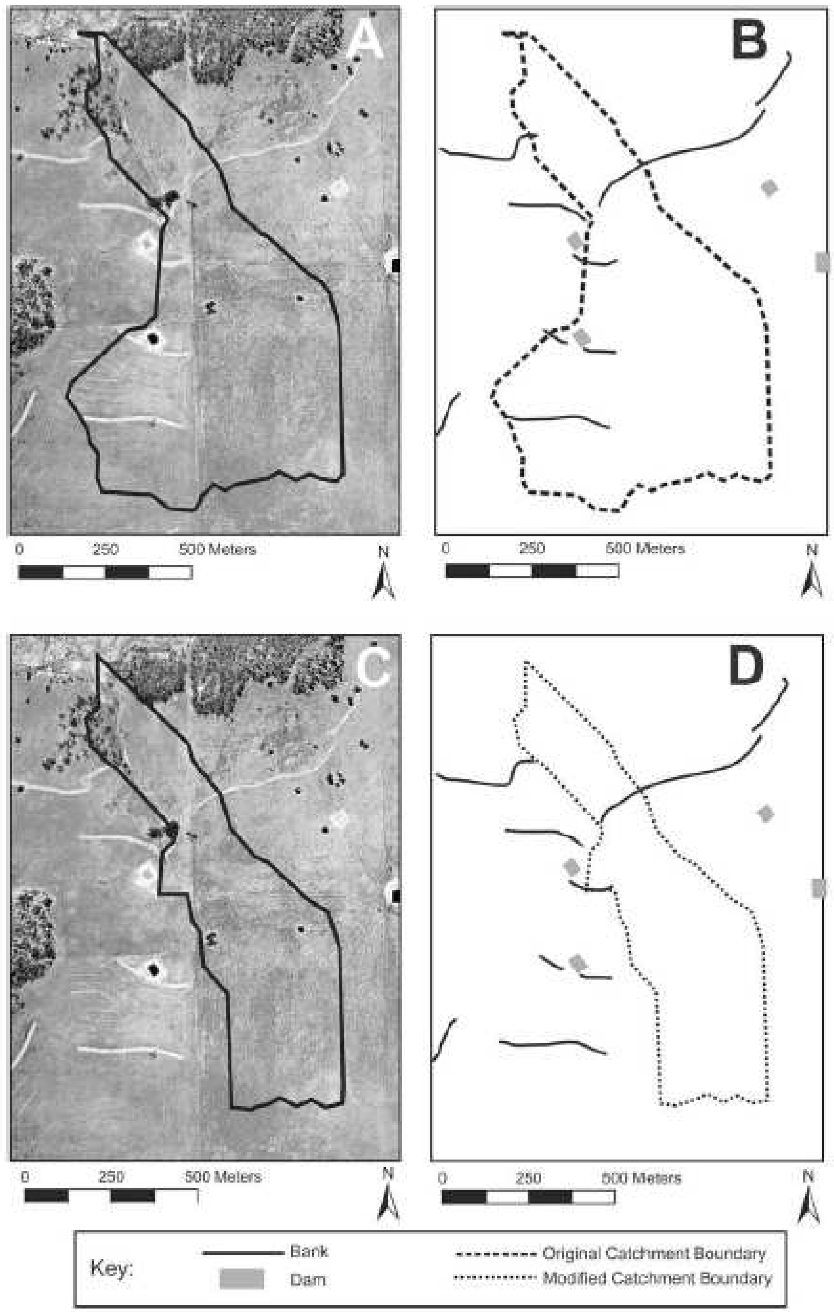
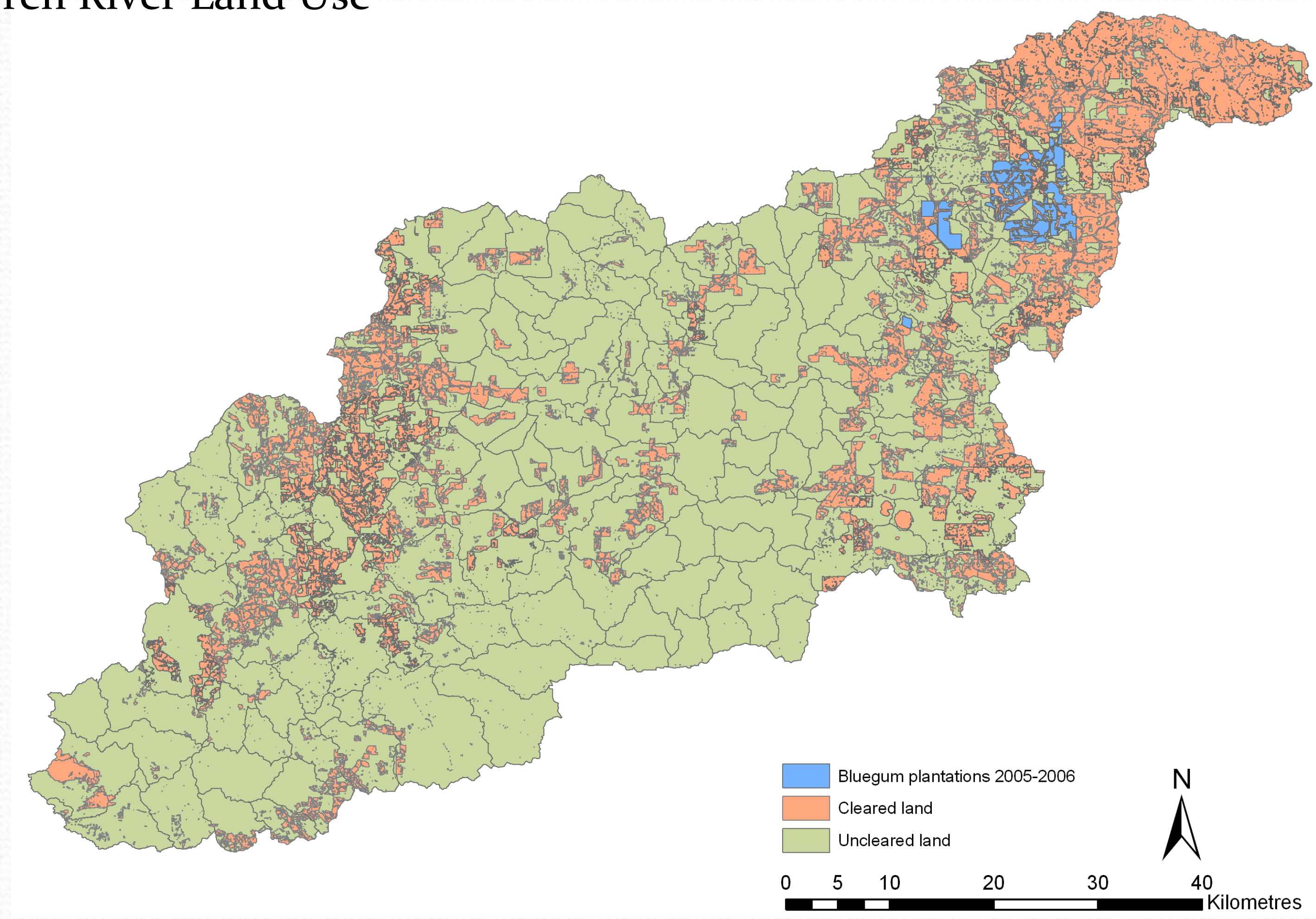
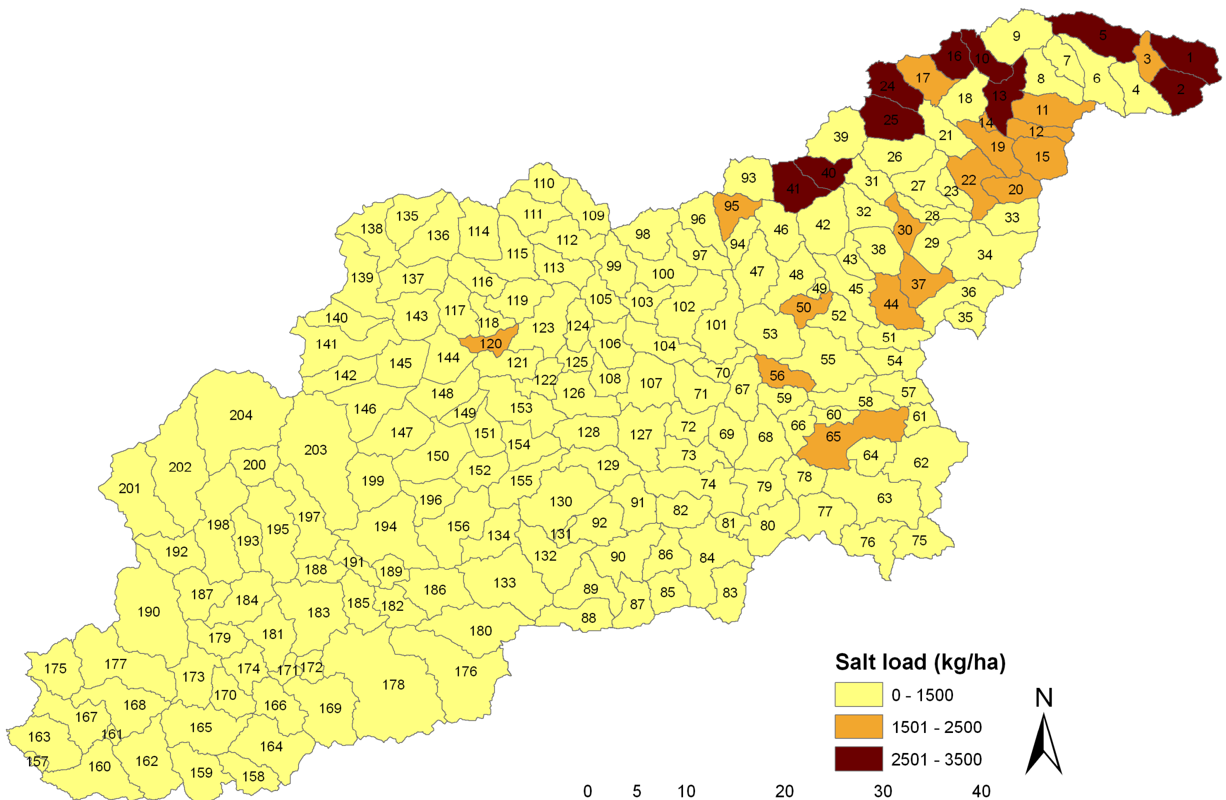


Fig. 4. Changes in area of the hillslope retaining a hydrological connection with the main river channel in Basin i, without (A & B) and with (C & D) the effects of banks and farm dams incorporated into the DEM.

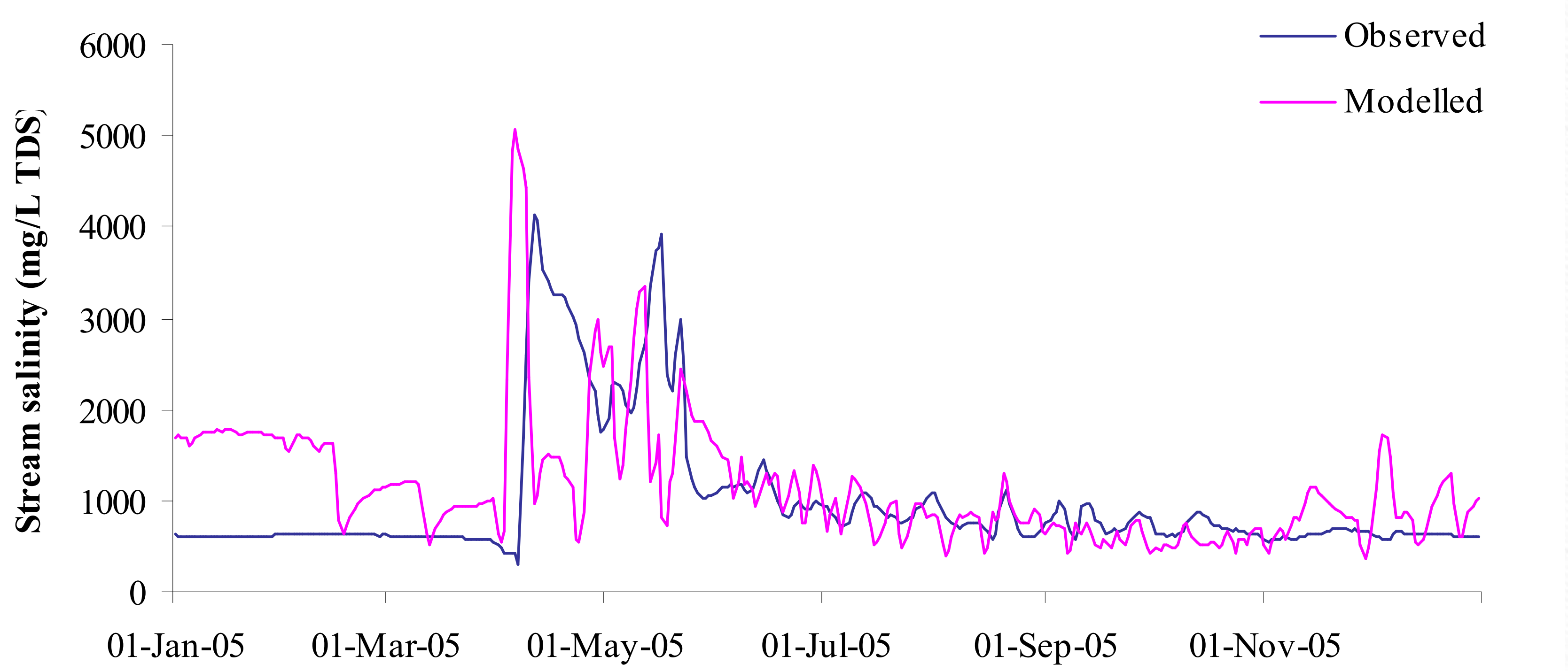
Warren River Land Use

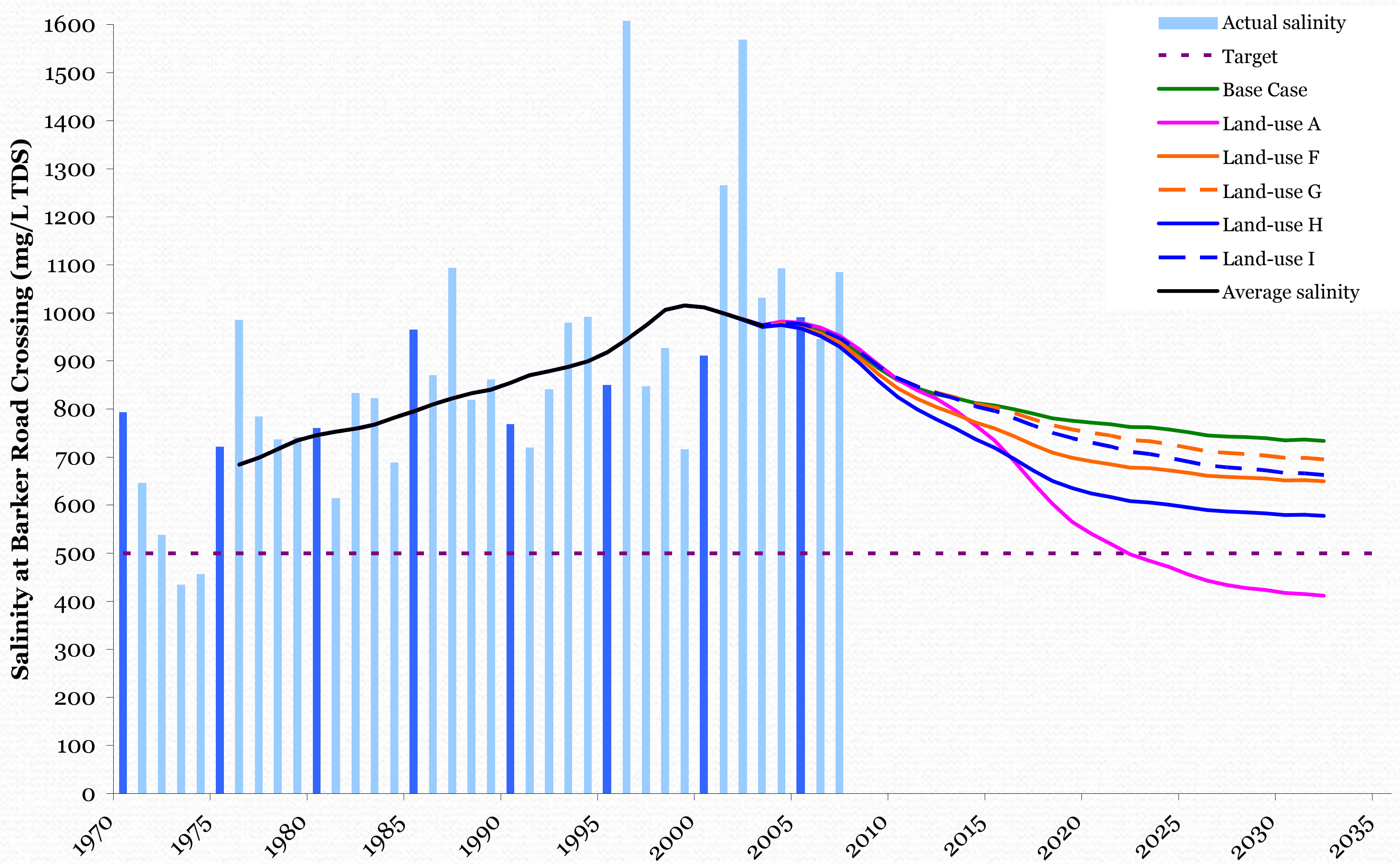



Salt load (kg/ha)
0 - 1500
1501 - 2500
2501 - 3500
N
0 5 10 20 30 40
Kilometres

With a 10% range in the sensitivity of the model LAI, the streamflow differs by 5%. This is half the impact that farm dams currently have on the system with 921 dams in two sub-catchments removing 10% of the total river flow.

Observed and Predicted daily salinity for the Warren River in 2005



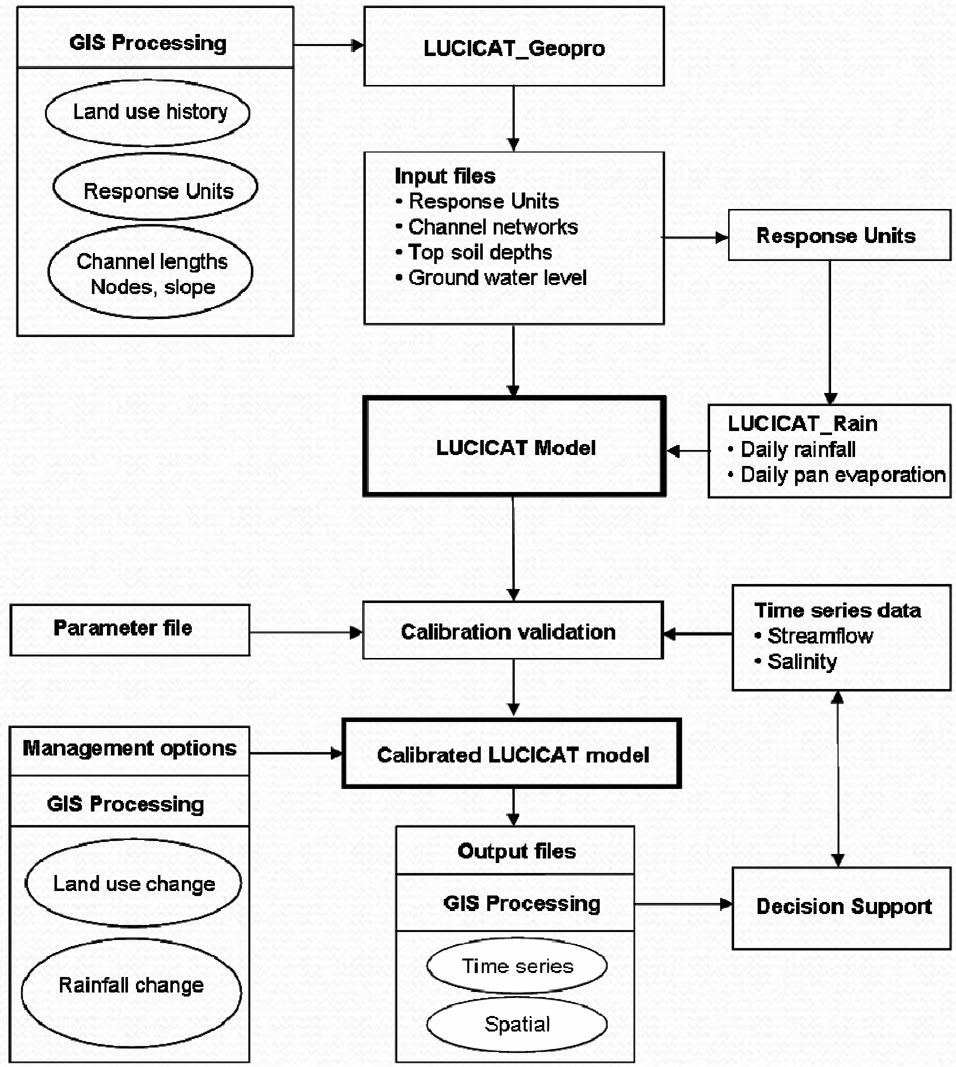


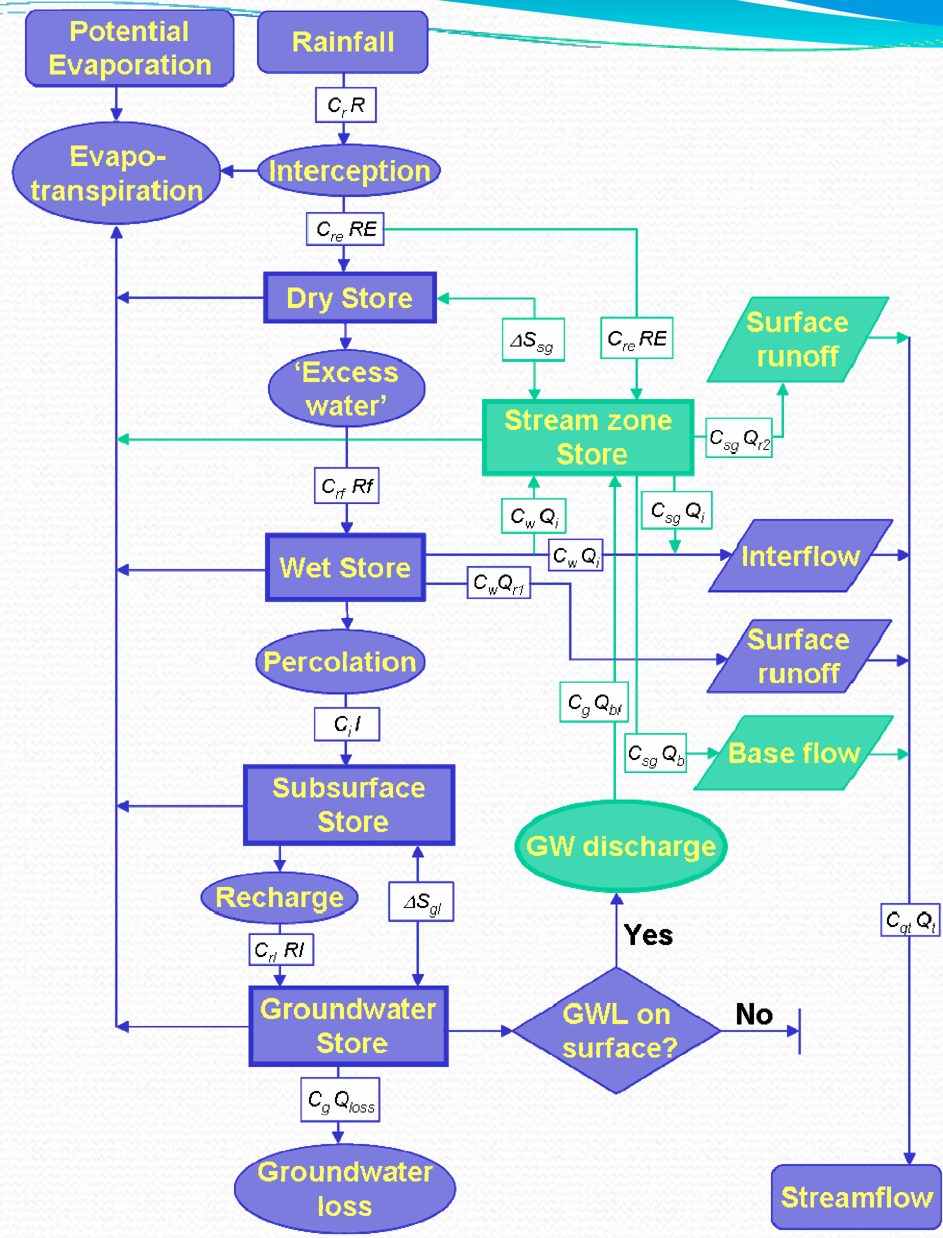
Salinity at Barker Road Crossing (mg/L TDS)
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030
2035
Actual salinity
Target
Base Case
Land-use A
Land-use F
Land-use G
Land-use H
Land-use I
Average salinity

Conclusions

Changes to MODIS LAI appear to reflect climatic conditions experienced by vegetation. We should take advantage of this data when building ecohydrologic models that more realistically incorporate vegetative responses to climate change.

Loss of connectivity in watersheds needs to be considered when seeking to understand the effects of climate change on water resources.


GIS Processing
Land use history
Response Units
Channel lengths
Nodes, slope
LUCICAT_Geopro
Input files
• Response Units
• Channel networks
• Top soil depths
• Ground water level
Response Units
LUCICAT Model
LUCICAT_Rain
• Daily rainfall
• Daily pan evaporation
Parameter file
Calibration validation
Time series data
• Streamflow
• Salinity
Management options
GIS Processing
Land use change
Rainfall change
Calibrated LUCICAT model
Output files
GIS Processing
Time series
Spatial
Decision Support


Potential Evaporation
Rainfall
$C_r R$
Evapo-transpiration
Interception
$C_{re} RE$
Dry Store
ΔS_{sg}
$C_{re} RE$
Surface runoff
'Excess water'
Stream zone Store
$C_{sg} Q_{r2}$
$C_{rf} Rf$
$C_w Q_i$
$C_{sg} Q_i$
Wet Store
$C_w Q_i$
Interflow
$C_w Q_{r1}$
Surface runoff
Percolation
$C_g Q_{bi}$
$C_i I$
$C_{sg} Q_b$
Base flow
Subsurface Store
GW discharge
Recharge
ΔS_{gl}
Yes
$C_{gt} Q_t$
$C_{rl} Rl$
Groundwater Store
GWL on surface?
No
$C_g Q_{loss}$
Groundwater loss
Streamflow