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Methods for estimating the effects of vegetation cover and climate change on streamflow

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CSIRO Water for a Healthy Country Flagship

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Outline

- **An overview of research on vegetation impact on streamflow**
- **Methods for estimating vegetation effects on streamflow**
  - Evaluation of pair-catchment methods
  - Evaluation of time-trend analysis method
  - Use of pre-change point period as the calibration period
- **Separation of the effects of vegetation and climate on streamflow**
- **Streamflow response to vegetation over larger catchments**

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Overview

Year	Study	Key findings	Ref
1903	WSL in Switzerland	Forest cover cause differences in streamflow, especially high flows	Engler (1919)
1919	Wagon Wheel Gap	Forest disturbances affect streamflow	Meisinger(1922)
1933	Coweeta in North Carolina	Forest cuttings increased streamflow	Hewlett (1964)
1948	HJ Andrews in Oregon	Forest cover change on water yield	Munns (1948)

WSL

Coweeta

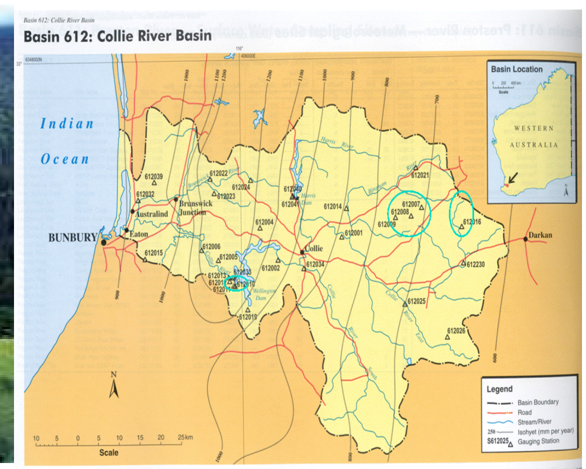
SMALL EXPERIMENTAL WATERSHED AT COWEETA

ALL FOREST GROWTH WAS CUT DOWN TO BROOM-HANDLE SIZE AND ALLOWED TO REMAIN WHERE IT FELL. SPROUTS HAVE BEEN KEPT CUT BACK TO THE GROUND SINCE, WITH NO DISTURBANCE. AS A RESULT, THERE IS A WEALTH OF FAUNA AND FLORA, AND THE SOIL IS EXCEEDINGLY POROUS AND OF A BEAUTIFUL CRUMBLIKE STRUCTURE.

HJ Andrews

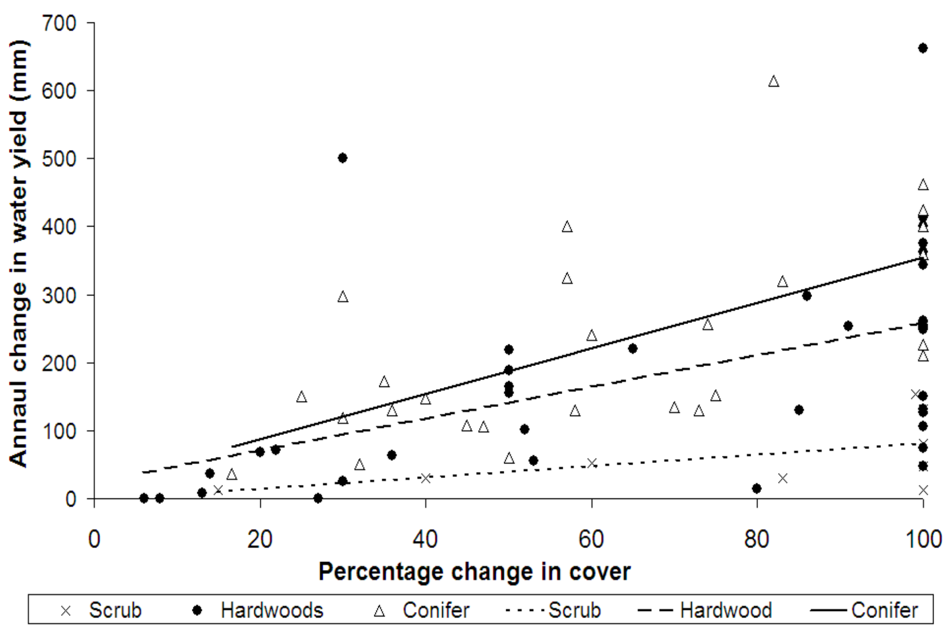
Overview

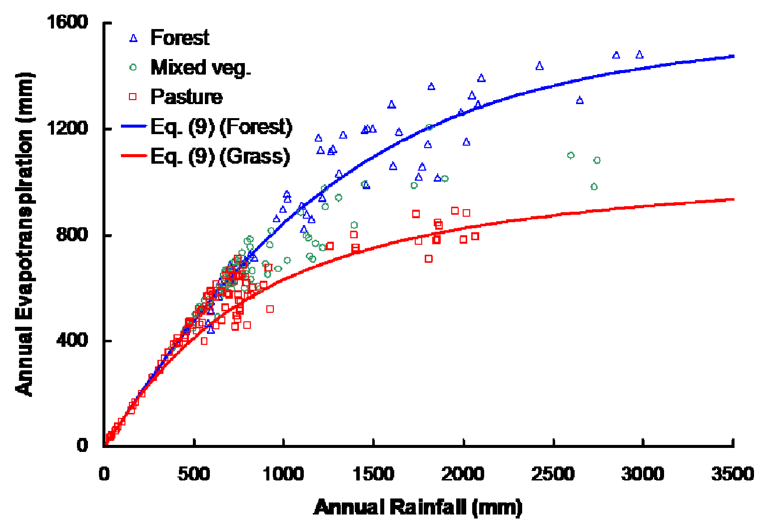
Year	Study	Key findings	Ref
1956	Guthega experiment, first Australian experimental study	Better management could improve water yield and reduce soil erosion	Costin (1967)
1956	Mokobulaan experiment, South Africa	Plantation reduced streamflow	Van Lill et al. (1980)
1977	Collie River Basin experiments	Clearing forest increased water yield and led to salinity	Ruprecht and Schofield (1989)



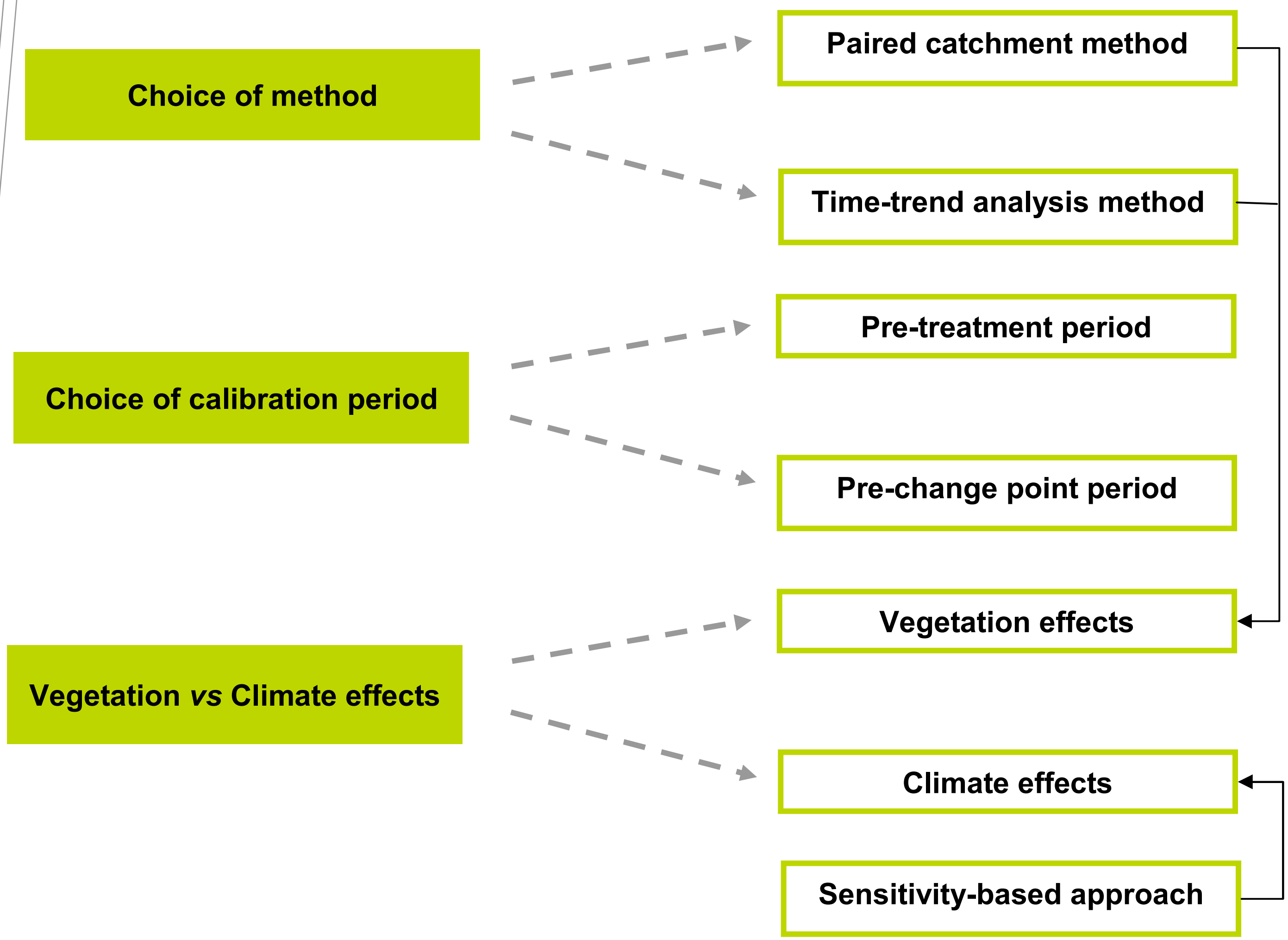
Overview

Year	Study	Key findings	Ref
1982	A review of 94 experimental catchment studies	Showed that forest reduction increased water yield and reafforestation decreased water yield	Bosch and Hewlett (1982)
2001	A conceptual framework developed with data from 250 catchments around the world	Trees use more water than grass	Zhang et al. (2001)





Methods for estimating vegetation effects on streamflow



Paired catchment method (Hewlett, 1982)

- In calibration period

$$Q_{t1} = aQ_{c1} + b \qquad (1)$$

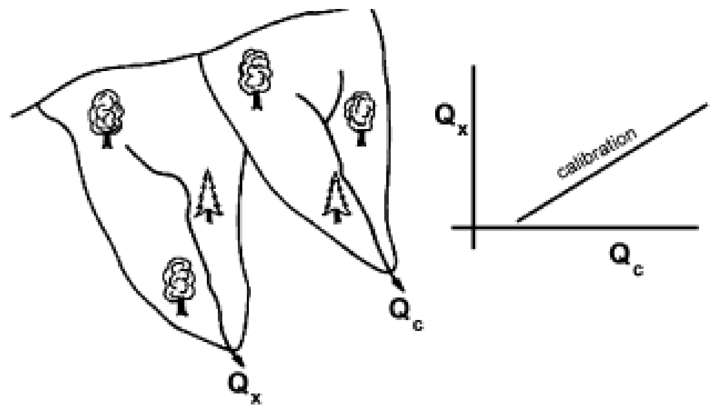
- In treatment period

$$Q_{t2}' = aQ_{c2} + b \qquad (2)$$

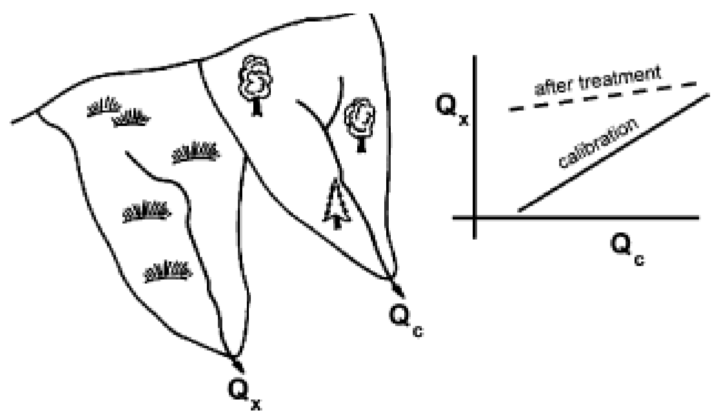
$$\Delta Q^{veg} = \overline{Q_{t2}} - \overline{Q_{t2}'} \qquad (3)$$

  - Q_t and Q_c: measured streamflow from treated and control catchments
  - Q_t': predicted streamflow for treated catchment
  - ΔQ^{veg}: change in mean annual streamflow due to veg. change

Calibration period



Treatment period



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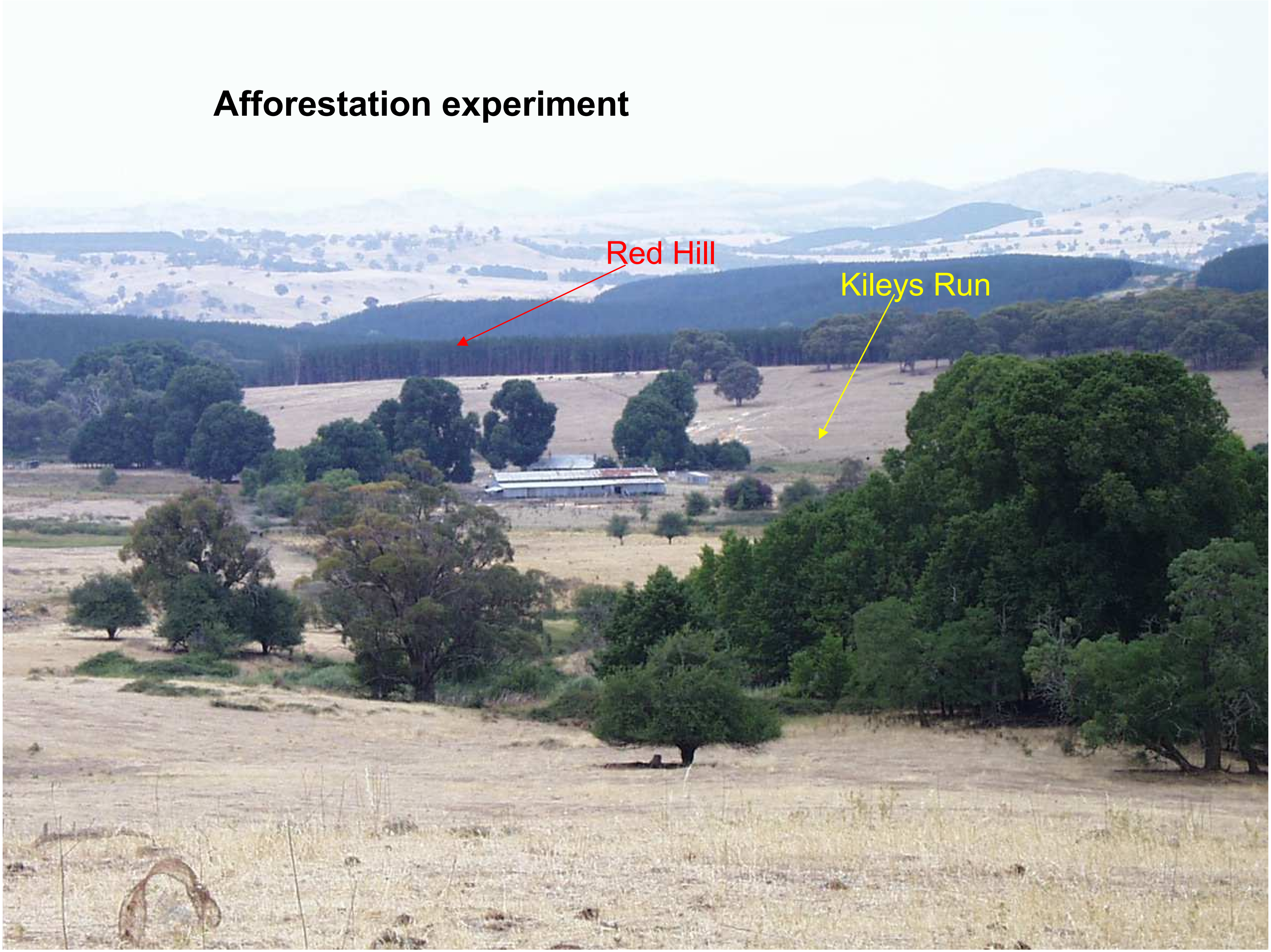
Afforestation experiment



Paired catchment method (Hewlett, 1982)

- Assumptions
  - The correlation between the streamflow of two physiographically similar catchments will remain the same provided that the vegetation of these catchments remains the same or changes in a similar fashion;
  - Annual variations in precipitation, and other climatological variables, affect both catchments equally;

Time-trend analysis method (Bosch and Hewlett, 1982; Lee, 1980)

- Calibrate the catchment on itself

- In calibration period

$$Q_1 = aP_1 + b \qquad (4)$$

- In treatment period

$$Q_2' = aP_2 + b \qquad (5)$$

$$\Delta Q^{veg} = \overline{Q_2} - \overline{Q_2'} \qquad (6)$$

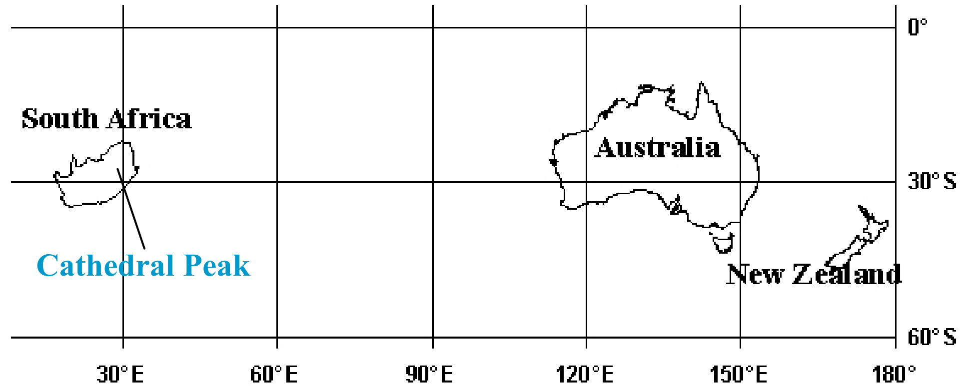
Assumption

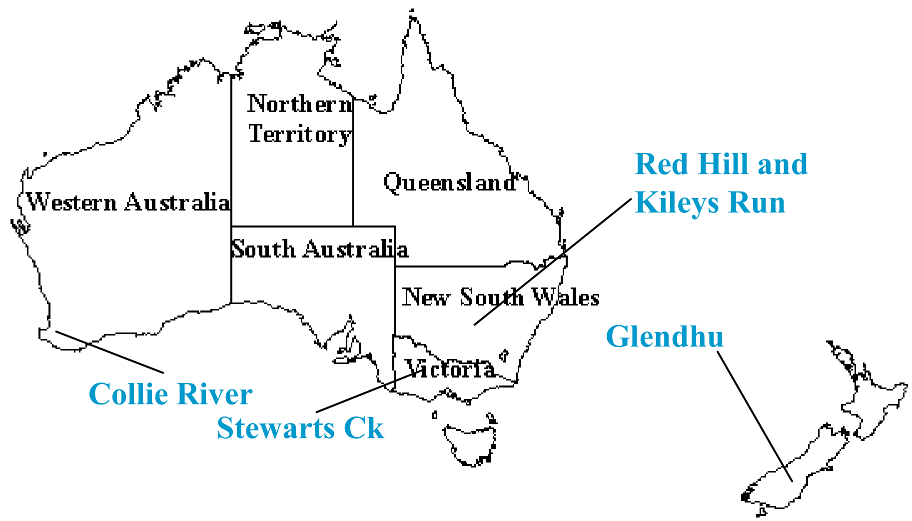
- Rainfall-runoff relationship remains the same unless vegetation changes

Pair catchments

- Deforestation
  - Lemon/Ernies
  - Dons/Ernies
  - Wights/Salmon

  } Collie
- Afforestation
  - Cathedral Peak III/IV
  - Glendhu 2/1
  - Red Hill/Kileys Run
- Forest conversion
  - Stewarts Ck 5/4





Summary of paired catchments

Catch.	Area/km^2	P/mm	Q/mm	PET/mm	Description of treatment	Data record
Lemon	3.44	702.6	55.5	1436.4	1976/1977, 53% clearing	1974-1997
Dons	3.5	678.5	19.6	1299.6	1977, 38% clearing	1974-1997
Ernies	2.7	707.4	8.6		Control for Lemon and Dons	1974-1997
Wights	0.94	961.1	406.4	1470.8	1976/1977, 100% clearing	1974-1997
Salmon	0.82	1112.1	133.0		Control for Wights	1974-1997
CPIII	1.42	1519.2	610.6	1298.4	1958, 83% afforestation	1952-1980
CPIV	0.99	1519.2	744.0		Control for CPIII	1952-1980
GH2	3.1	1282.4	697.3	615.5	1982, 67% afforestation	1980-2000
GH1	2.18	1279.4	832.3		Control for GH2	1980-2000
RH	1.95	836.7	108.6	1340.0	1988/1989, 78% afforestation	1990-2005
KR	1.35	836.7	166.5		Control for Red Hill	1990-2005
Ck5	0.18	1156	311.2	1052.3	1969/1970, 100% forest conversion	1960-1995
Ck4	0.25	1156	224.0		Control for Stewarts Ck 5	1960-1995

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Determination of the calibration period

- Necessity
  - Most of the catchments have short or no pre-treatment data

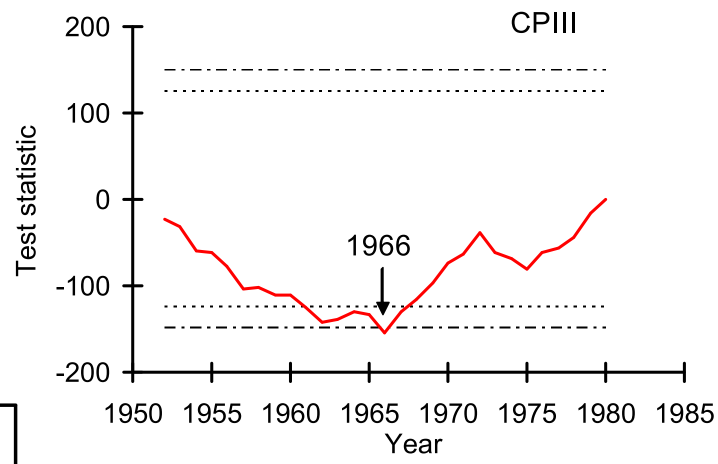
- Assume
  - Streamflow in the first a few years after treatment can be used to represent the pre-treatment condition

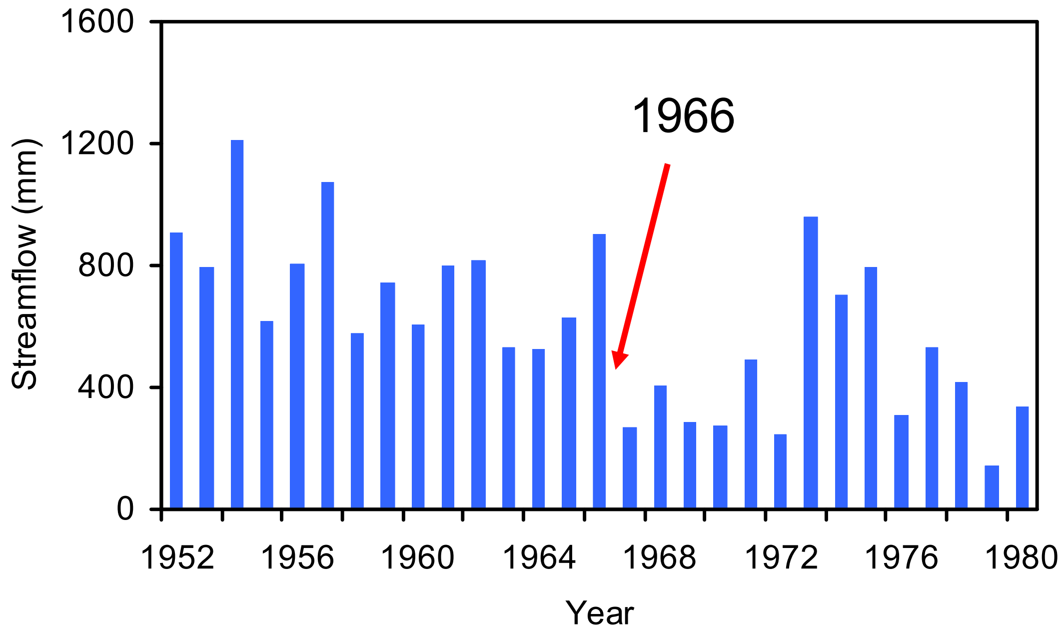
Change point identification

The non-parametric approach of Pettitt (1979):

$$U_{t,N} = U_{t-1,N} + \sum_{j=1}^{N} \operatorname{sgn}(x_t - x_j)$$

$$k(t) = Max_{1 \le t \ge N} \left| U_{t,N} \right|$$





Statistics for evaluation of the regression models
(Legates and McCabe, 1999)

- The coefficient of determination

$$R^2 = \left\{ \frac{\sum_{i=1}^{N}\left(O_i - \overline{O}\right)\left(P_i - \overline{P}\right)}{\left[\sum_{i=1}^{N}\left(O_i - \overline{O}\right)^2\right]^{0.5}\left[\sum_{i=1}^{N}\left(P_i - \overline{P}\right)^2\right]^{0.5}} \right\}$$

- The modified coefficient of efficiency

$$E_1 = 1.0 - \frac{\sum_{i=1}^{N}\left|O_i - P_i\right|}{\sum_{i=1}^{N}\left|O_i - \overline{O}\right|}$$

- The modified index of agreement

$$d_1 = 1.0 - \frac{\sum_{i=1}^{N}\left|O_i - P_i\right|}{\sum_{i=1}^{N}\left(\left|P_i - \overline{O}\right| + \left|O_i - \overline{O}\right|\right)}$$

- The mean absolute error

$$MAE = N^{-1}\sum_{i=1}^{N}\left|O_i - P_i\right|$$

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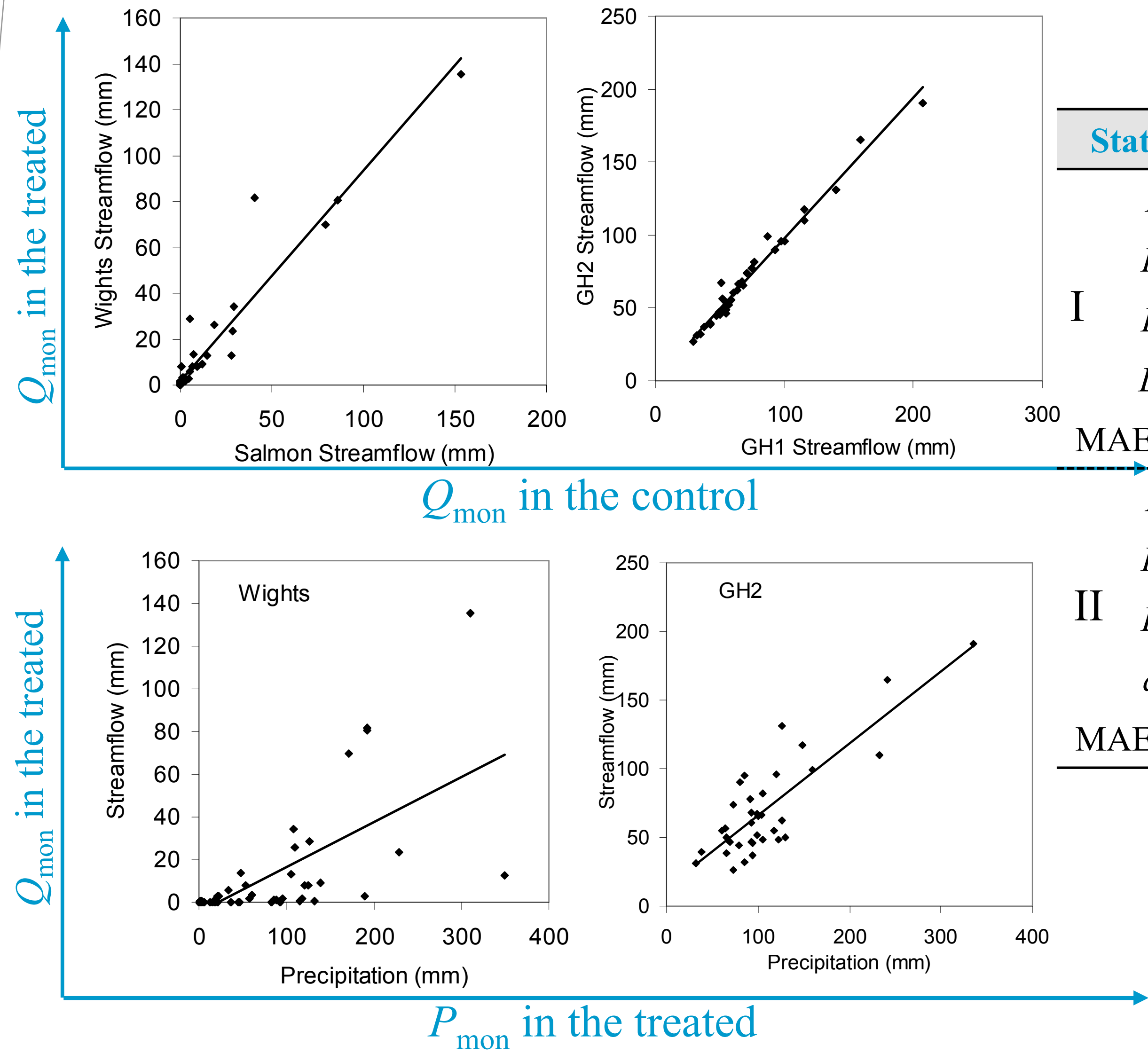
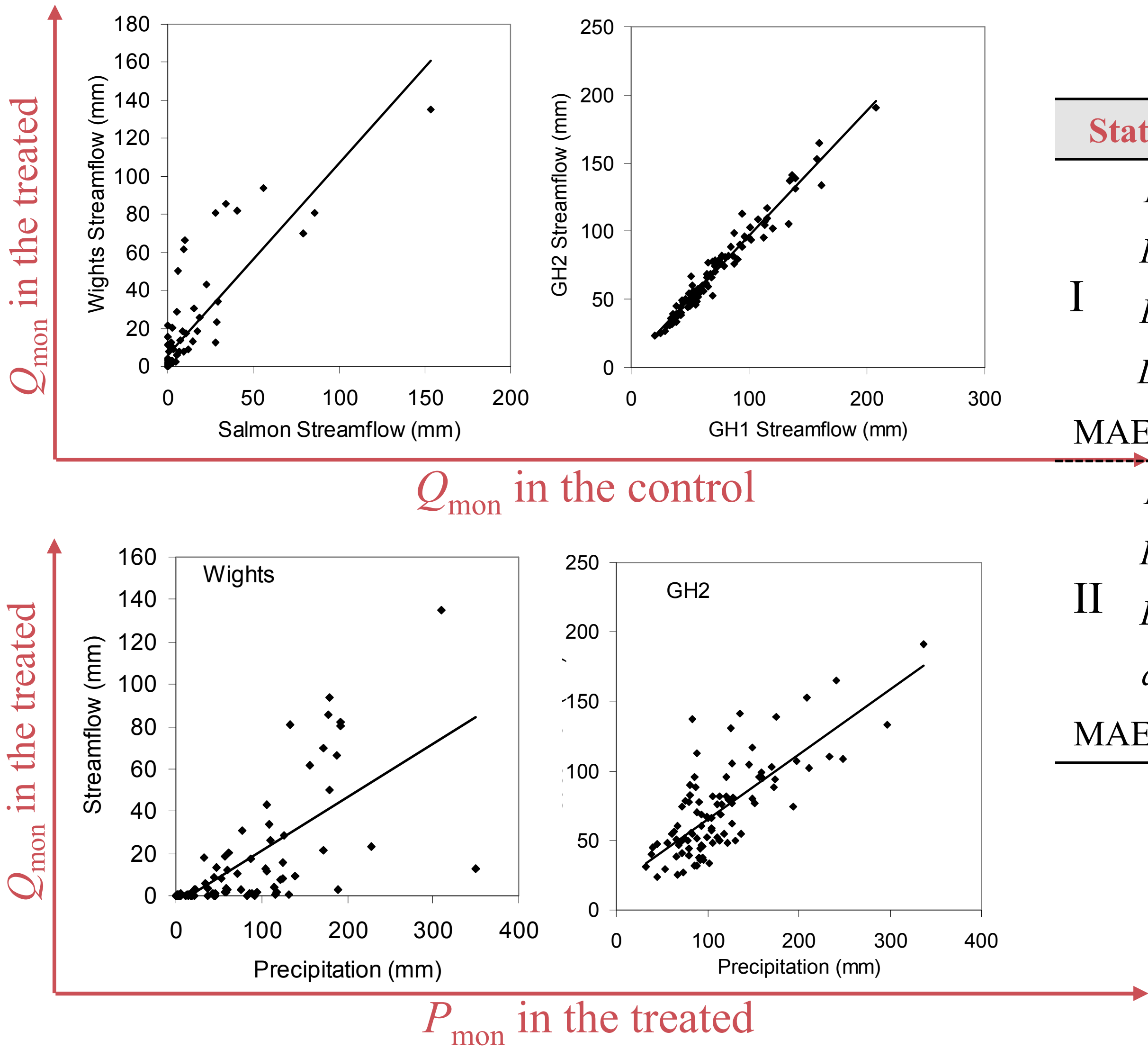
Regression models (pre-treatment)



	Statistics	Wights/Salmon	GH2/1
I	N	48	36
	R^2	0.91	0.98
	E_1	0.77	0.85
	D_1	0.88	0.92
	MAE (mm)	3.66	4.11
II	N	48	36
	R^2	0.42	0.69
	E_1	0.27	0.40
	d_1	0.59	0.65
	MAE (mm)	11.69	16.13

Regression models (pre-change point)



	Statistics	Wights/Salmon	GH2/1
	N	84	96
	R^2	0.71	0.96
I	E_1	0.49	0.81
	D_1	0.70	0.90
	MAE (mm)	9.32	5.04
	N	84	96
	R^2	0.47	0.56
II	E_1	0.35	0.36
	d_1	0.63	0.62
	MAE (mm)	11.91	16.87

Vegetation effects on streamflow

Based on pre-treatment period (unit: %)

Catchment	Paired catchment method	Time-trend analysis method
Lemon	98	78
Dons	80	28
Wights	98	89
CPIII	57	84
GH2	83	91
SC5	69	82

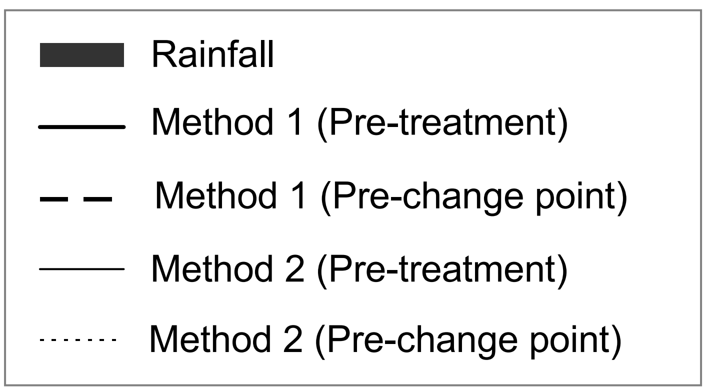
Based on pre-change point period (unit: %)

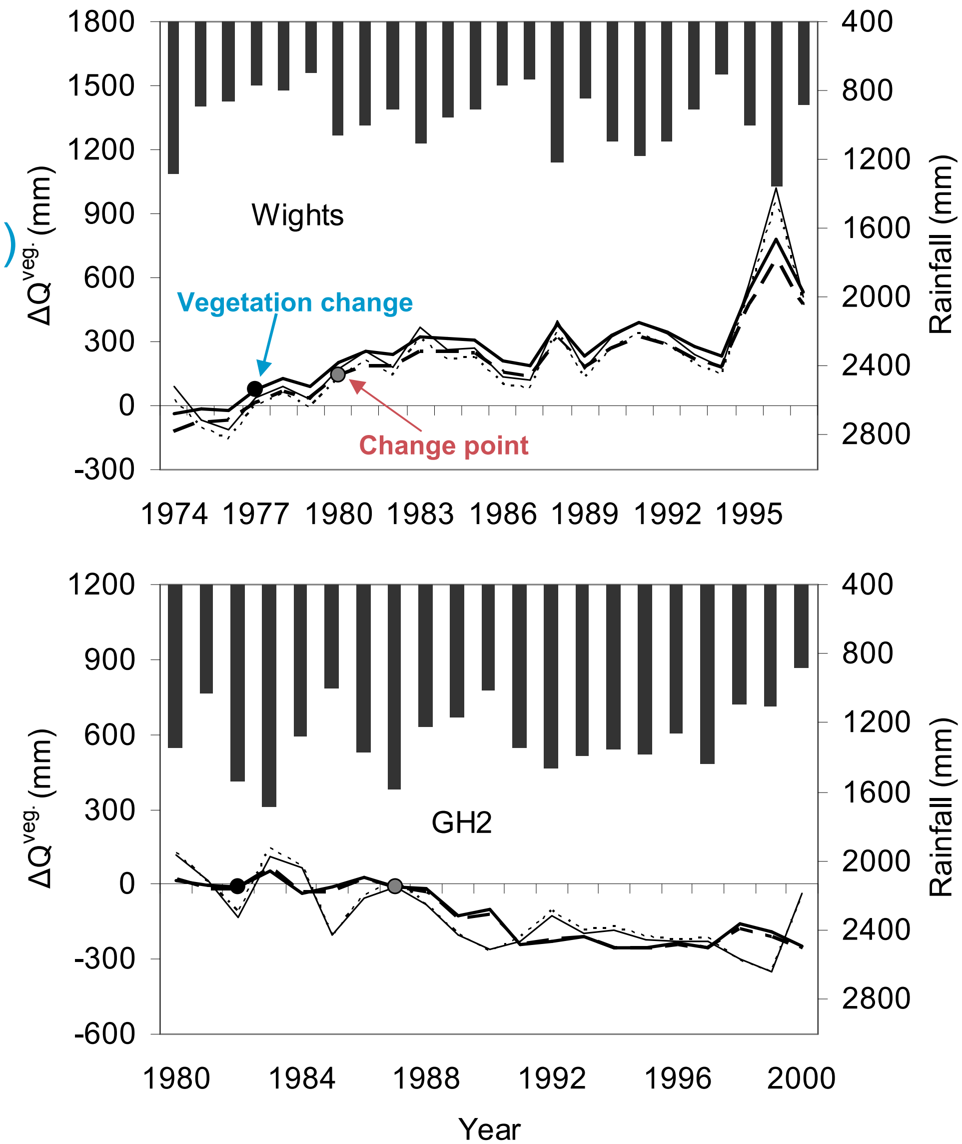
Catchment	Paired catchment method	Time-trend analysis method
Lemon	100	92
Wights	94	91
CPIII	100	102
GH2	78	78
RH	27	71

Vegetation effects on annual streamflow

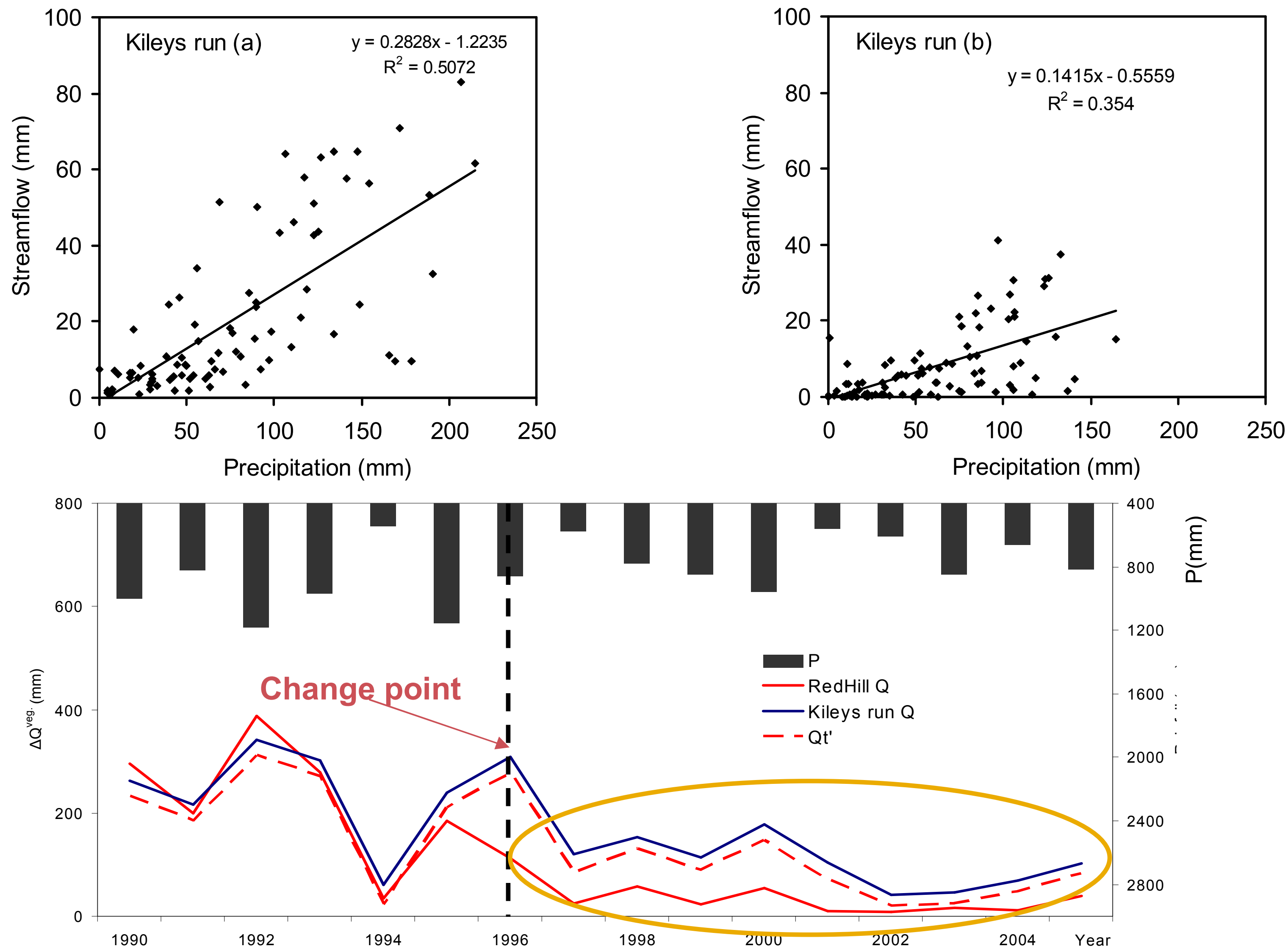
- Consistent estimates were provided using paired catchment method (Method 1) and time trend analysis method (Method 2)

- Obvious streamflow changes were detected after the change point





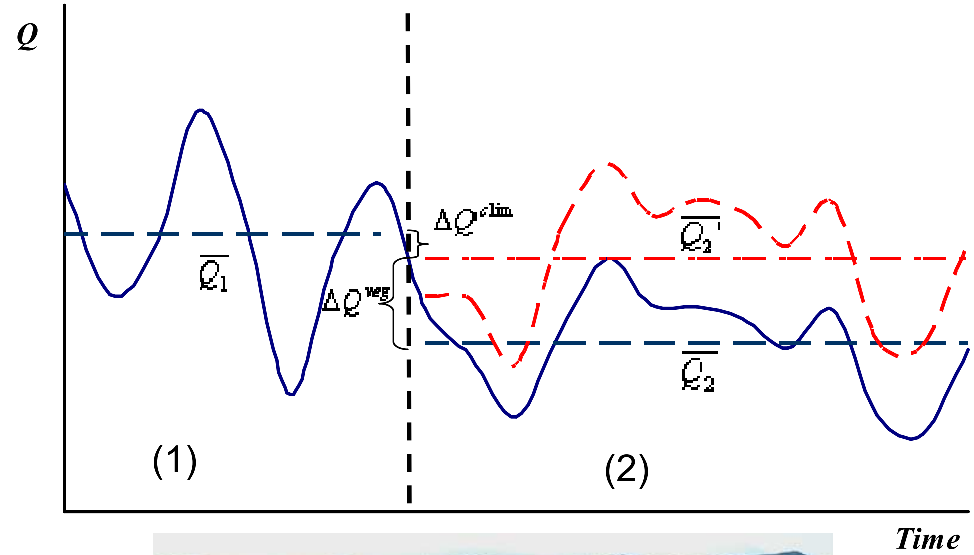
Effect of control catchment



Separate climate and vegetation effects

Total change in streamflow:

$$\Delta Q^{tot} = \overline{Q}_2^{obs} - \overline{Q}_1^{obs}$$



Assume:

$$\Delta Q^{tot} = \Delta\overline{Q}^{c\lim} + \Delta\overline{Q}^{Veg}$$

Climate impact on streamflow:

$$\Delta\overline{Q}^{c\lim} = \beta\Delta P + \gamma\Delta E_0$$

Sensitivity-based approach (Jones et al., 2006)

- To calculate the effect of climate on streamflow

$$\Delta Q^{clim} = \beta \Delta P + \gamma \Delta E_0$$

- β and γ are the sensitivity coefficients of streamflow to precipitation and potential evaporation, defined as

$$\beta = \frac{1 + 2x + 3wx^2}{(1 + x + wx^2)^2}$$

$$\gamma = -\frac{1 + 2wx}{(1 + x + wx^2)^2}$$

where x is the index of dryness, $x=E_0/P$ and w is a model parameter mainly related to vegetation type (Zhang et al., 2001).

So,

$$\Delta Q^{veg} = \Delta \overline{Q}^{tot} - \Delta \overline{Q}^{clim}$$

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Vegetation effects on streamflow

Based on pre-treatment period (unit: %)

Catchment	Paired catchment	Time-trend analysis	Sensitivity-based method
Lemon	98	78	84
Dons	80	28	28
Wights	98	89	90
CPIII	57	84	73
GH2	83	91	80
SC5	69	82	70

$$\Delta Q^{veg} = \Delta Q^{tot} - \Delta Q^{c\lim}$$

Based on pre-change point period (unit: %)

Catchment	Paired catchment	Time-trend analysis	Sensitivity-based method
Lemon	100	92	81
Wights	94	91	86
CPIII	100	102	105
GH2	78	78	52
RH	27	71	57

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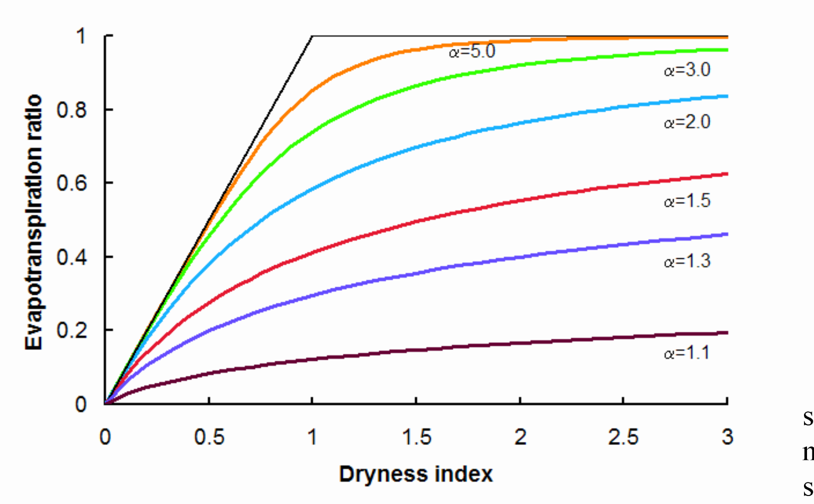
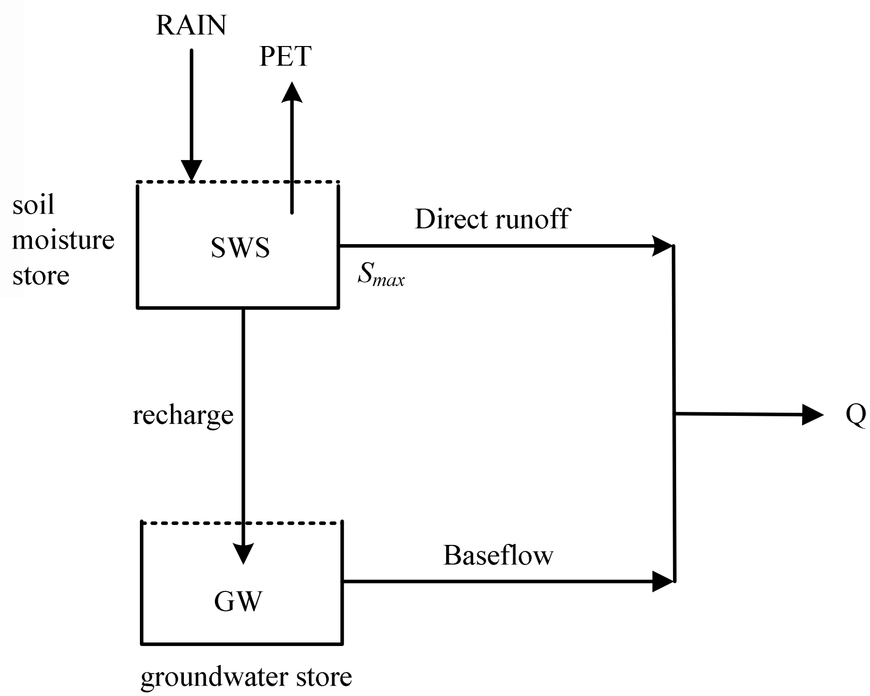
Streamflow response over larger catchments

- Dynamic Water Balance Model (Zhang et al., 2008)





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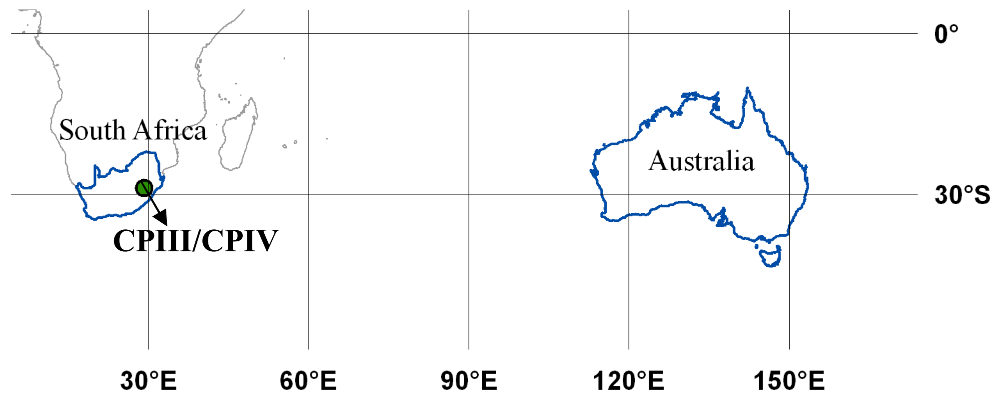
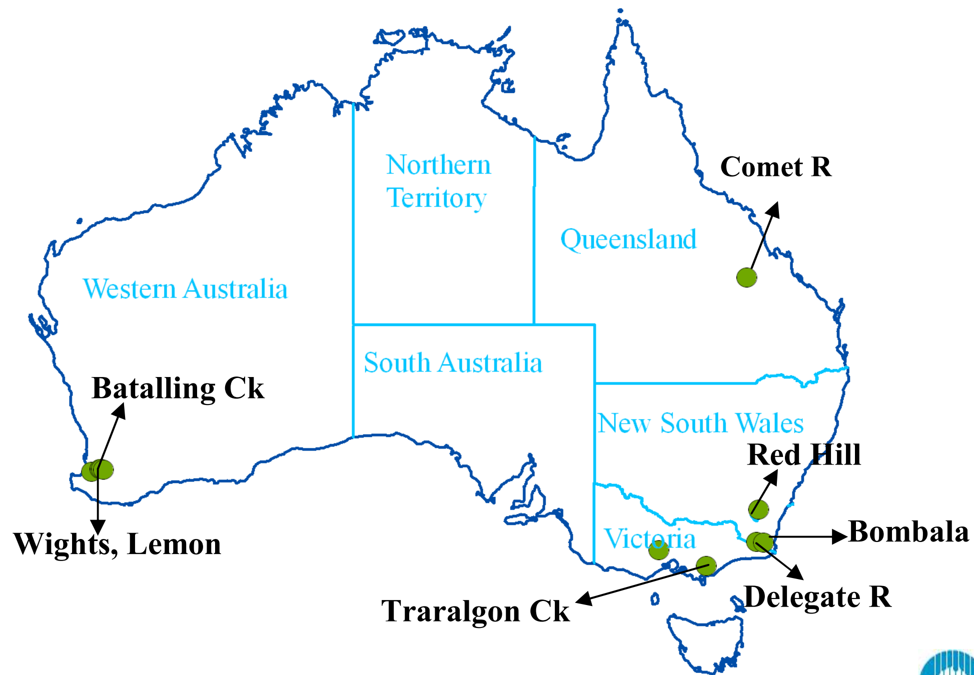
Study Catchments

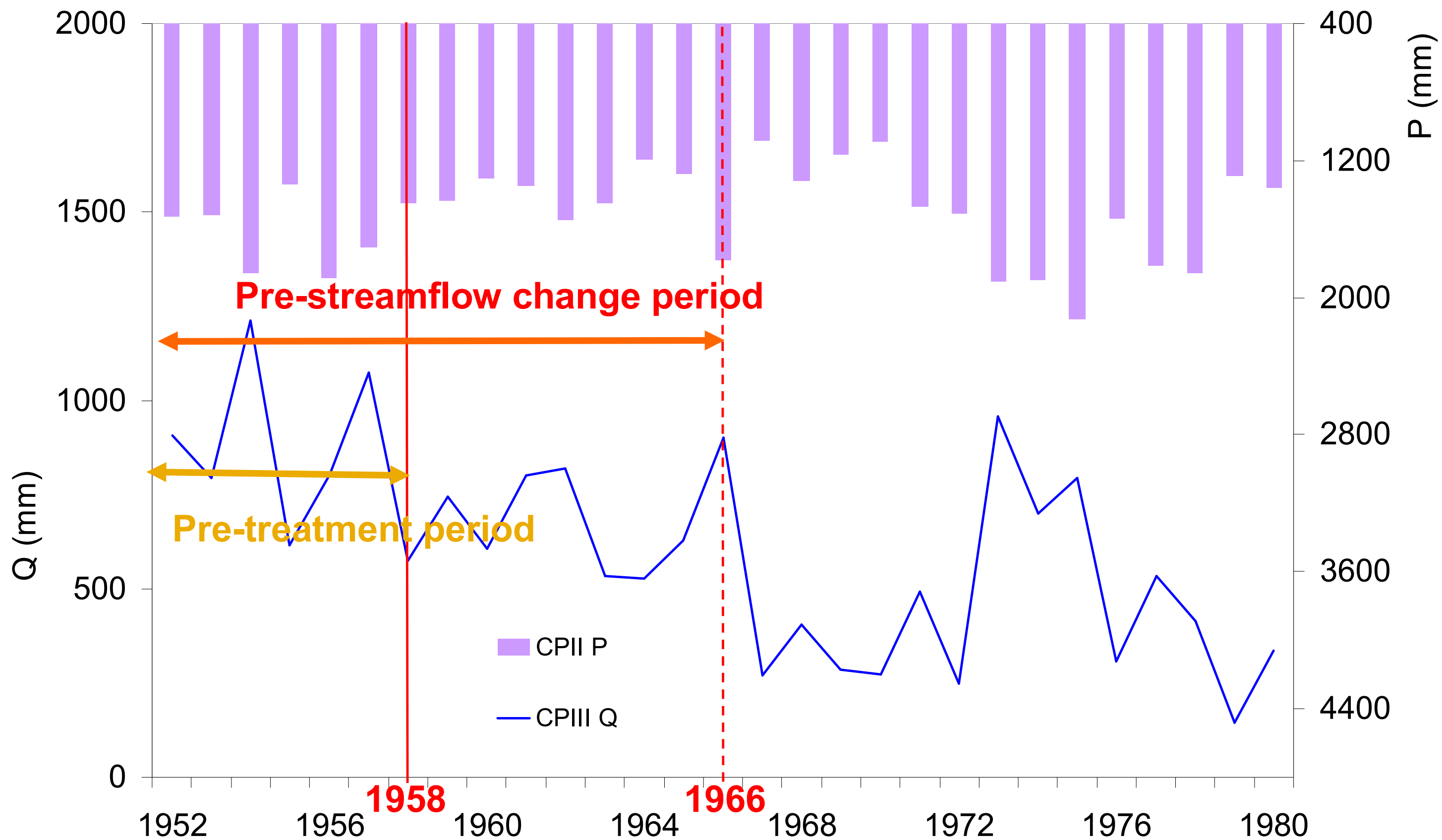
- Deforestation
  - Wights (0.94km^2)
  - Lemon (3.44km^2)
  - Comet (16400km^2)
- Afforestation
  - Cathedral Peak (1.42km^2)
  - Red Hill (1.95km^2)
  - Traralgon (87km^2)
  - Delegate (1135km^2)
  - Bombala (1363km^2)
- Reforestation
  - Betalling Ck (16.64km^2)





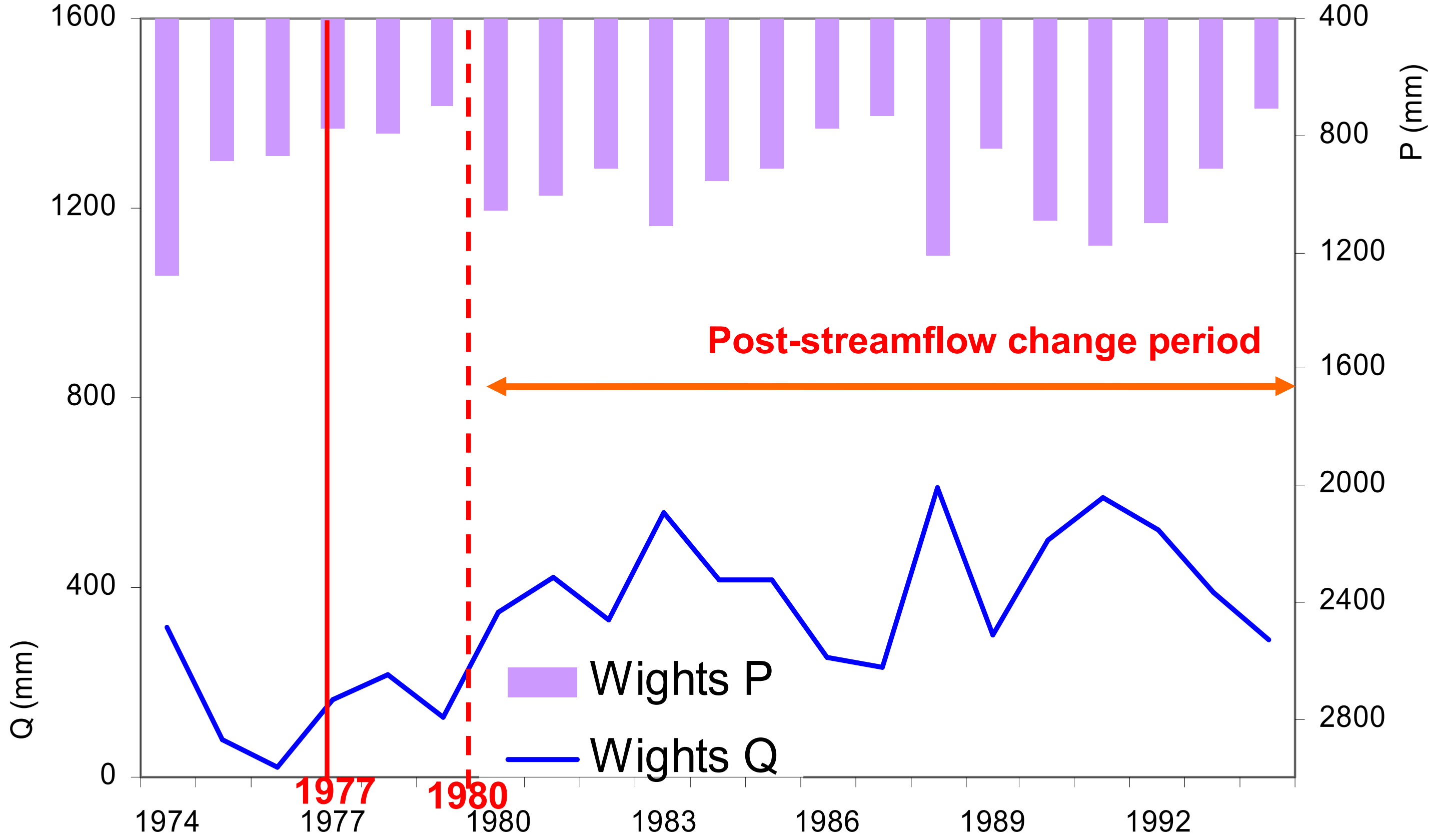
Model calibration for estimating the effects of vegetation change on streamflow

- Calibration period
  - For afforestation and reforestation catchments



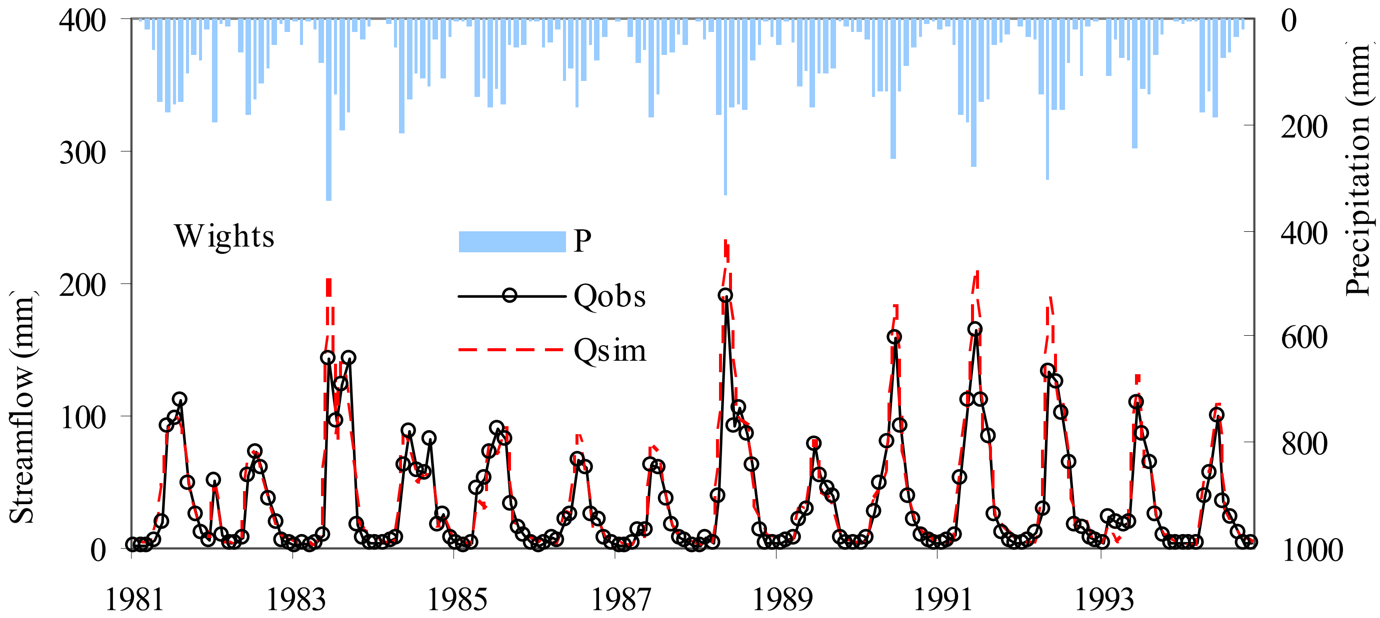
Reverse process of model calibration

- Calibration period
  - For deforestation catchments: Reverse process of model calibration



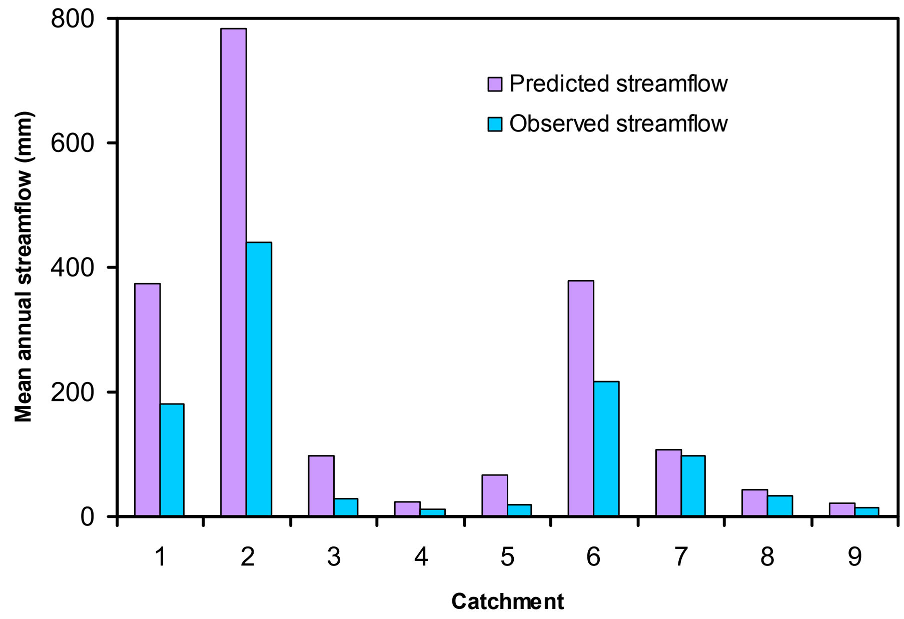
Results of model calibration

- Comparison of observed and simulated monthly streamflow in the calibration period for Wights



Effects of forest cover change on streamflow

- Predicted and observed mean annual streamflow in the prediction period for all the catchments



- The effect of vegetation cover change on mean annual streamflow from large catchments is consistent with that obtained from small experimental catchments

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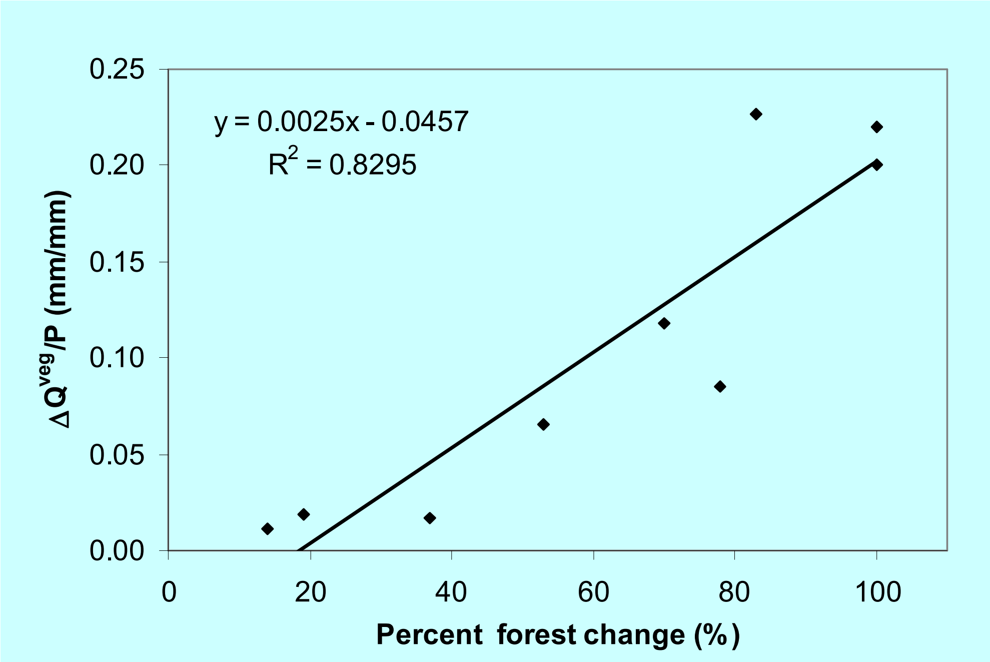
Streamflow change *vs* forest cover change



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Summary

- Paired catchment method generally provides accurate estimates of vegetation effect on streamflow
- It is appropriate and practical to use the pre-change point period as the calibration period
- The framework for estimating effects of climate and vegetation change on streamflow is accurate when combined with the sensitivity-based approach
- The normalized mean annual streamflow change can be approximated as a linear function of the percent forest cover change for catchments ranging from 1 to 10,000 km^2

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Thank you

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