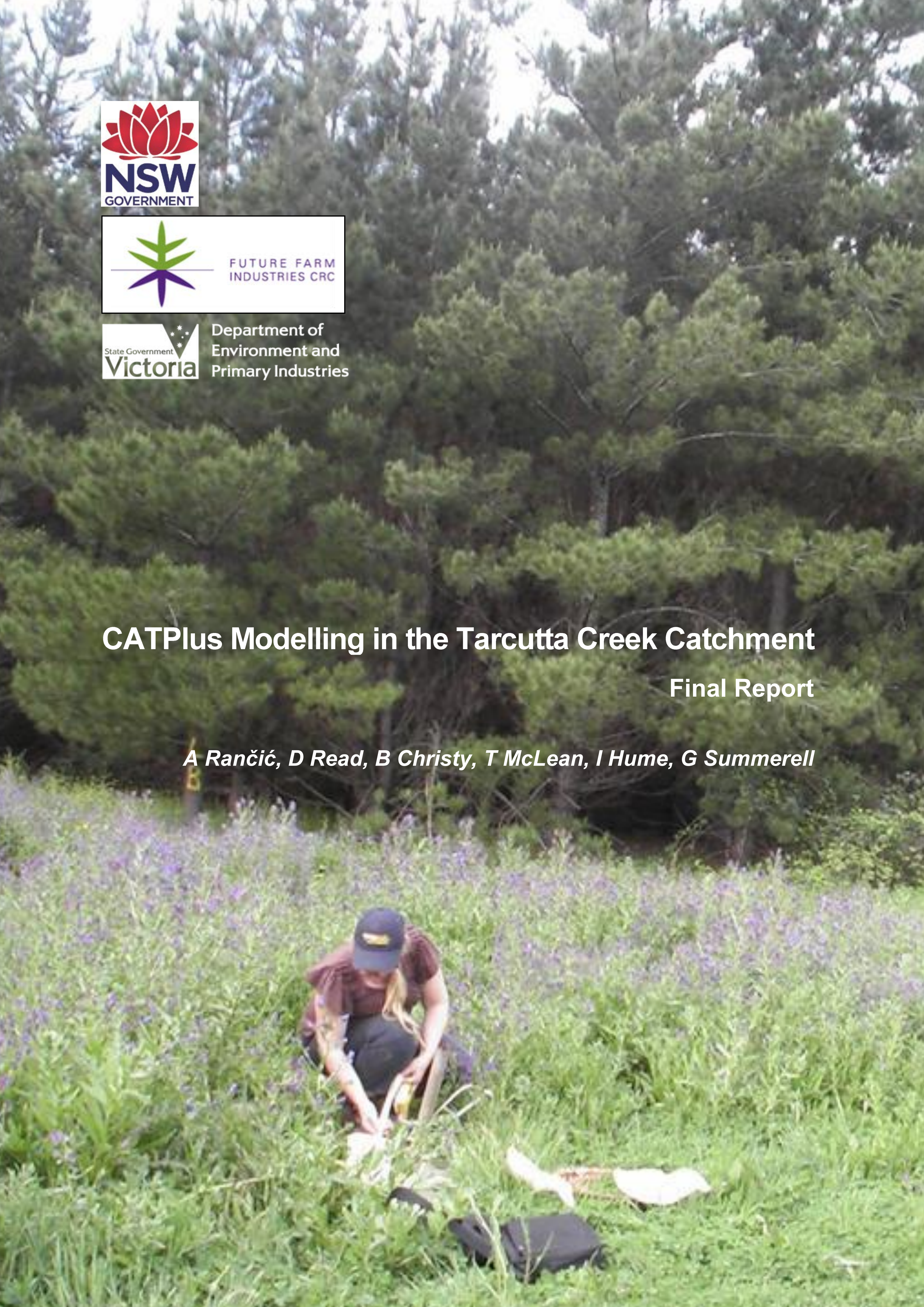

CATPlus Modelling in the Tarcutta Creek Catchment

Final Report

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Cover photo: Bore monitoring at Downfall in Tarcutta Creek catchment (Dr David Read)

Acknowledgments

Probably the greatest success of the CATPlus–Tarcutta project was in the landholders' participation. They repeatedly showed that they owned the project. They welcomed the bore monitoring program, and helped to identify bore locations. Several helped by measuring groundwater levels. Some proactively requested inclusion and monitoring of piezometers on their properties. Others contributed decades of rainfall records, or provided literature related to the Tarcutta Creek catchment. Most shared their personal knowledge of the land-use history of the catchment or provided guidance on relevant literature. The authors are thankful for the landholders' invaluable and meaningful discussions and advice and their active participation in User Group meetings and presentations. The trust established is fertile ground for future cooperation in water and land use and overall catchment management.

Exemplary cooperation between the united team of NSW and Victorian researchers (OEH, DPI NSW, DEPI VIC) saw this project through, thanks to funding from the Future Farm Industries Cooperative Research Centre (CRC).

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Executive summary

Tarcutta Creek catchment modelling tests the hydrologic effects of potential land-use changes. The aim of this phase of the modelling was to test the CATPlus model's ability to reproduce adequately all components of the hydrologic cycle: surface, unsaturated subsurface and groundwater hydrology. The model was set up to run from the start of the twentieth century, thus maximising the climatic variability and avoiding the bias that would be imposed by the predominantly wet 1975–2005 period. The model was also extended to March 2012 and captured the important transition from the Millennium Drought to the extremely wet spell and record flooding events of 2010 and 2011. Historic land use was reconstructed to contribute to the model's accuracy.

The newly acquired information from the field, coupled with the data from the Groundwater Database System (GDS), published reports and invaluable landowners' original records, provide the most comprehensive dataset in NSW and Eastern Australia.

Each of the early bore records (1920–1950) clearly demonstrates the groundwater levels positioned below the stream beds, and therefore (a) the groundwater systems were not discharging locally during first half of the twentieth century, and (b) streams in the proximity of these bores were loosing water to groundwater below, instead of gaining the baseflow. This important finding should be taken into consideration in conceptualisation and modelling of groundwater systems.

The groundwater measuring program engaged more than 20 landholders who became connected to the project. After the 2010 floods the bores in the discharge areas of the Borambola region started discharging at rates comparable to those of the 1980s, at the height of the area's salinity problems. The research team has presented twice to Landcare-type groups and were asked specifically if the salt scalds were likely to recur. Because of improved land-management and grazing practices with perennial pastures and strategically positioned native tree plantations, the scalding did not eventuate. Further expansion of these practices will insure that these problems do not resurface under longer wet spells.

The model successfully reproduced unsaturated subsurface hydrology when tested by comparison with the soil moisture data collected at the EverGraze site near Borambola, measured by neutron probes and integrated over the top 1.5 metres of soil profile. Three plots were planted with annual pasture and another three with lucerne. Readings were taken between 6 August 2007 and 19 April 2010. Neutron probe readings were taken 33 times over 3.7 years. Data were obtained courtesy of the NSW Department of Primary Industries. The CATPlus model reproduces the soil water profile under lucerne better than under annual pasture. Simulated data plot very close to the median time series of experimental data and correlate well, with the correlation coefficient of changes between consecutive readings reaching 0.82 for lucerne and 0.76 for annual pasture.

The CATPlus model introduced the adjustment of ANUCLIM rainfall surfaces to match the values of rainfall records at the point of sampling. Two options for adjustment were investigated: one based on monthly average, and one on annual average. In some catchments, where seasonality and a large rainfall gradient are important hydrologic drivers, a monthly, rather than annual rainfall adjustment could lead to improved modelling. Unlike most of the Victorian catchments modelled, which have less pronounced relief and rainfall gradients, Tarcutta is a very hilly catchment where spatial interpolation smooths rainfall gradients close to ridges. The switch from a monthly, to a much simpler, annual adjustment therefore reduced the model performance in the Tarcutta Creek catchment.

Groundwater hydrographs were successfully reproduced in the model, by calibrating parameter Alpha. Alpha represents the number of months needed for the hillslope storage to reduce its volume to half (decay coefficient). Values of Alpha, obtained by calibration, range from 10 to 50 months; however, to reproduce the baseflow component of the stream trace, the value of Alpha needs to be close to one month. This in effect keeps the hillslope reservoir very depleted by allowing rapid transfer of incoming fluxes to the alluvial aquifer and stream; therefore groundwater levels and the fluxes to the stream could not be reproduced simultaneously.

To be able to reproduce these fluxes simultaneously, alluvial storage should be allowed to discharge at the faster rate, independent of the incoming flux from the hillslope storage. This is the most important modification required for the model to become a fully integrated hydrologic model, capable of accurately and simultaneously reproducing surface and subsurface hydrologic processes.

CATPlus differs from some hydrologic models which use a decay coefficient function for modelling of groundwater. While the bottom of the conceptual groundwater reservoir in these hydrologic models is fixed and static, the bottom of the hillslope reservoir in CATPlus model varies over time, because it is linked to the top of the alluvial reservoir. This might pose a conceptual problem, and could be investigated by fixing the bottom of the hillslope and alluvial reservoirs to the level defined by the stream bed. The model might also benefit from the lower boundary condition of the alluvial aquifer being linked to the stream height, via a rating curve, rather than to the stream bed.

Rainfall is the first order driver of the hydrologic regime. The improvement expected from the additional decade of land-use reconstruction was diluted due to model performance being lowered by simplified rainfall transformation. However, the land-use reconstruction of the entire 170,000 ha of the Tarcutta Creek catchment since 1949 represents the largest areal land-use reconstruction in Australia at 1 ha resolution. Reconstruction since 1949 was based on aerial photography, satellite imagery and a sequence of maps and spatial layers that provided information on advancement of pine plantation. The historic overview of the land-use changes since the 1830s was based on an extensive literature search, archived information and interviews with farmers. Based on this reconstruction, it was evident that the nineteenth century was dominated by tree clearing that accompanied European settlement, while the twentieth century saw the extensive development of the tree plantation industries, especially *Pinus* species.

The versatility of the CATPlus model was demonstrated by the ease with which it was expanded to address the erosion impacts from the flooding. Study of flows in Tarcutta Creek showed that the amount of water generated in the lower parts of the catchment, where clearing was most pronounced, increased the most. This increase caused the energy of the water to also increase, and this stimulated erosion. These modelling results, together with an explanation of erosion processes, were presented at an erosion workshop in September 2012 held for the Kyeamba and Oberne–Tarcutta Landcare groups by Murrumbidgee Landcare. The presentation bore testimony to the ability of the CATPlus model and the modelling team to adapt to the needs of stakeholders. Teaming up with Dr Ken Page, the local expert in stream morphology from the Charles Sturt University, contributed to building productive networks and links with universities, and enlarging organisational capacity.

The evaluation survey from the workshops showed that 80% of respondents intended to undertake action to reduce erosion in the catchment within three months, 10% within a year and the remaining 10% within more than 12 months. As increasing perenniality was the suggested measure for this action, the anticipated rate of adoption of EverGraze principles can be considered extremely successful. The PowerPoint presentation from the workshop remains available for the landholders through the Murrumbidgee Landcare site and a short article followed in their newsletter.

1 Catchment characteristics

1.1 Location and boundary

The Tarcutta Creek catchment area is 1700 km^2 (170,000 ha). The catchment is located in southern NSW and is part of the Murrumbidgee catchment. Its north-west corner is approximately 30 km east of Wagga Wagga.

The Hume Highway is the main route between Sydney and Melbourne. It passes through the Tarcutta Creek catchment (Figure 1). It follows the boundary between the flatter landscape in the north-west and the hillier uplands, which have a lower proportion of arable land.

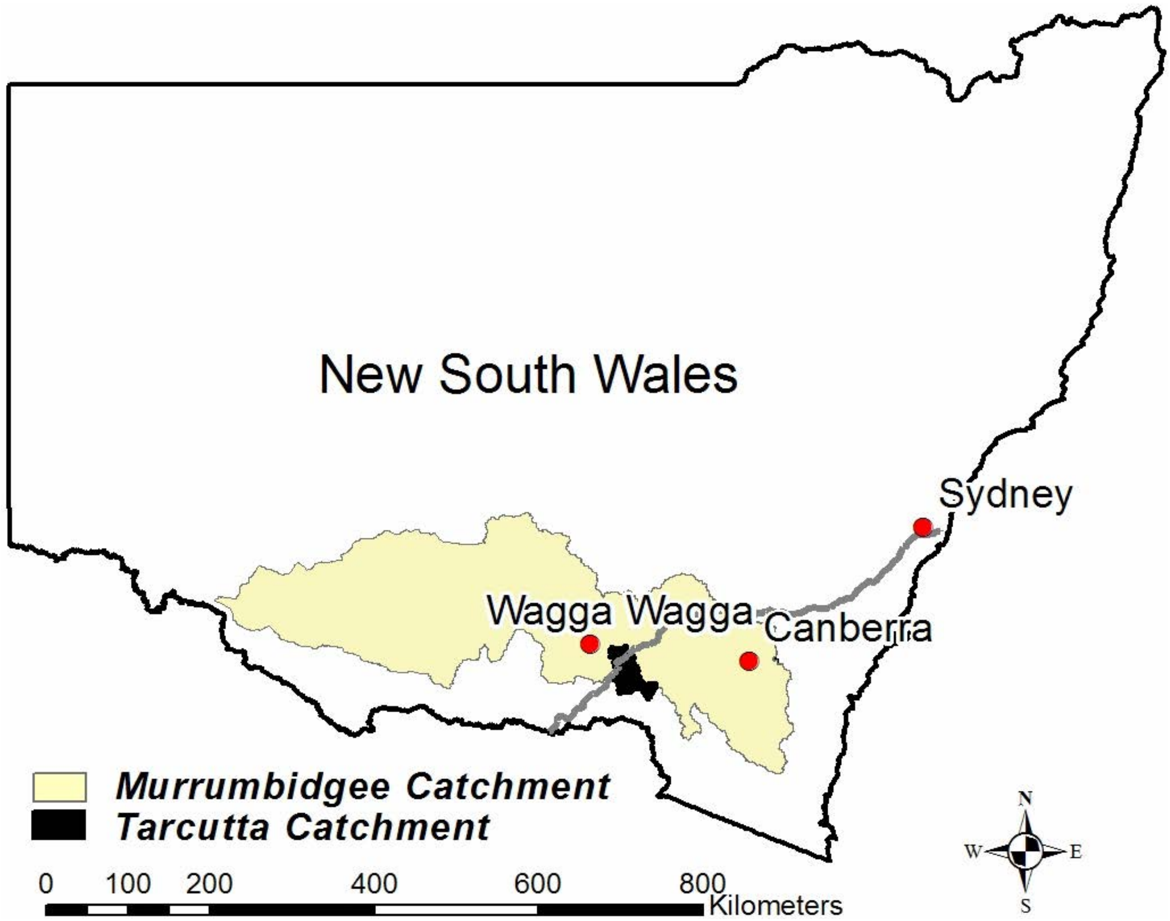


Figure 1: Location of the Tarcutta Creek catchment in NSW

1.2 Geology

The Tarcutta Creek catchment is overlayed by Palaeozoic fractured rock of the Lachlan Fold Belt. The majority of catchment is in metasediments, as shown in green in Figure 2. These sediments were deposited during the Ordovician under marine conditions, and later subjected to various tectonic events that caused uplift, folding, faulting and metamorphosis (Degeling 1980). Magma intruded during the Silurian and cooled to form granitic batholiths, visible in the highlands (brown shading). The largest batholith dominates Tarcutta Creek headwaters a few kilometres above Westbrook. Tarcutta Creek crosses a smaller batholith outcrop further down, between Westbrook and Oberne. Some granitic outcrops exist in the western part of the catchment, bordering Kyeamba valley, in the Keajura and Murraguldrie creeks headwaters. There are no Mesozoic rocks.

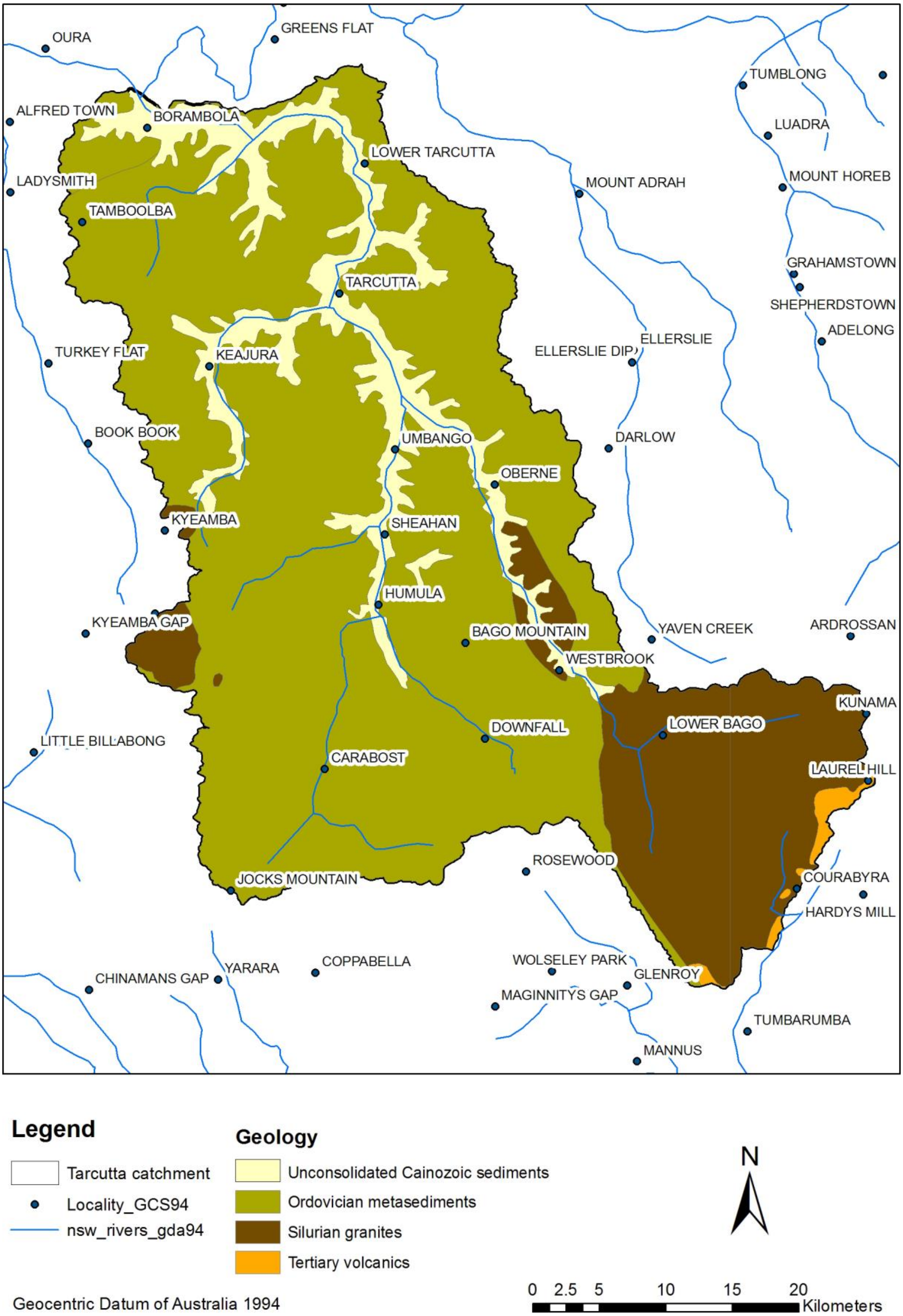


Figure 2: Geology of the Tarcutta Creek catchment

Volcanos erupted in the Cainozoic (during the Tertiary), solidifying as basalt and forming the south-east margin of the large batholith (orange shading).

In the stream valleys there are unconsolidated sediments that were weathered, transported and deposited during the Cainozoic (pale yellow shading). Deeper, older alluvial sediments (Tertiary Lachlan Formation, from two to 12 million years old) are coarser, allowing groundwater to flow faster than through the overlying deposits (Quaternary Cowra Formation, from one to two million years old). Water quality of the deeper, confined layer is better (less saline) than of the surface layer.

A major fault-line runs in the SSE–NNW direction along the western edge of the southern batholith, forming a straight catchment boundary, towards Humula. Investigations in Wagga Wagga, 30 km west of the Tarcutta Creek catchment showed similar primary fracture orientation: average bedding strike 330–340° at two out of three investigated sites (Cook et al. 2001). Lineaments observed in airborne magnetic survey data of neighbouring Kyeamba Creek catchment indicate NE trending dykes and faults, which were found to be responsible for offsets in the creek's general NNW trend (Cresswell et al. 2003). Similar offset can be observed in the sharp, ~90° change in direction of Keajura Creek and Tarcutta Creek near Tarcutta village.

1.3 Salinity and waterlogging

Work by Summerell et al. (2004) on Fuzzy Landscape Analysis GIS (FLAG), which uses soil wetness as an indicator of salinity, reveals relatively small lowland areas of Tarcutta to be prone to salinity. A more detailed overview and analysis of salinity and waterlogging in the Tarcutta Creek catchment can be found in Tuckson (1995a, 1995b) and Rutherford (2007). Tuckson (1995b) analysed the catchment area upstream of Tarcutta township. He reports small saline discharge areas in about a quarter of the small sub-catchments of the undulating country (slopes typically 2–10%, max. 20% and relief typically <20 m, max. 40 m), with a significant concentration in the tributaries of lower Umbango Creek. He reports some salinisation pre-dating 1940 as being stable, while the new scalds were still expanding in 1995.

2 Overview of the modelling approach

The CATPlus model is an extension of the Catchment Analysis Tool (CAT) developed by the Department of Primary Industries Victoria (DPI-Vic) and the former Cooperative Research Centre for Plant-based Management of Dryland Salinity (CRC Salinity) (Future Farm Industries CRC 2011). The model enables enhanced prediction of catchment water yield to stream. It uses a range of farming system and forest growth models to determine catchment water use, recharge and quick flow. It is combined with CATNode, a nodal model, designed to predict catchment scale stream flow. In the early 2000s DPI-Vic and the CRC Salinity provided funding for model development (Weeks et al. 2008). The model initially predicted the impacts of various land-use scenarios on dryland salinity. Since the early 2000s, CAT has included additional modules that address other aspects of landscape processes. This empowered CAT to simulate a broader range of land management questions than originally intended.

CAT links paddock-scale land use, climate, soils and topography to catchment-scale groundwater systems and stream flows on a daily time-scale. A suite of crop growth and farm management models allows evaluation of the impacts of various types of land use, land cover, and management strategies on surface hydrology and landscape system dynamics. Model outputs can be produced for a range of temporal and spatial scales. After the model is calibrated for a given area, it is used to evaluate the impacts of land-use change scenarios.

Tarcutta Creek catchment modelling tests the hydrologic effects of potential land-use changes. Changes in the arable land are tested using EverGraze principles derived from the Wagga Wagga proof site and for non-arable land from Albury/Wodonga proof site (www.evergraze.com.au). Modelling efforts focused on a maximised simulation period (>112 years, Jan 1900 – Mar 2012) and calibration period (1937–2012), to encompass as much climatic variability as possible, to provide reliable calibration and a wide temporal base for testing of modelling scenarios. To do so, the comprehensive and detailed reconstruction of land use was undertaken to reflect clearing history and the timing of pine plantation advancement within the catchment. In addition to surface water data, groundwater hydrographs were used for integrated calibration of catchment water balance.

3 Data

The CATPlus model requires input of spatial, temporal and spatial-temporal information.

The spatial layers are represented as raster-gridded surfaces. In the Tarcutta Creek catchment the cell size is 100 m, with an area of 1 ha. Spatial layers consist of:

- topography (DEM model) used to derive slopes
- mean annual rainfall and temperature
- distribution of climate stations with corresponding Thiesen polygons
- soil types with corresponding parameters
- geology with hydro-geologic parameters
- current land use
- location of monitoring bores and stream gauges, used for model calibration.

Temporal information, with the daily time-step is comprised of:

- climate data: rainfall, evaporation, solar radiation
- stream and groundwater hydrographs, used for model calibration.

The spatial-temporal layer of historic land use, used for model calibration, has been created with decadal frequency.

3.1 Groundwater monitoring program

The groundwater monitoring program was successful and captured the important transition from the extreme of the Millennium drought to the record-breaking floods in 2010–2012. The program was initiated in October 2009 and finalised in October 2013. Newly acquired information from the field, coupled with the data from the Groundwater Database System (GDS), published reports and invaluable landowners' original records, provide the most comprehensive dataset in NSW and Eastern Australia. Over time, the bore and piezometer network was expanded to >60 observation points (Figure 3).

The Big Dry from 2000–2009 caused falling watertables throughout the catchment, due to reduced recharge. Levels fell more in fractured rock than in alluvial groundwater systems. High rainfall due to La Niña conditions in 2010–2012 caused a watertable rise of around 5 m (2–9 m). Watertable rise is much faster than watertable fall. The bores in discharge areas which dried out during the Big Dry were still flowing in October 2013. The bores west of the Sydney–Melbourne highway had a deeper watertable before 1990, and a much deeper watertable before 1950, than over the past two decades. The watertable of bores sunk in fractured rock across Borambola in the 1960s rose and peaked in the early 1990s, then receded back to its1960s level by early 2010, partially recovering since. In Keajura the rise of the watertable until 1990 was dramatic, its fall up to 2010 modest and recovery fast (Figure 4). The smallest variations in watertable are present in the mid Tarcutta Creek catchment and Tarcutta Creek alluvial. The watertable in the Downfall area has fallen 8.5 m since 1985 and recovered only 2.25 m.

Figure 3: Tarcutta Creek catchment groundwater monitoring network

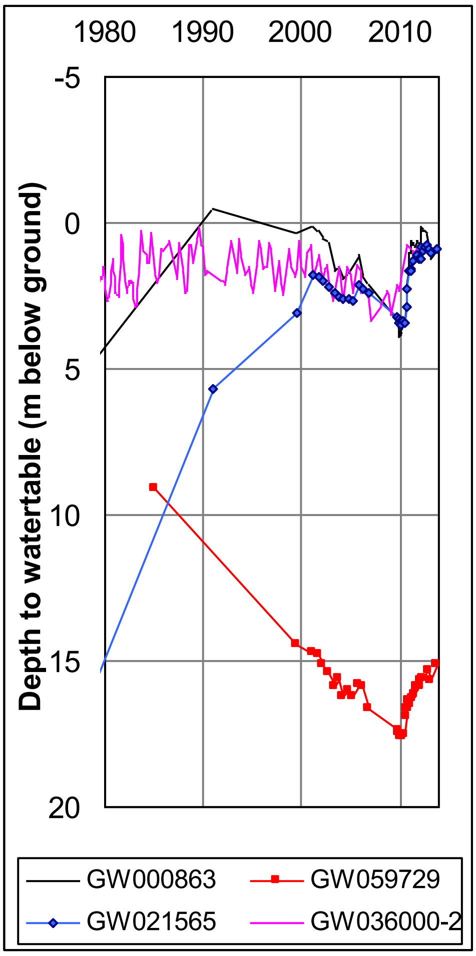


Figure 4: Watertable trends in Tarcutta: (a) rising (Keajura, GW021565): (b) falling (pine plantation areas, GW059729); and (c) stable (mid Tarcutta GW000863 and Tarcutta alluvial GW036000-2)

Early bore records (1920–1950) are available for the Tarcutta Creek catchment downstream of the Sydney–Melbourne highway (Figure 5). They clearly show the groundwater levels to be positioned below the stream beds (5–10 metres deep) in these flat areas, and therefore (a) the groundwater systems were not discharging locally and consequently, during first half of twentieth century (b) streams in proximity of these bores were losing water to groundwater below, instead of gaining the baseflow. This important finding should be taken in consideration in conceptualisation and modelling of groundwater systems.

The information presented above is from the A0 poster, *Groundwater Levels in the Tarcutta Creek catchment*, which presents the historic bore data and the results of the four years of frequent monitoring. It will be submitted to the appropriate groundwater conference.

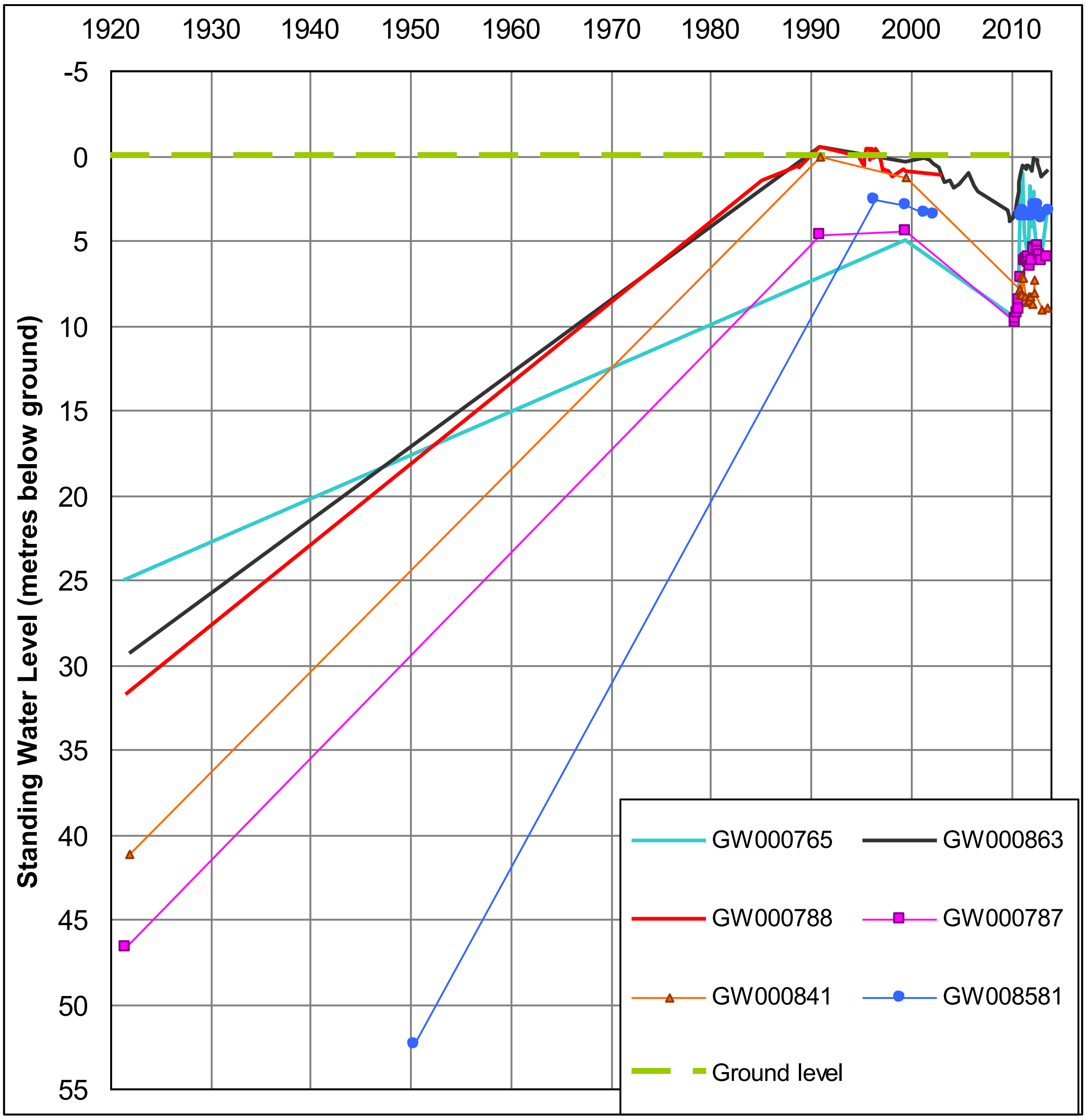


Figure 5: Early bore records showing watertables below stream beds

4 Adjustment of ANUCLIM rainfall surfaces

The CATPlus model introduced the adjustment of ANUCLIM[1] rainfall surfaces to match the values of rainfall records at the point of sampling. Two options for adjustment were investigated: one based on monthly average, and one on annual average.

Adjustment of the rainfall surface for the Tarcutta Creek catchment was done for each month. The average over the 1975–2005 period was calculated for every rainfall station (rs) and for each month (m): AV(rs, m). This was compared with the values of ANUCLIM monthly surfaces derived for the 1975–2005 period at the point of location of each rainfall station: ANUav(rs,m). The array of coefficients was derived for each month as the ratio of

[1] ANUCLIM is a software package that enables users to obtain estimates, in point and grid form, of monthly, seasonal and annual mean climate variables from supplied climate surfaces (ANU 2013).

these averages: RATIO(m)=AV(rs,m)/ANUav(rs,m) and the ANUCLIM surfaces were adjusted in the proximity of each station used in the model by using this ratio. This substantially improved the model performance, raising R2 from <0.6 to >0.8. The option of using a simpler model with only a single, annual adjustment has been tested on some Victorian catchments with good outcomes and it was concluded that the principle of parsimony should to be adopted. The monthly adjustment model was therefore removed.

For the Tarcutta Creek catchment this simpler model reduced the overall model performance, bringing R2 down to (0.7–0.75). In some catchments, where seasonality and large rainfall gradients are important hydrologic drivers, monthly, rather then annual rainfall adjustment could provide better modelling. Unlike most of the Victorian catchments modelled, which have less pronounced relief and rainfall gradients, Tarcutta is a very hilly catchment where spatial interpolation smooths rainfall gradients close to ridges, lifting the entire rainfall surface and simulating conditions wetter than in reality. It is likely that this smoothing is more pronounced during the wetter part of the season, distorting the seasonal variability. It is therefore recommended that the monthly adjustment option be reinstated and both options be allowed in the model.

5 Calibration

Groundwater hydrographs were successfully reproduced in the model, by calibrating parameter Alpha. Alpha represents the number of months needed for the hillslope storage to reduce its volume to half (decay coefficient). Values of Alpha, obtained by calibration of groundwater hydrographs, range between 10 and 50 months; however, to reproduce the baseflow component of the stream trace, the value of Alpha needs to be close to one month or less (Table 1). This in effect keeps the hillslope reservoir very depleted by allowing rapid transfer of incoming fluxes to the alluvial aquifer and stream. Therefore groundwater levels and the fluxes to the stream could not be reproduced simultaneously.

Table 1: Calibration parameters

Zone	410095	410058	410047
Alpha	0.1	0.90293	1
Lambda	0.5	0.33339	1
Delta	0.1	1.2027	0.74149
Evap_d	0.5	48.9401	11.1001
AS_d	19.9943	3.3907	6.0249

Table 2: Calibration statistics

Zone	410095	410058	410047
R2	0.726	0.824	0.805
Volume ratio, observed:simulated	0.988	1.005	0.988

5.1 Groundwater hydrographs

The example below demonstrates the ability of the CATPlus model to reproduce groundwater hydrographs. Bore GW050335 was destroyed when the area was planted to pines, so its measurements could not continue. It was situated within the Humula catchment, close to the catchment boundary, in the recharge area, and it was drilled into the metasedimentary rock. Bore GW503467 was discovered in the adjacent catchment, less than 2 km away (Figure 3), so its monitoring was started to supplement the information available from GW050335. As seen in Figure 6, the model reproduced well: (1) a couple of isolated measurements in the 1980s, (2) the level to which the groundwater receded during the Big Dry, and (3) the hydrograph recovery following the 2010 La Nina event.

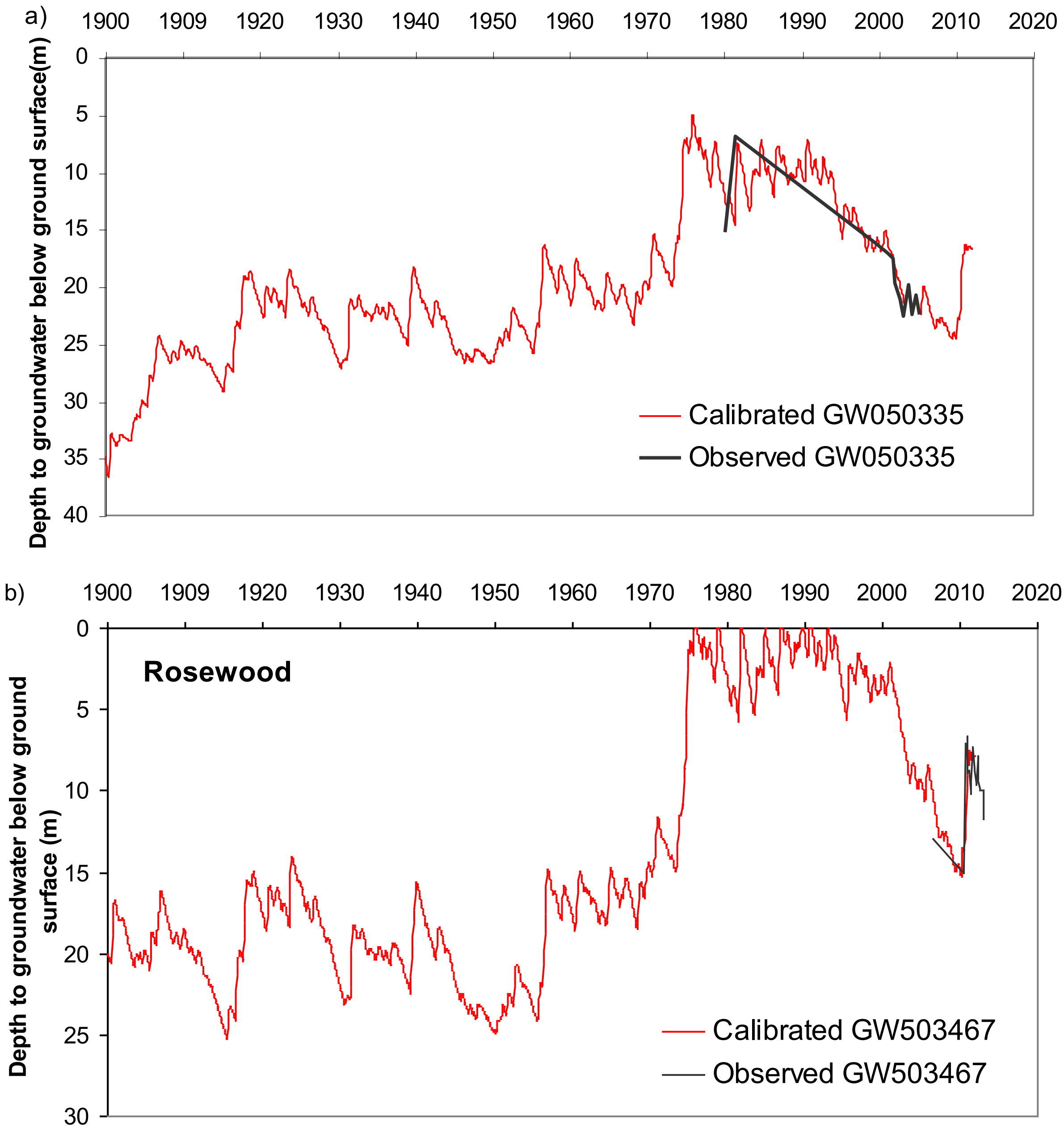


Figure 6: Calibration of two hydrographs north-west of Rosewood – fractured rock groundwater system

5.2 Flows

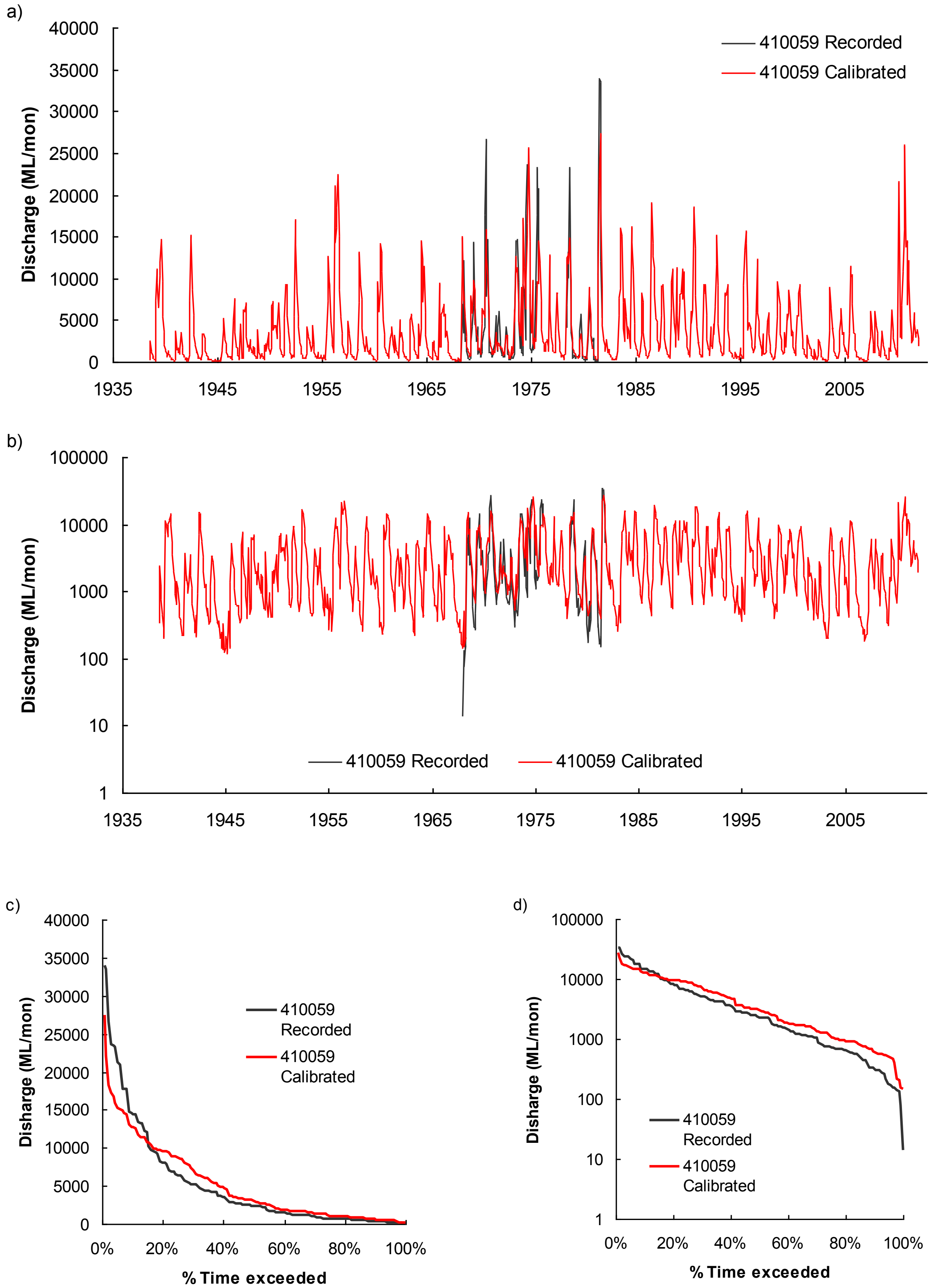


Figure 7: Humula gauge 410059: Monthly time series a) and b), and ranked curves c) and d) in normal and log-normal scale, respectively

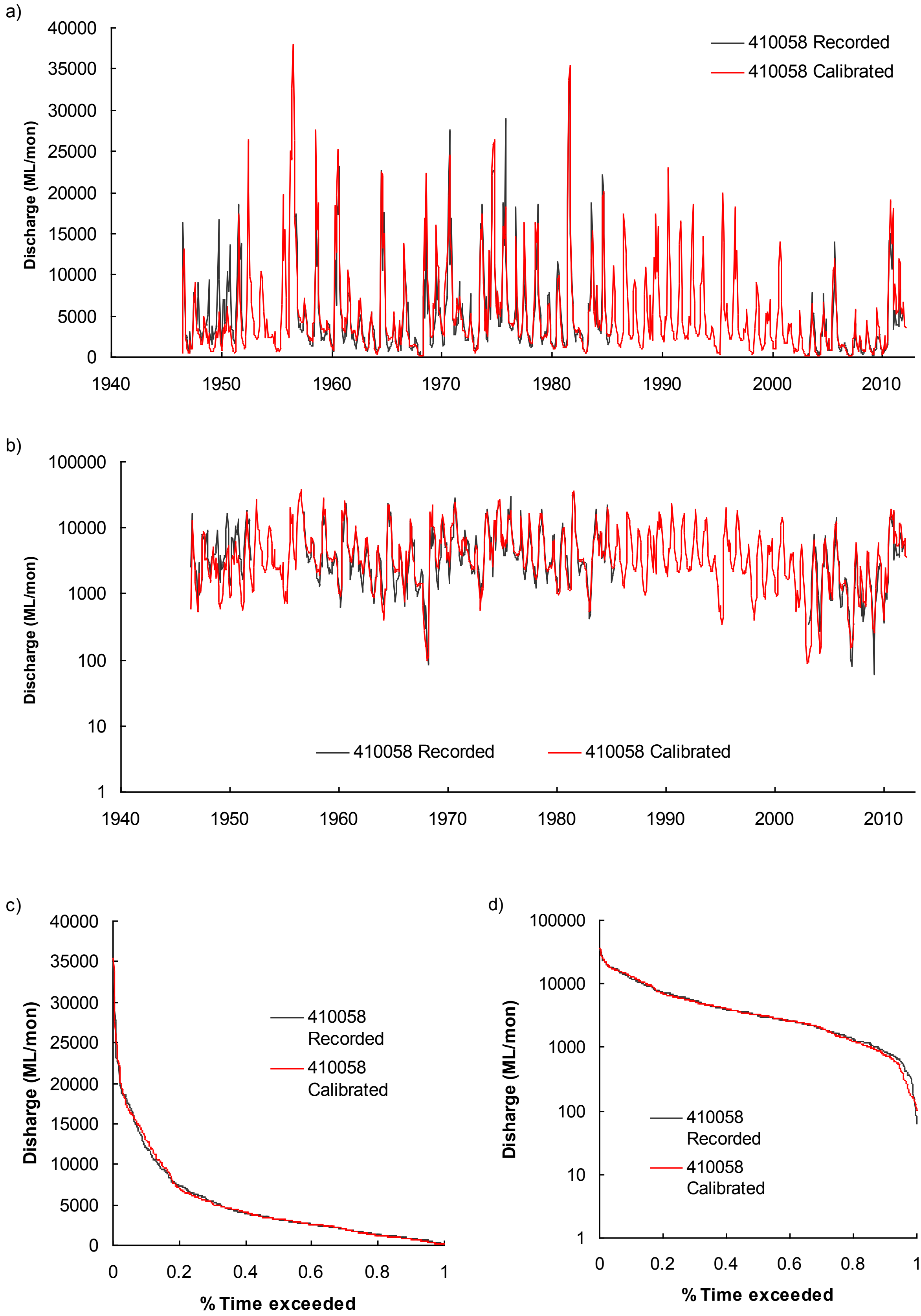


Figure 8: Westbrook gauge 410058: Monthly time series a) and b), and ranked curves c) and d) in normal and log-normal scale, respectively

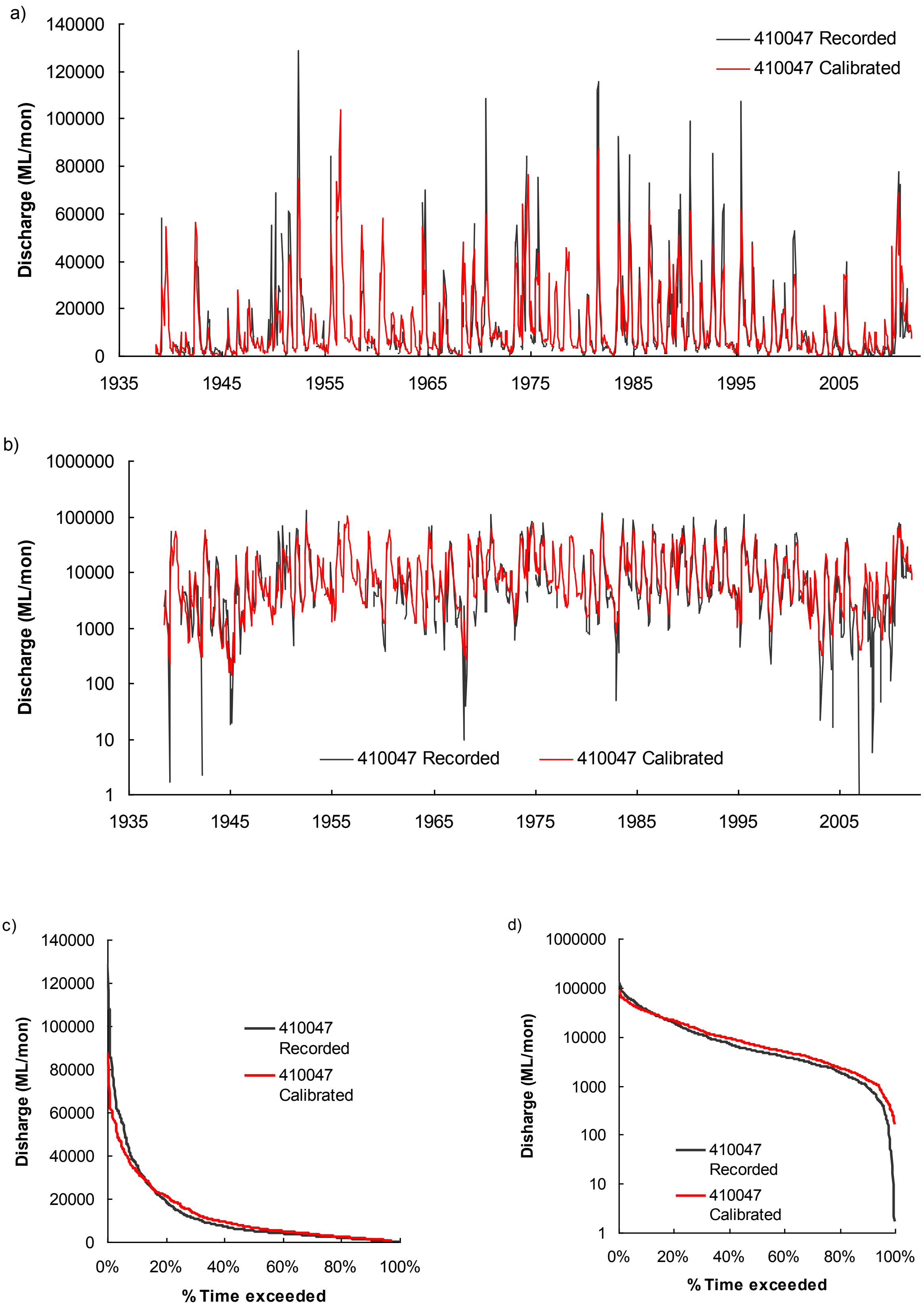


Figure 9: Borambola Gauge 410047: Monthly time series a) and b), and ranked curves c) and d) in normal and log-normal scale, respectively

5.3 Suggested improvements

To be able to reproduce these fluxes simultaneously, alluvial storage should be allowed to discharge with the faster rate, independent of the incoming flux from the hillslope storage. This is the most important modification required for the model to become a fully integrated hydrologic model, capable of accurately and simultaneously reproducing surface and subsurface hydrologic processes.

CATPlus differs from some hydrologic models which use a decay coefficient function for modelling of groundwater. While the bottom of the conceptual groundwater reservoir in these hydrologic models is fixed and static, the bottom of the hillslope reservoir in the CATPlus model varies over time, because it is linked to the top of the alluvial reservoir. This might pose a conceptual problem, and could be investigated by fixing the bottom of the hillslope and alluvial reservoirs to the level defined by the stream bed.

Finally, the model might also benefit from the lower boundary condition of the alluvial aquifer being linked to the stream height, via a rating curve, rather than to the stream bed.

The model successfully reproduced unsaturated subsurface hydrology when tested by comparison with the soil moisture data collected at the EverGraze site near Borambola, measured by neutron probes and integrated over the top 1.5 m of the soil profile. Three plots were planted with annual pasture and another three with lucerne. Readings were taken between 6 August 2007 and 19 April 2010. Neutron probe readings were taken 33 times over 3.7 years. Data were obtained courtesy of DPI NSW.

6 Validation of unsaturated subsurface hydrology

CATPlus model performance in the domain of unsaturated subsoil hydrology was assessed based on observed soil water data measured for lucerne and annual pastures on duplex soils.

6.1 Location

EverGraze site near Borambola on David Sackett's property;

Coordinates: (-35.187506 °S, 147.645800 °E); Slope: 10%

Figure 10: EverGraze site location in the Tarcutta Creek catchment

6.2 Methods

Soil water data were integrated over the top 1.5 m of the soil profile.

Methods employed for evaluation of model performance were:

- computation of median and mean soil water time series
- computation of mean and standard deviation for each of the time series
- correlation between experimental and modelled time series and correlation of change in soil water between two consecutive measurements
- comparison of experimental and modelled time series, and
- comparison of basic statistics: mean, standard deviation, and correlation for experimental and modelled time series.

The CATPlus Tarcutta model was extended until March 2012. Daily data time series and time series of data corresponding to the periods of experimental observations were derived.

6.3 Data

The observed data consist of six time series of soil water data, measured by neutron probes and integrated over the top 1.5 m of the soil profile. Three plots were planted with annual pasture and another three with lucerne. Readings were taken between 6 August 2007 and 19 April 2010. Neutron probe readings were taken 33 times over 3.7 years.

6.4 Results, discussion and conclusions

The model reproduced well the base level of soil moisture for both crops, as the simulated soil moisture mean is positioned within the range of observed data. However, the standard deviation of simulated data is lower than the standard deviation of the recorded time series (Table 3).

Table 3: Mean and standard deviation of the observed and simulated data

Soil water. Sample size n=33					
Annual pasture	**Mean**	**Standard deviation**	**Lucerne**	**Mean**	**Standard deviation**
	(mm)	**(mm)**		**(mm)**	**(mm)**
Plot 1	125	44	Plot 2	249	44
Plot 7	270	33	Plot 4	105	29
Plot 10	231	35	Plot 9	185	32
Median	230	34	Median	185	32
Mean	209	36	Mean	180	35
Simulated	237	29	Simulated	163	23

Table 4: Correlation coefficient (R) between modelled and experimental soil water data: (a) of actual soil water time series (Series) and (b) of changes in soil water between two consecutive readings (Differences)

Soil water. Sample size: n = 33 for series; n = 32 for differences					
Annual Pasture	**Series**	**Differences**	**Lucerne**	**Series**	**Differences**
Plot 1	0.65	0.78	Plot 2	0.74	0.85
Plot 7	0.45	0.66	Plot 4	0.60	0.80
Plot 10	0.75	0.78	Plot 9	0.77	0.82
Median	0.72	0.76	Median	0.77	0.82
Mean	0.65	0.77	Mean	0.72	0.85

The model predicts slightly dryer initial soil moisture conditions (in 2007) and a stronger reaction to the event in early 2008 (Figure 12 and Figure 15). The drier initial soil moisture of the modelled profile could be the consequence of the modelled crops being better established and having higher LAI than the crops at the EverGraze site, or due to the local rainfall anomalies. The stronger modelled reaction to the 2008 event is due to the local rainfall anomalies.

The model predicts correctly the base level of the soil water, but with somewhat lower amplitudes than the recorded data. Time series graphs (Figure 11, Figure 12, Figure 14 and Figure 15) also illustrate that the variation of experimental data exceeds the variation of simulated data for both crops.

Simulated data plot very close to the median time series of experimental data (Figure 12 and Figure 15). Modelled soil water changes between consecutive readings correlate well with the corresponding changes captured by the experimental data, with R between 0.66 and 0.85 (Table 2). Correlation between actual series varies between 0.45 and 0.77. Correlation of soil water under lucerne is slightly stronger than under annual pastures. Correlation is strongest with the plots that exhibit median soil water for annual pasture: Plot 10, R=(0.75, 0.78). For lucerne, direct correlation with Plot 9 is the highest (R= 0.77), but changes between two readings correlate best with Plot 2 (R=0.85). Simulated time series for lucerne are fully contained within envelopes of recorded data, within one standard deviation from the mean and one standard deviation from the median. Simulated series for annual pasture exceed the sum of the mean and one standard deviation on 12 March 2008, and the envelopes during the preceding sampling (13 February 2008), following sampling (20 May 2008), and on 16 September 2008. Soil moisture is reproduced better under lucerne than under annual pasture.

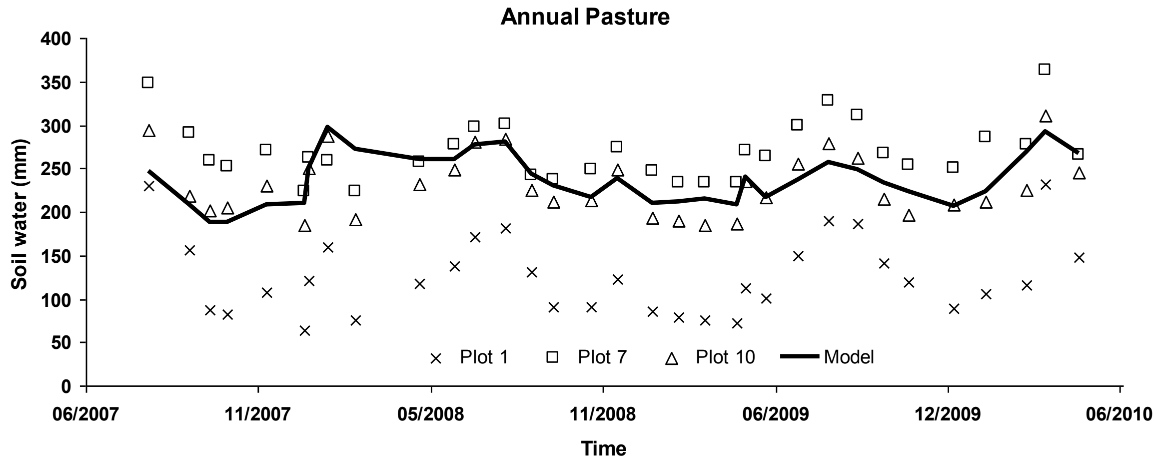


Figure 11: Soil water under annual pasture measured in three plots (1, 7 & 10) up to 150 cm depth, compared to corresponding values simulated by the CATPlus model

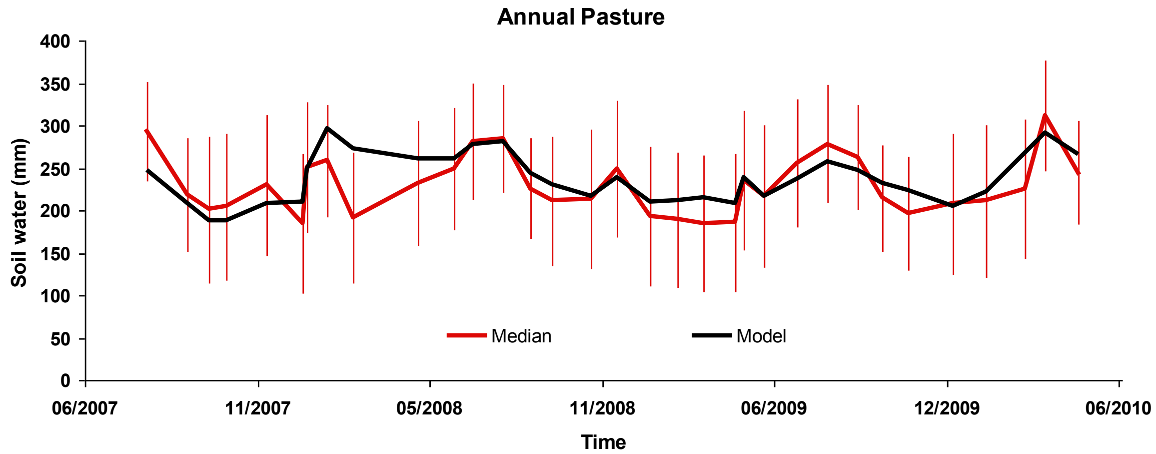


Figure 12: Median values of measured soil water under annual pasture up to 150 cm depth at sampling intervals, with error bars equal to one standard deviation, compared to corresponding values simulated by the CATPlus model for the period of observation

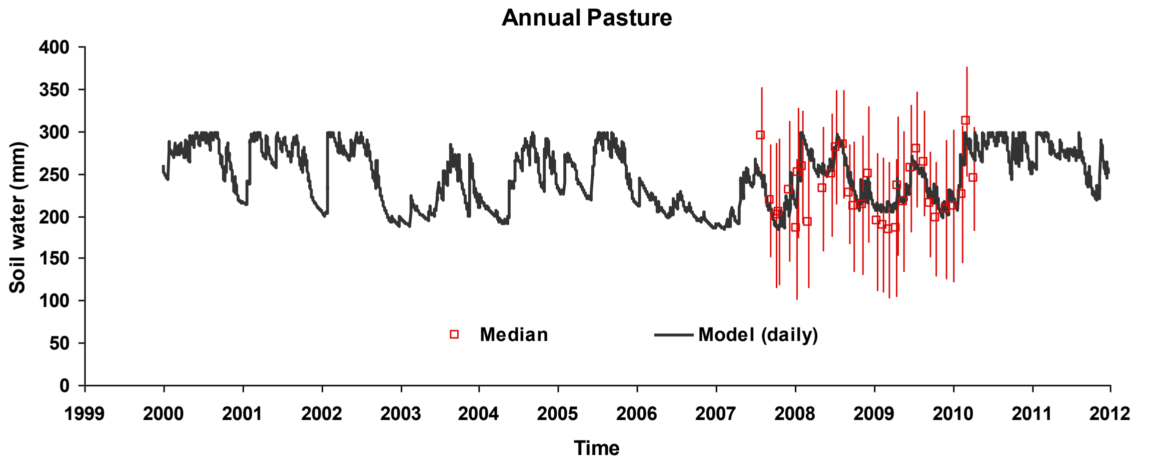


Figure 13: Median values of measured soil water under annual pasture up to 150 cm depth at sampling intervals, with error bars equal to one standard deviation, compared to daily values simulated by the CATPlus model 2000–2011

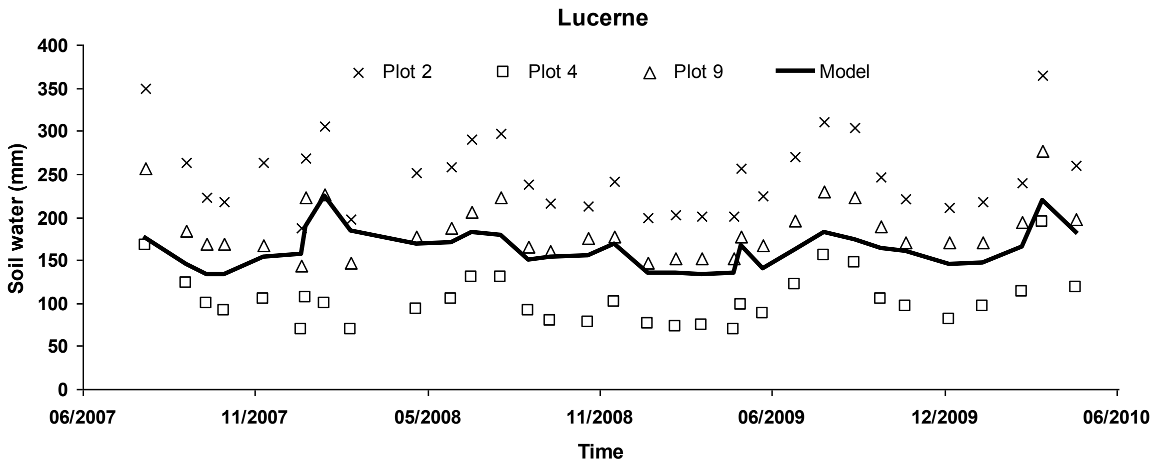


Figure 14: Soil water under lucerne in three plots (2, 4 & 9) up to 150 cm depth, compared to corresponding values simulated by the CATPlus model

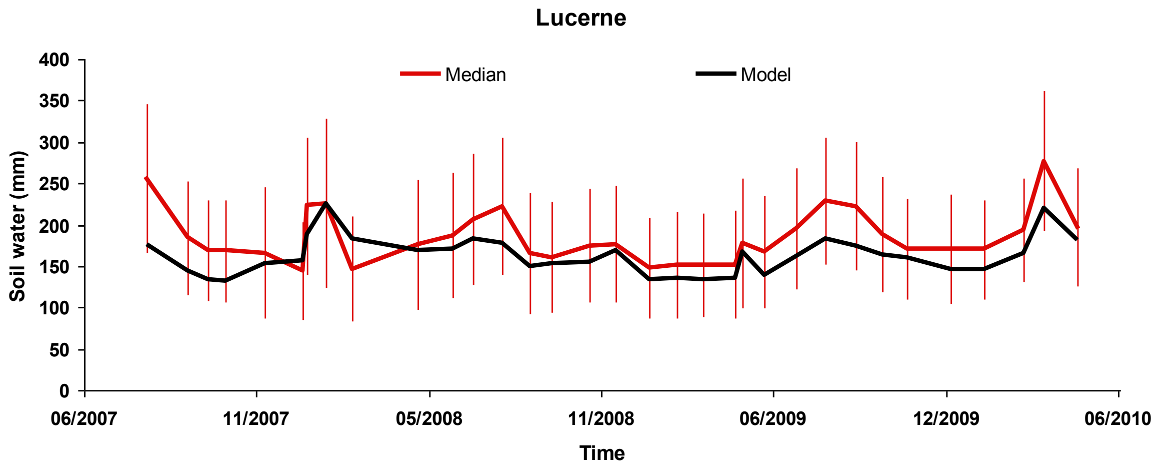


Figure 15: Median values of measured soil water under lucerne up to 150 cm depth at sampling intervals, with error bars equal to one standard deviation, compared to corresponding values simulated by the CATPlus model for period of observation

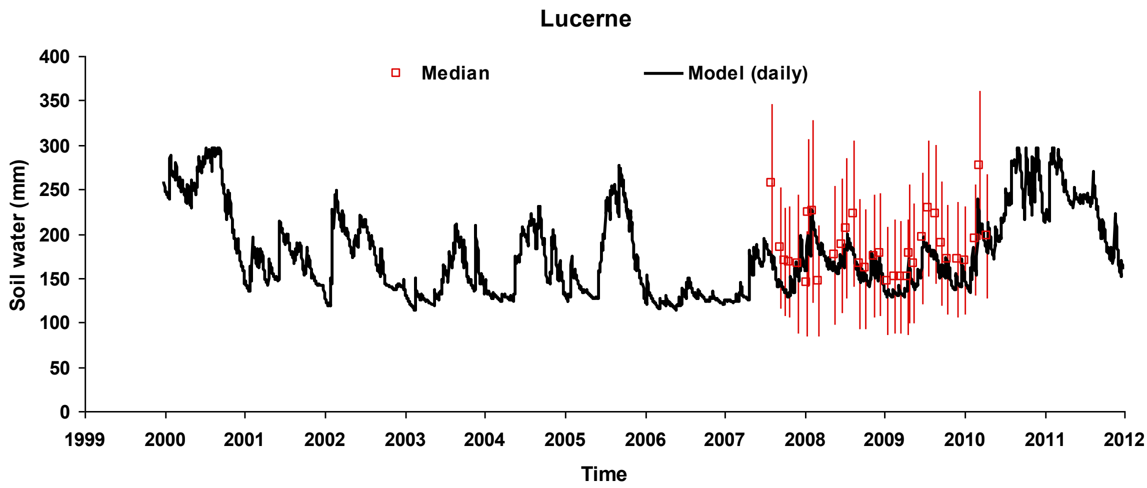


Figure 16: Median values of measured soil water under lucerne up to 150 cm depth at sampling intervals, with error bars equal to one standard deviation, compared to daily values simulated by the CATPlus model 2000–2011

It is most unfortunate that the period of observation ended on 19 April 2010, just when increased rainfall caused by La Niña started wetting the soil profile during the March event, so that the valuable change from very dry to extremely wet conditions were not captured by neutron probe data. The model simulation shows (Figure 13 and Figure 16) that the climatic conditions in 2006 and early 2007 created the driest profile during the Big Dry decade, so even the dry extreme is not captured by the experimental data, which start in August 2007.

The model performance is very good. The CATPlus model reproduces the soil water profile under lucerne better than under annual pasture. Simulated data plot very close to the median time series of experimental data and correlate well, with the correlation coefficient of changes between consecutive readings reaching 0.82 for lucerne and 0.76 for annual pasture.

7 History of land use

Rainfall is the first order driver of the hydrologic regime. The improvement expected from land-use reconstruction was diluted due to model performance being lowered by simplified rainfall transformation. However, the land-use reconstruction of the entire 170,000 ha of the Tarcutta Creek catchment since 1949 represents the largest aerial land-use reconstruction in Australia at 1 ha resolution. Reconstruction since 1949 was based on aerial photography, satellite imagery and a sequence of maps and spatial layers that provided information on advancement of pine plantation. The historic overview of the land-use changes since the 1830s was based on an extensive literature search, archived information and interviews with farmers. Based on this reconstruction, it was evident that the nineteenth century was dominated by tree clearing that accompanied European settlement, while the twentieth century saw the extensive development of the tree plantation industries, especially *Pinus* species.

7.1 Data sources

To create a dynamic land-use layer for the hydrologic modelling of the Tarcutta Creek catchment, eight sources of information were explored: historic documents, information from the Australian Bureau of Statistics (ABS), an archive search, interviews with the farmers, 1976 and 1983 printed forestry maps, 2005 and 2009 GIS-based forestry maps, aerial photographs since 1949, and satellite imagery. The availability of aerial photography since 1949 allowed the detailed land-use reconstruction needed for hydrologic modelling. Although the extensive review of historic documents, archived material and interviews with the local landowners lacked the fine-scale spatial resolution needed for the modelling, it provided a valuable insight into the dynamics of changes in the catchment since it was settled in the 1830s.

Data compiled from the ABS were: *Historical Selected Agriculture Commodities, by State (1861 to present)* (7124.0), *Agricultural Commodities, Australia, 2010–11* (7121.0), *Australian Historical Population Statistics, 2008* (3105.0.65.001), *Australian Demographic Statistics, June 2011* (3101.0) and *State and Regional Indicators, December 2010* (1338.1).

The ABS information was combined with sheep number values for NSW from Wadham and Wood (1950), to reconstruct historic graphs of a) sheep numbers, b) area under wheat, oats and barley cereal crops, and c) population of NSW since 1840.

An archive search was conducted in Wagga Wagga Archives in conjunction with the NSW archive website to produce a spatial layer of WWI soldier settlement properties, the lots for which were bought from large properties by the Australian Government and made available to returned soldiers under favourable conditions.

The historic written records with parcel numbers and time of purchase for each individual WWI soldier settlement block were extracted from the archives. Parcel numbers were located on the corresponding map from the archives, to identify the position of the parcel. This location was marked on the cadastral map and the time of purchase was recorded. This information was then imported into the spatial GIS cadastral layer to produce the map of WWI soldier settlement blocks.

Landholders with a long history of farming in the Tarcutta Creek catchment were targeted to provide an insight into historic changes in land use on their properties. Eleven landholders were interviewed. The landholders provided information on the time-line of ringbarking, clearing, and succession of crops and stock on their properties, and often volunteered anecdotal information diverging from this scope. The complete interviews are reported in Rančić et al. (2011).

Four forestry maps, courtesy of Duncan Watt (Forests NSW, DPI, Tumut), were used to reconstruct pine plantation advancement: the 1976 and 1983 maps, colour print A0 format, and 2005 and 2009 electronic maps.

The printed maps contained information on the last year of planting, revealing the beginning of pine plantations in Murraguldrie and Carabost in the early 1920s. Both maps were scanned, rectified, imported into the spatial GIS map, and information on the year of planting for each parcel was incorporated.

The electronic maps were supplied as shapefiles. Information from all four maps has been embedded in a single shapefile, from which the history of pine progression has been traced. The maps covered all of the State forest plantations and most, but not all of the private pine plantations.

The earliest aerial photography that covers most of the Tarcutta Creek catchment region dates back to 1949–50: Sheets no. I55-I5-754 (Tarcutta) and I55-I5-764 (Rosewood). The catchment was photographed from the air and satellites on an approximately decadal basis: in 1959–61, 1969–72, 1980, 1989, 2000, 2004 and 2010. Mosaics compiled from aerial photographs were available for parts of the catchment from around 1960 and 1970. Where mosaics were available these were used instead of individual photographs. The photographs and mosaics were scanned, imported into the GIS layer and rectified. The aerial photographs and mosaics were sourced from OEH and purchased from the National Library of Australia (Canberra office) and from United Photo and Graphic Services, Melbourne. The rectified satellite imagery was sourced from the OEH office.

The images were overlayed with the 1 ha grid cells corresponding to raster elements of the CATPlus model. Each grid cell was classified into seven categories:

1. Roads and urban
2. Water bodies
3. Orchards
4. Pines
5. Trees = tree cover >50%
6. 35% trees 65% cleared = tree cover 20–50%
7. Cleared = tree cover <20%.

7.2 Early history

The early history of the Tarcutta Creek catchment and its settlement is described in Bradley (1979), Docker (2005), Freeman (1985), Martin (1985), Mitchell (1839), Belling & Belling (1984), Morris (1999) and White (1997). These sources contain information on the early settlement from the 1830s onwards and maps indicating locations of properties: Borambola (Morris 1999); Umutbee and Tonga: Mate's properties and birth of Tarcutta township (Docker 2005); Eastern portion of Kyeamba run in Tarcutta Creek catchment (White 1997); American Yards, which was to become Humula (Bradley 1979); two properties in the Oberne (Docker 2005); Carabost (Docker 2005, Martin 1985); Bago (Martin 1985) and Coorabyra (Martin 1985). The original vegetation was open eucalypt woodland composed principally of red gum, grey box and ironbark with a kangaroo grass understory (Mitchell 1839, Docker 2005, Priday & Mulvaney 2005). Nancarrow et al. (2001), provide a summary of Stelling (1998), dividing Tarcutta into four botanical regions: Lower Tarcutta and Mate's Gully; Oberne–Mid Tarcutta; Murraguldrie and Umbango; and Upper Tarcutta/Carabost.

The early settlers described the streams as being like 'chains-of-ponds'. The chain-of-ponds streams had elevated watertables, and prolonged baseflow existed in the 1830s (Mitchell 1839, Eyles 1977, Page & Garden 1998, Docker 2005, Wilson et al. 2005). With increasing development, the catchment was progressively cleared, starting with the riparian vegetation in valleys and lower slopes (Page & Garden 1998), which was replaced with introduced grasses (clover, prairie, lucerne and rye), other European plants (apples, walnuts, plums, cherries, pears, apricots, peaches, grapes and willows), and crops (Benson 1991, Robertson et al. 1993, Outhet & Faulks 1995, Hardwick 1998, Page & Garden 1998, Docker 2005). Stocking rates progressively increased (Docker 2005), followed by morphologic changes of the streams: erosion, and incised channels (Smith et al. 1996, Page & Garden 1998, Docker 2005), as well as hydrologic changes: a decrease in concentration time and reduction in flow duration (Page & Garden 1998, Scott 2001, Docker 2005). By 1850, the entire Tarcutta Creek catchment was settled and leased by fewer than 10 pastoralists. Gold was discovered, not only in Victoria, but also in the Tarcutta Creek catchment (Scott 2001, Docker 2005) and trees were unmercifully cut down for fuel, dwellings, fences around paddocks, to make more room for the sheep and cattle and for anything that the gold digger might need (Eyles 1977, Scott 2001). Riparian vegetation was cut down, stream banks eroded and sediment transport increased (Page & Garden 1998, Scott 2001).

A major objective of the Robertson Selection Act of 1861 was to give more people ownership of the land; however, it initiated the most intense period of clearing (Docker 2005), to make room for an increasing population, stock and stocking rate numbers, which peaked and crashed in the 1890s (Docker 2005). By 1860 the best land with water frontages had already been cleared or thinned by the original settlers (Docker 2005, Martin 1985). Squatters kept and purchased these best paddocks (Martin 1985, Scott 2001, Docker 2005). Judging by the successive historic maps of the region (Map RM 666, Tile b2 MacDonald AC 1883, Parish of Umutbee 1886 – Figure 4), in 1886 the purchased area amounted to about half of the previously leased properties, leaving the worst and less-cleared areas for selectors. New settlers kept on arriving, and were initially allowed to select only very small parcels of land, up to 320 acres. To survive, the land had to be utilised to its full potential, and clearing was the only way to achieve this. An additional stimulus for clearing was that the conditional purchases required land improvements, which could be documented by receipts for clearing work. Ringbarking, introduced in the 1860s (Docker 2005), made clearing easy; it was very efficient and much less labour intensive and expensive (Martin 1985). Legislation passed in 1875 attracted even more selectors, with parcel size being increased to a maximum of 640 acres, and from 1876 parents could make selections in the names of their children (Docker 2005):

'In 1876 the Privy Council decision to make selection of minors legal, opened the way to any Victorian, forbidden to do so in his own colony, to select in his own name, names of his children and even more relatives besides.'

A flood of former gold diggers arrived in the Riverina from Victoria and 90% of clearing in the NSW slopes in the Murray–Darling Basin was done before or at the beginning of the twentieth century (K Wells, historian, pers. comm., Dec 2008, Canberra). Probably the most vivid evidence of the development of the colony is the steep rise in sheep numbers in NSW, from six million to 62 million between 1861 and 1892 (Figure 17a), and its sudden fall in 1893. Sheep numbers declined after this, during the drier spells of the first half of the twentieth century, ending the need for further massive land clearing (Rančić et al. 2009). Rabbits arrived in the Tarcutta Creek catchment in 1884 (Docker 2005) and caused devastation by taking the pastures over from the flocks, eroding the landscape and preventing trees from regenerating (Rolls 1969).

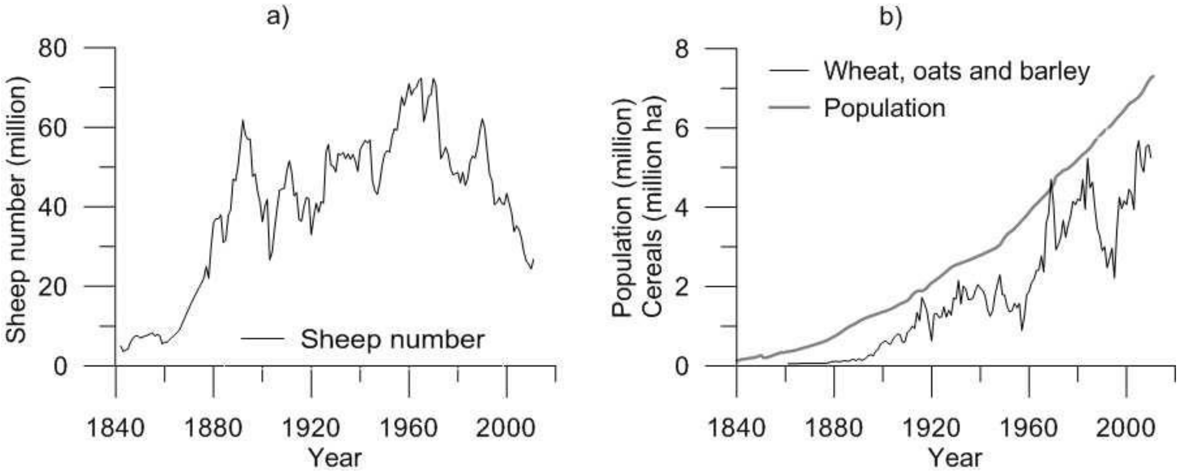


Figure 17: a) Sheep numbers 1842–2011 (Wadham & Wood 1950 and historical ABS data), and b) area under cereals 1861–2011 compared to population growth 1840–2011, NSW (compiled from historical ABS data)

In Figure 17, sheep numbers are reconstructed to illustrate the lack of need for further clearing after the start of the twentieth century. Area under cereal crops is used to estimate the spread of cropping within the cleared area. Population expansion in NSW was presented to illustrate its correlation with the expansion of area under cereal crops.

7.3 Detailed reconstruction

Expansion of State forest plantations was halted in 1997 due to introduction by the NSW Government of the *Native Vegetation Conservation Act 1997*. This Act was introduced to prevent broad-scale clearing of native trees; however, the increase in private plantations boomed, taking grazing land fully cleared of native vegetation. The increase in area under pines slowed down, but was not halted (Figure 18).

Clearing extent reached its maximum of 67% of the catchment in the 1970s. After that the spread of pine plantations reversed the trend, reducing cleared area to 58% by 2010. Deforested area has therefore reduced by 7% since 1950. The effect of pine plantations on catchment hydrology moved it marginally back towards its original state before European settlement; however, this introduced monoculture caused native forest habitat fragmentation and its reduction from 33% of the catchment in 1950 to 22% in 2010, a one third decrease.

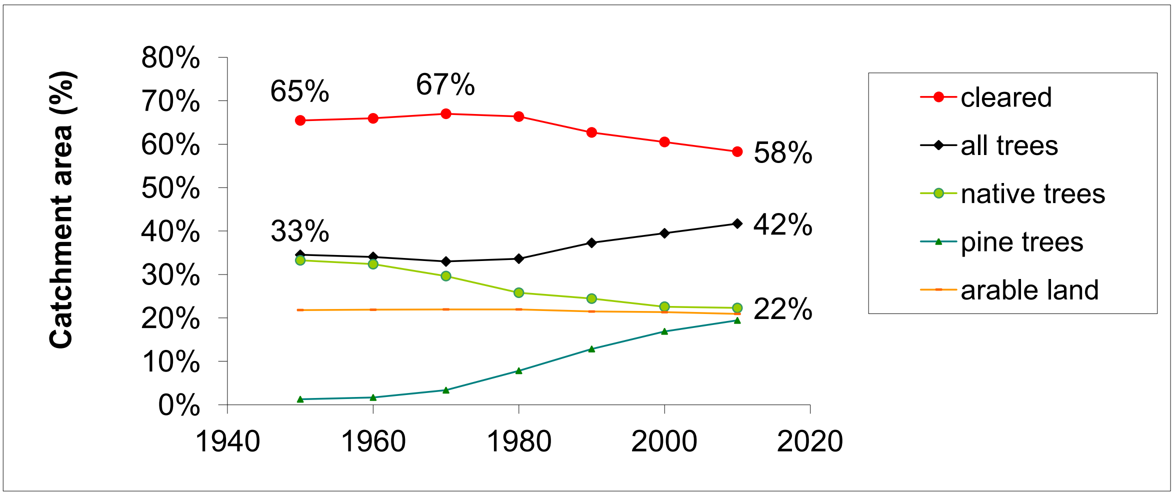


Figure 18: Vegetation extent in the Tarcutta Creek catchment 1950–2010

Loss of native forest habitat connectivity in the lower Tarcutta is prominent in the 1950 map, and based on the information gathered from the literature review and surveys it is likely that this connectivity was lost in the late decades of the nineteenth century. Except for the small gap in the Carabost area, the upper Tarcutta maintained east–west connectivity until 1950. The most prominent deterioration can be observed in the south-west portion of the catchment with major fragmentation and loss of habitat. The expansion of pine plantations fragmented the native vegetation habitats into four large areas: Murraguldrie, south-west Carabost, a partially fragmented central area along the fault-line south-east of Humula, and a smaller area in the central portion of the sub-catchment of Tarcutta Creek above Westbrook. In the heavily deforested central and lower portions of the catchment, below the pine areas, the native tree cover has remained largely unchanged since 1950. The exception is the eastern catchment boundary south of the Hume Highway where connectivity has improved.

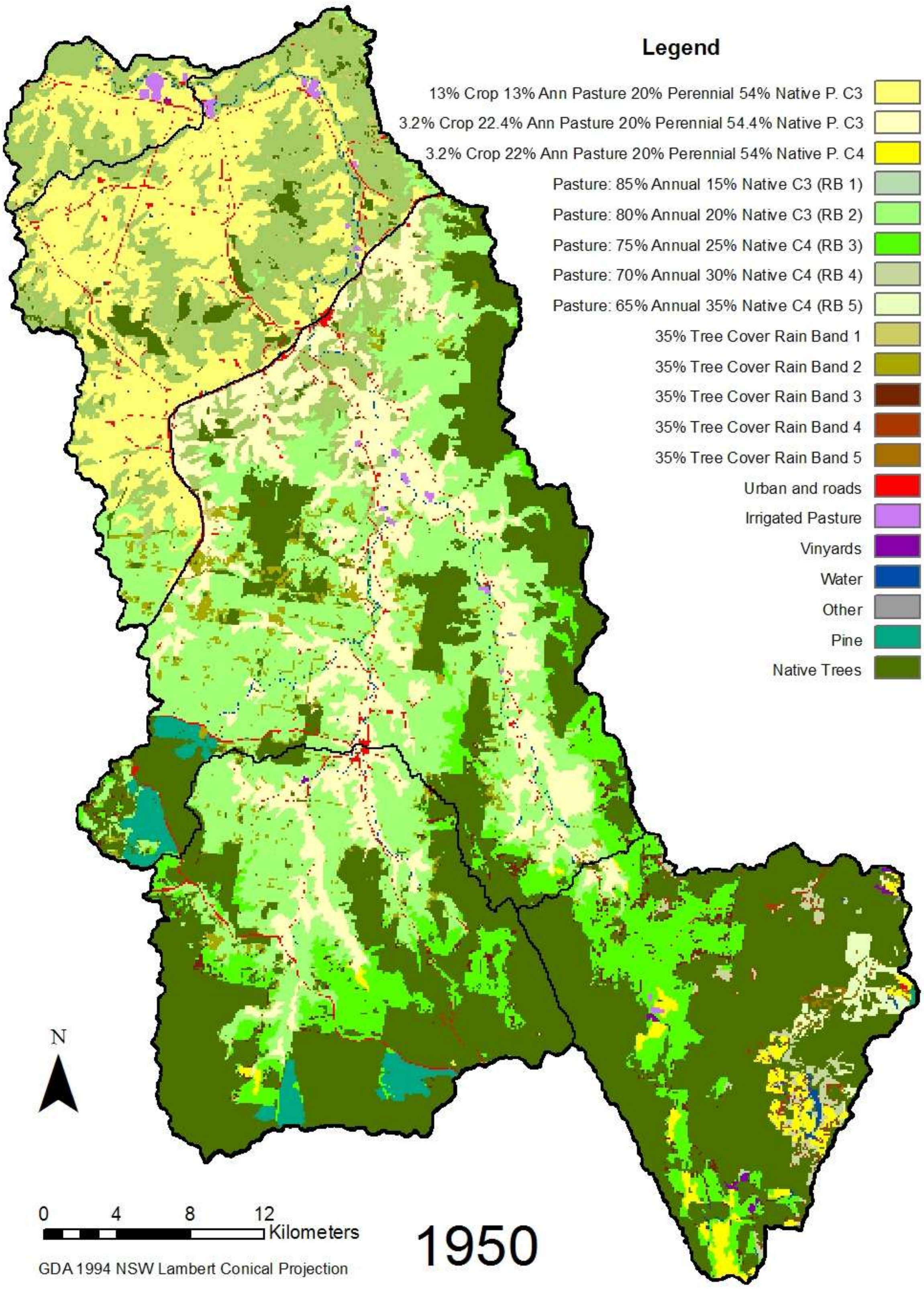


Figure 19: Land-use reconstruction: 1950

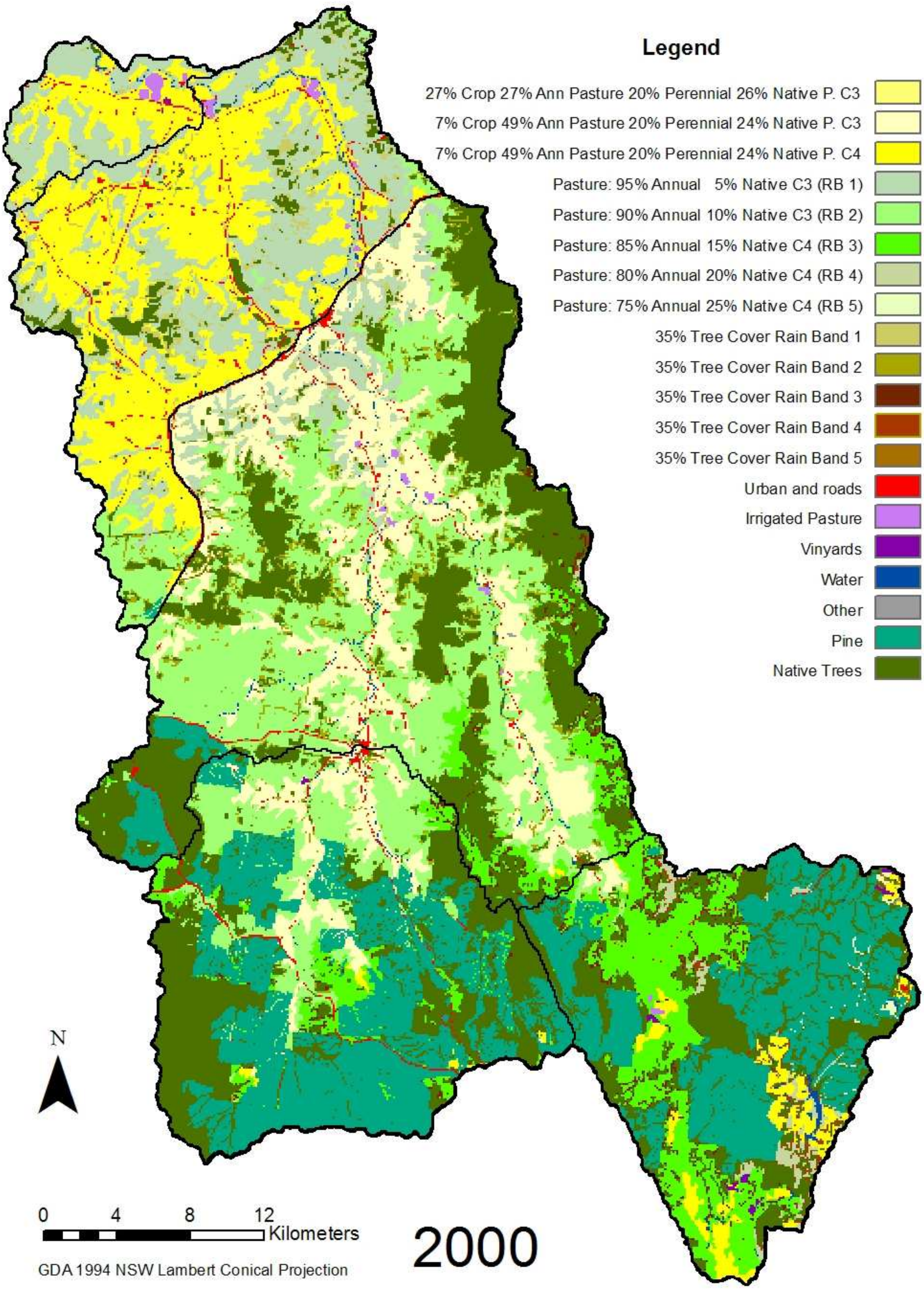


Figure 20: Land-use reconstruction: 2010

8 Catchment health

The groundwater measuring program engaged more than 20 landholders who became connected to the project. After the 2010 floods the bores in discharge areas of Borambola region started discharging at rates comparable to the 1980s, the height of the area's salinity problems. The research team presented twice to Landcare-type groups and were asked specifically if the salt scalds were likely to recur. Because of improved land-management and grazing practices with perennial pastures and strategically positioned native tree plantations, the scalding did not eventuate. Further expansion of these practices will ensure that these problems do not resurface under longer wet spells. Meeting with landholders raised awareness and acceptance that maximising perenniality and healthy pastures on the recharge areas and seeps was the best way to prevent scalding in the future.

The wet weather spell that started in 2010 changed the management focus of the landholders from drought management to consequences associated with a wetter climate. Erosion became one of the immediate concerns.

8.1 Erosion workshop

The research team embraced the invitation to an erosion workshop as an opportunity to present the CATPlus modelling results to Kyeamba and Tarcutta Landcare groups and Murrumbidgee Landcare, and at the same time obtain information on likely adoption rates of EverGraze options through a carefully designed survey.

The versatility of the CATPlus model was demonstrated by the ease with which it was expanded to address the erosion impacts from the flooding. Study of flows in Tarcutta Creek showed that the amount of water generated in the lower parts of the catchment, where clearing was most pronounced, increased the most (see the table presented in the Murrumbidgee Landcare newsletter on the following pages). This increase in discharge caused the energy of the water to also increase, stimulating erosion. These results, together with an explanation of erosion processes, were presented at the erosion workshop held for the Kyeamba and Oberne–Tarcutta Landcare groups by Murrumbidgee Landcare in Tarcutta on 12 September 2012. The presentation bore testimony to the ability of the CATPlus model and the modelling team to adapt to the needs of stakeholders. Teaming up with Dr Ken Page, the local expert in stream morphology from the Charles Sturt University, contributed to building productive networks and links with universities, and enlarging organisational capacity.

The evaluation survey from the workshops showed that 80% of respondents intended to undertake action to reduce erosion in the catchment within three months, 10% within a year and the remaining 10% within more than 12 months. As increasing perenniality was the suggested measure for this action, the anticipated rate of adoption of EverGraze principles can be considered extremely successful.

The PowerPoint presentation *Erosion in Tarcutta Creek Catchment: causes and solutions* (www.murrumbidgeelandcare.org.au/files/Tarcutta%20Creek%20Erosion%20-%20Causes%20and%20Solutions%20-%20Aleks%20Rancic.pdf)

is made available by Murrumbidgee Landcare through their site: www.murrumbidgeelandcare.org.au/projects/erosion/workshop.

The short article below was published in the Tarcutta Valley Landcare Group newsletter, and incorporated Tarcutta modelling results with the management advice which advocates an increase in perenniality (article reproduced with permission).

Causes of erosion in watercourses - and how to reduce it!

By Aleksandra Rancic, NSW Office of Environment and Heritage

Causes of erosion in the Tarcutta Creek catchment

While erosion is a natural process, clearing of vegetation in the Tarcutta Creek catchment has worsened it. The majority of the catchment was ringbarked between 1850 and 1900. The erosion process was well on the way in 1874, as described by Docker in "The Bardwells of Bardwell Park":

"Tarcutta Creek, when the Mates arrived there in 1830s looked like a chain of ponds, the water gliding from pond to pond and grass growing to the water edge. The trampling of sheep, with subsequent loss of protection to the soil, had helped convert a pleasant stream into what was becoming in places a deeply incised waterway with no attraction to the eye at all. In times of heavy rain, the rush of water scoured the banks, cut channels deeper and deeper and left the creek bone dry until the next rain".

Erosion is a process driven by energy of flow. This energy depends on:

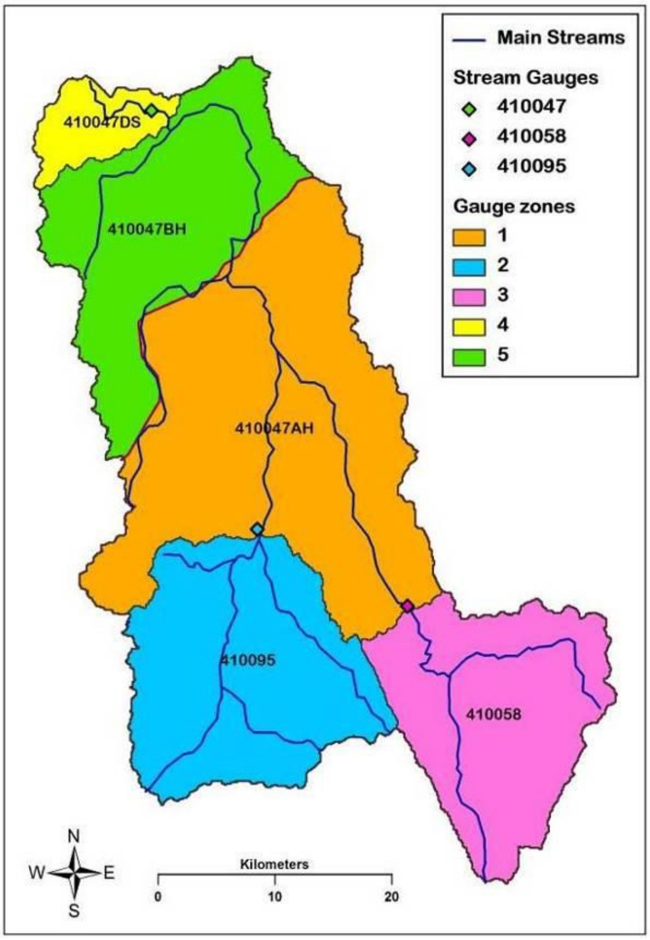
- The speed of the water – for example, water flowing three times as fast has 9 times more energy (3 x 3 = 9)
- Surface cover, that causes roughness, which can slow down the speed of water
- The slope of the land
- The amount of water.

Changes in flow in the Tarcutta Creek catchment

By clearing dense native vegetation, the surface cover - or "roughness" - was minimised, which allowed water to flow faster and be more energetic. As deep-rooted trees use more water than pastures and crops, the amount of water that flowed down the creek also increased.

The table at right shows the changes in flow in the Tarcutta Creek catchment, as measured by a series of stream gauges situated at various points along the Creek (indicated by the different colours, with locations shown by the relevant coloured section in the map). This study of flows in Tarcutta Creek shows that the amount of water generated in the lower parts of the catchment, where clearing was most pronounced, increased the most. This increase caused the energy of the water to also increase, as shown in the table.

The location of stream gauges in the Tarcutta Creek catchment



Changes in flow at the stream gauges in the Tarcutta Creek catchment

*

Location of stream gauge	Flow (mm/year)*		Flow increase	Energy increase
	Native	Present		
Below Borambola	2.8	24	8.6	18
Below the highway	3.6	40	11	25
Above the highway	18	97	5.5	9.7
Above Humula	33	68	2.1	2.6
Above Westbrook	83	146	1.8	2.1
Entire catchment	***30***	***86***	***2.9***	***4.1***

"Flow" refers to the amount of rainfall that ended up in the Creek

(article continued from previous page)

The data for the table is based on flow measurements since 1937 at Borambola, and provide an excellent record of changes in flow during this time. This data, together with shorter flow records at Humula and Westbrook, along with the reconstructed changes in land-use for the area, were used to setup the "CATplus" model, by matching the modelled flows to recorded flows. As the rainfall records were available from the start of the twentieth century, it was possible to calculate how much flow would have occurred in each section of the catchment if there was no clearing, and compare this with the flows that would have occurred if the current land-use had existed since 1900. (It should be noted that records do not exist for the 1800s, the time when the most significant flow - and erosion - events are thought to have occurred).

How can we reduce erosion in our catchment?

By planting deep-rooted vegetation, such as trees, as well as perennial grasses, the amount of water intercepted can be increased, which will reduce the severity of water flow in creeks and rivers. If just 10% of the cleared area below the highway (marked as green in the map/table at left) is planted with trees, the flow will decrease by 20% and energy will drop by 27%. This would have a dramatic impact on the potential erosion in the Creek.

When pastures replaced native vegetation on the floodplains, surface roughness was decreased by about three times - meaning water was allowed to flow three times faster, and the energy of the water became nine times higher. De-snagging of Tarcutta Creek around Jane Harvey Bridge had the same effect, starting erosion by deepening and widening the creek. This is now resulting in changes to the watercourse, with it becoming straighter and therefore shorter, steeper and more energetic. The Tarcutta Creek will eventually become stable, on its own, after nature takes its course and the erosion process is finished. While the amount of funding needed to reverse this process might not be available, erosion of the many small watercourses that flow into Tarcutta Creek can be prevented and reversed. It is important to do so, as we expect that the next decades and centuries will bring flooding events more often as the ocean waters warm up.

The most important and the most effective method to reduce and reverse erosion is to slow water down by planting vegetation in its path. This can result in an almost ten-fold effect, everywhere it is applied. Slowing down the flow of waters in smaller creeks will take the edge off erosion from the downstream creeks. This battle will be effective only if the repair is done in sequence, tackling first the smaller watercourses, and working our way towards the lower, larger ones. Every intervention in slowing down waters of a smaller watercourse has a beneficial ripple effect downstream.

Above left: Tarcutta Creek, downstream of Jane Harvey Bridge. The removal of logs many years ago led to the commencement of significant erosion, through deep incision and channel widening (photo by Dr Ken Page)

Above right: A positive example of where erosion was reversed. This photo was taken on the day of the rainfall event in 2010, just above Tarcutta village. Prior to the removal of vegetation, this area was a swamp which used to help slow water down, preventing destructive erosion downstream. Revegetation of the area has allowed it to once again serve this purpose. The vegetation is now well established, and stock are able to graze here again

9 Key findings

We used the CATPlus model to identify potential impacts of increasing catchment perenniality on stream flow, groundwater, water energy and erosion. The perennial species used to assess the impact on water yield included: lucerne, tall fescue, native grasses and plantation forestry (softwood and hardwood). Different adoption rates were analysed within the natural resource management (NRM) solutions.

Some of the key results of the study include:

- The groundwater monitoring program was successful, capturing an important transition from the Millennium Drought to the floods in 2010–2012. Newly acquired information from the field, coupled with the data from the Groundwater Database System (GDS), published reports and the landowners' invaluable original records, now provide the most comprehensive dataset in NSW and Eastern Australia.
- The early bore records (1920–1950) demonstrate: (a) the groundwater systems were not discharging locally and (b) consequently, during the first half of the twentieth century streams in the proximity of these bores were losing water to groundwater below, instead of gaining the baseflow. This important finding should be taken into consideration in conceptualisation and modelling of groundwater systems.
- The groundwater measuring program engaged more than 20 landholders who became connected to the project. After the 2010 floods the bores in discharge areas of Borambola region started discharging at rates comparable to the 1980s, the height of the area's salinity problems. The research team presented twice to Landcare-type groups and were asked specifically if the salt scalds were likely to recur. Because of improved land-management and grazing practices with perennial pastures and strategically positioned native tree plantations, the scalding did not eventuate. Further expansion of these practices will ensure that these problems do not resurface under longer wet spells.
- The model successfully reproduced unsaturated subsurface hydrology when tested by comparison with the soil moisture data collected at the EverGraze site near Borambola, measured by neutron probes and integrated over the top 1.5 m of the soil profile. The correlation coefficient of changes between consecutive readings reached 0.82 for lucerne and 0.76 for annual pasture.
- The CATPlus model introduced the adjustment of ANUCLIM rainfall surfaces to match the values of rainfall records at the point of sampling. Two options for adjustment were investigated: one based on monthly average, and one on annual average. In some catchments, where seasonality and a large rainfall gradient are important hydrologic drivers, a monthly, rather than annual rainfall adjustment could lead to improved modelling. Unlike most of the Victorian catchments modelled, which have less pronounced relief and rainfall gradients, Tarcutta is a very hilly catchment where spatial interpolation smooths rainfall gradients close to ridges. The switch from a monthly, to a much simpler, annual adjustment therefore reduced the model performance in the Tarcutta Creek catchment.
- Groundwater hydrographs were successfully reproduced in the model, by calibrating parameter Alpha. Alpha represents the number of months needed for the hillslope storage to reduce its volume to half (decay coefficient). Values of Alpha, obtained by calibration, range between 10 and 50 months; however, to reproduce the baseflow component of the stream trace, the value of Alpha needs to be close to one month. This in effect keeps the hillslope reservoir very depleted by allowing rapid transfer of incoming fluxes to the alluvial aquifer and stream. Therefore groundwater levels and the fluxes to the stream could not be reproduced simultaneously. To be able to do so three actions are recommended:

    - Alluvial storage should be allowed to discharge at the faster rate, independent of the incoming flux from the hillslope storage.
    - Fixing the bottom of the hillslope storage at the stream bed level when applying the decay coefficient function should be investigated as an alternative to the currently variable bottom, linked to the top of the alluvial storage.
    - The lower boundary condition of the alluvial aquifer could be linked to the stream height, via a rating curve, rather then to the stream bed.
- The improvement expected from an additional decade of land-use reconstruction was diluted due to model performance being lowered by simplified rainfall transformation. However, the land-use reconstruction of the entire 170,000 ha of the Tarcutta Creek catchment since 1949 represents the largest aerial land-use reconstruction in Australia at 1 ha resolution. Based on this reconstruction, it was evident that the nineteenth century was dominated by the tree clearing that accompanied European settlement, while the twentieth century saw the extensive development of the tree plantation industries, especially *Pinus* species.
- Management advice remains largely unchanged from the last phase of the project:
    - NRM solutions in the lower parts of the Tarcutta Creek catchment (NW of the highway) would lead to minimal reduction in stream flow and a huge positive impact on profitability, catchment health, prevention of waterlogging, salinity, soil degradation and erosion. Maximum implementation of the NRM solutions in this zone is highly beneficial, necessary and fully recommended.
    - NRM solutions in the mid parts of the Tarcutta Creek catchment (SE of the highway, downstream of Humula and Westbrook) would have a considerable impact on the stream flow and lead to water yield reduction. The flatter portion of this section has a very low perenniality and it is estimated that 10% of this area has problems with erosion, waterlogging and salinity, especially during prolonged wetter climatic spells. A high adoption rate of EverGraze solutions is recommended within the boundary of these areas that have problems. A high adoption rate outside these areas, and especially in the higher rainfall bands, would have a considerable negative impact on water yield and is therefore not recommended.
    - Adoption of NRM solutions in the upper parts of the Tarcutta Creek catchment would have a very high impact in terms of flow reduction; EverGraze solutions are not recommended, except locally and within a very limited extent, if necessary for interventions dealing with soil erosion or soil degradation caused by waterlogging.
- In addition to the planned outcomes, CATPlus modelling was expanded to address the erosion impacts from the flooding. The amount of water generated in the lower parts of the catchment, where clearing was most pronounced, increased the most. This increase caused the energy of the water to also increase, and this stimulated erosion. The Tarcutta modelling results, together with an explanation of erosion processes, were presented at the erosion workshop held for the Kyeamba and Oberne–Tarcutta Landcare groups by Murrumbidgee Landcare in September 2012.
- The evaluation survey from the erosion workshop showed that 80% of respondents intended to undertake action to reduce erosion in the catchment within three months, 10% within a year and the remaining 10% within more than 12 months. As an increase in perenniality was the suggested measure for this action, the anticipated rate of adoption of EverGraze principles can be considered extremely successful. This was a result of full integration of the community with the modelling team. The trust established is fertile ground for future cooperation in water and land use and overall catchment management.

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