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Estimated streamflow changes due to bauxite mining and forest management in the Seldom Seen catchments

ESTIMATED STREAMFLOW CHANGES DUE TO BAUXITE MINING AND FOREST MANAGEMENT IN THE SELDOM SEEN CATCHMENTS

by

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Cover photograph:
Gauging station of the More Seldom Seen catchment
by Dacre Allen

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The effects of bauxite mining and forest management on the streamflows of the Seldom Seen and More Seldom Seen catchments were studied. Forest clearing for mining led to an initial increase of up to 36% of streamflows compared with a simulated unmined scenario; but by 2002 there were reductions below the unmined scenario of 13–42%, as the mine revegetation grew.

The maximum increases in annual streamflow due to forest clearing for mining were estimated to be 62 mm/yr in 1978 for Seldom Seen (36% of flow in 1978) and 90 mm/yr in 1981 for More Seldom Seen (31% of flow in 1981). Elevated streamflows lasted 32 years for Seldom Seen and 20 years for More Seldom Seen. The modelling also implied that young mine revegetation has a higher evapotranspiration rate than unmined forest and is thus reducing streamflow. The streamflow reductions at simulation end (in 2002) were estimated to be 12 mm/yr for Seldom Seen (13% of flow in 2002) and 55 mm/yr for More Seldom Seen (42% of flow in 2002). The water balance calculations indicated that the soil water storages of the catchments were still decreasing and further reductions in streamflow could be expected. Whether the reductions in streamflow are permanent or transient could not be determined in this study.

It was estimated that the leaf area for the unmined forest increased during the study period, creating reductions in streamflow beyond those due to revegetation following mining. The streamflow reductions at simulation end, compared with a constant LAI scenario, were estimated at 55 mm/yr for Seldom Seen (36% of flow in 2002) and 54 mm/yr for More Seldom Seen (29% of flow in 2002).

These study results imply that, from a water resources viewpoint, present mine revegetation practices may be too successful. Additional studies are required to refine the streamflow change estimates and to define the key differences in catchment hydrology which cause them.

1 Introduction

1.1 Background

The Northern Jarrah Forest on the Darling Plateau of the south-west of Western Australia supplies up to 70% of Perth's reticulated water (Stokes et al. 1995). It is expected that Perth's population will increase to two million by 2021, raising the water demand further. Stream yields in the Northern Jarrah Forest are low by normal standards, an average of 7% of annual rainfall (Ruprecht & Stoneman 1993), due to the high rates of evapotranspiration (ET) by the vegetation cover. These low yields have been further exacerbated by the below-average rainfall since the mid 1970s (IOCI 2002). For these reasons there has been ongoing research into the effects of land management, such as forest logging and bauxite mining, on catchment hydrology. Alcoa World Alumina Australia has surface-mined bauxite in the Northern Jarrah Forest for more than 35 years. Particular research emphasis has been placed on studying the long-term effects of mine revegetation on stream yields in the High Rainfall Zone (HRZ, > 1100 mm/annum rainfall) and the effects of mining on stream salinities in the Intermediate Rainfall Zone (IRZ, 900–1100 mm/annum rainfall). The study presented in this report is part of the HRZ research.

This study is based on the Seldom Seen, More Seldom Seen and Waterfall Gully catchments that are part of the Wungong Water Supply Catchment. The Water and Environmental Consultants-Catchment model (WEC-C), used for streamflow simulations in this study, is specifically designed to predict the effects of land management on stream yields. A complex model like WEC-C was chosen for this exercise because there is considerable uncertainty about the predictions made so far using the Waterfall Gully catchment as a control in paired-catchment studies. This doubt has been due, in part, to the lack of pre-treatment record (less than three years for both catchments) and a number of operational issues with the stream monitoring. Also, the Seldom Seen and More Seldom Seen catchments have been subjected to so many vegetation treatments, both within the forest and the revegetated mine areas, that it would be difficult to separate the effects of mining from those of forest density changes without the use of a deterministic model like WEC-C.

1.2 Study objectives

The primary objective of this study was to assess the effects of bauxite mining on stream water yields by applying the WEC-C model to the Seldom Seen and More Seldom Seen catchments. However, due to the mosaic of forest management and mine revegetation activities in these catchments, this objective could not be achieved in isolation and required the completion of a number of steps. In particular, it was necessary to generate an accurate vegetation history of the catchments to separate water yield variations due to forest density changes from those due to bauxite mining and mine revegetation.

The expected outcome was not only a tabulation of the streamflow effects, but also the production of models that could improve the understanding of Darling Plateau hydrology and how it might be affected by mining. In particular, questions are presently being raised about long-term stream yields following revegetation of mine areas. Models like WEC-C are able to define hydrological processes at the point, hillslope and catchment scales, and can be used to evaluate the full effects of transient land uses such as mining on catchment hydrology.

2 Description of catchments

2.1 Location and climate

The adjacent, treated catchments, Seldom Seen (7.15 km^2) and More Seldom Seen (3.25 km^2), are located within the Wungong Water Supply Catchment, approximately 40 km south of Perth and 5 km north-east of Jarrahdale (Fig. 1). The Waterfall Gully control catchment (9.54 km^2) is also within Wungong and 5 km north of the Seldom Seen and More Seldom Seen catchments.

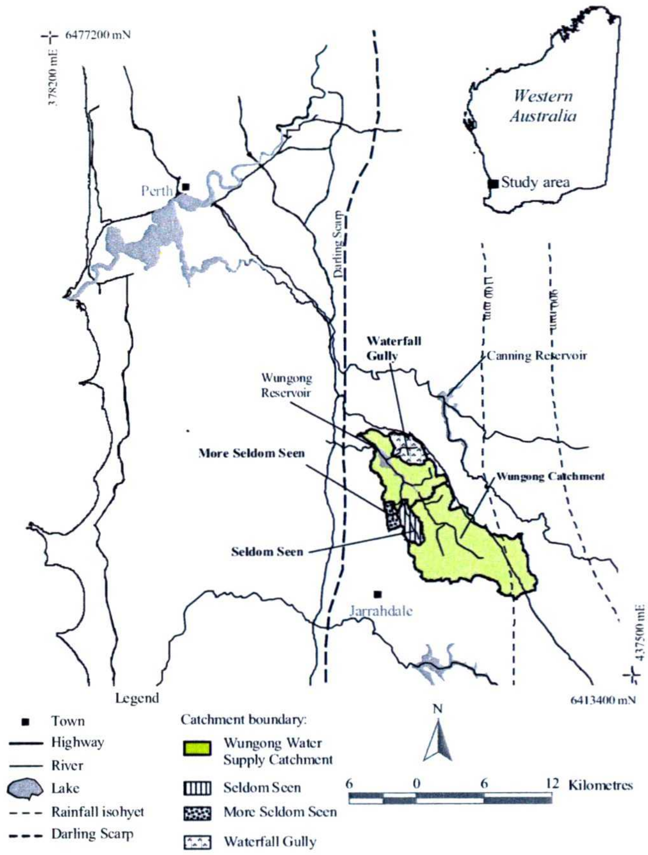

Figure 1. Location of the Seldom Seen, More Seldom Seen and Waterfall Gully catchments

The climate of the Northern Jarrah Forest is of Mediterranean type; that is, characterised by hot summers and wet cool winters with most rainfall occurring between May and October. Average annual rainfalls for the study period (1966–2002) were: Seldom Seen (1126 mm), More Seldom Seen (1158 mm) and Waterfall Gully (1058 mm). These are below the long-term averages of 1250 mm for Waterfall Gully and 1275 mm for Seldom Seen and More Seldom Seen (Hayes & Garnaut 1981) due to the below-average rainfall period since the mid 1970s (IOCI 2002). Based on Luke et al. (1988), the average annual Standard Class A pan evaporation for the catchments is 1690 mm (without correction for the effects of the bird guard).

2.2 Geology and soils

Geologically, the catchments are located within the south-western province of the Archaean Yilgarn Block, and, while no formal descriptions of the geology of the catchments have been made, they are assumed to be typical of the Darling Plateau. This consists of a primarily granitic bedrock that has been divided by the intrusion of numerous sheet-like doleritic dykes that vary in thickness from a few millimetres to tens of metres. Deep *in-situ* weathering has produced a soil profile with a typical depth range of 10–40 m, average about 25 m. On the side slopes, the soil profile consists of a surface layer of gravelly sand from 0–2 m deep (average 0.4 m) overlying a duricrust 0–3 m thick, (average about 1.5 m). The duricrust is generally underlain by a mottled zone that includes an alumina-rich friable layer that transitions into a deep, pallid, sandy-clay zone. This pallid zone is divided from the parent rock by the weathering zone which, with a significantly greater sand fraction than the pallid zone, acts as the lateral conducting layer for the main aquifer. The valley floor soil profile often lacks the duricrust and is usually more silty. Peat is commonly found in swamp areas. Vertical preferential water flow structures, in the form of sand-infilled root-channels, are very common and typically extend from the duricrust to the weathering zone.

2.3 Vegetation

The Seldom Seen and More Seldom Seen catchments were fully forested prior to mining and there has been some forest clearing for agriculture in the Waterfall Gully control catchment. The dominant over-storey species on the middle and upper slopes are jarrah (*Eucalyptus marginata*) and marri (*Corymbia calophylla*), with bullich (*E. megacarpa*) and yarri (*E. patens*) on the lower slopes (Havel 1975). The forest of these catchments had been significantly altered from its natural state by logging and jarrah dieback (*Phytophthora cinnamomi*); the result is a forest with highly variable age and composition. In 1941 approximately 21% of the Seldom Seen catchment showed presence of the disease, by 1968 it was 28%, and by 1975 it was 35% (Bartle 1976). There are no detailed data on the prevalence of dieback in the More Seldom Seen and Waterfall Gully catchments, but these two catchments were considered to be less affected.

2.4 Forest logging and dieback rehabilitation

Department of Conservation and Land Management (CALM) FMIS database records indicate a patchwork of logging for the Seldom Seen and More Seldom Seen catchments spreading from 1945 till 1980 (Fig. 33 in Appendix 1). Unfortunately, the FMIS records show only the most recent logging for a given area. For the Seldom Seen and More Seldom Seen catchments, aerial photographs from the 1960s indicate a forest cover already thin from logging and jarrah dieback, while the FMIS records indicate most of the catchment areas were logged in the 1970s. It appears likely, therefore, that the actual sequence was that all commerical grade timber was cut from the catchments during the logging activities of 1945, with a follow-up over limited areas in 1965. The logging of the 1970s and 1980 appears to be the cutting of the few remaining trees of commerical grade.

The Forest Improvement and Rehabilitation Scheme (FIRS) was established to rehabilitate dieback-affected areas and to improve the resistance of healthy forest to dieback (Olsen 1991). Within the Seldom Seen catchment, the FIRS activities were conducted during the period 1979–90 with approximately 41% of the catchment area treated (Table 1 & Fig. 34 in Appendix 1). In the More Seldom Seen catchment, FIRS was conducted in 1983–85 with approximately 16% treated. Between 1993–99, approximately 18% of Seldom Seen and 28% of More Seldom Seen were treated, using a revised rehabilitation programme named Dieback Forest Rehabilitation (DFR) (Fig. 34 in Appendix 1).

Table 1. Mine clearing, FIRS and DFR histories

	Seldom Seen (catchment area 733 ha)			**More Seldom Seen** (catchment area 327 ha)		
Treatment	*Period*	*ha*	*%*	*Period*	*ha*	*%*
Mine clearing	1967–1994	251	34	1969–1990	202	62
Mine revegetation	1970–2002	251	34	1971–1994	202	62
Forest FIRS*	1979–1990	300	41	1983–1985	53	16
Forest DFR*	1993–1999	130	18	1993–1999	93	28
Undisturbed forest	1967–2002	182	25	1967–2002	24	7

*FIRS and DFR were often applied to the same forest areas

2.5 Bauxite mining and rehabilitation

Clearing for mining started in 1967 in Seldom Seen and in 1969 in More Seldom Seen (Fig. 35 in Appendix 1). Approximately 34% of the Seldom Seen catchment was cleared and 62% of More Seldom Seen. Revegetation of mined areas commenced in 1970 in Seldom Seen and in 1971 in More Seldom Seen. By 1997, approximately 32% of Seldom Seen had been revegetated; the remaining 2% was replanted by 2002. All revegetation of mined areas within More Seldom Seen was completed by 1994 (Table 1).

During the period 1970–87, eastern Australian eucalypts were the predominant revegetation species planted on mine areas as it was believed that native jarrah was unsuitable due to its dieback susceptibility (Schofield & Bartle 1984). Between 1970–77, approximately 87% of revegetated areas in Seldom Seen and 97% in More Seldom Seen were replanted with eastern Australian eucalypts. Between 1978–87, these figures had fallen to 62% for Seldom Seen and 66% for More Seldom Seen as wandoo (*E. wandoo*) was extensively trialled, along with other native jarrah forest species. The species composition since 1988 closely resembles the original forest with jarrah, marri and blackbutt as the principal overstorey species.

3 Hydrology of the catchments

3.1 Streamflow characteristics

Streamflows from the Seldom Seen and More Seldom Seen catchments were perennial during the pre-mining period though the summer baseflows were small. The Waterfall Gully streamflow was also perennial but its baseflow was greater; probably due to the presence of doleritic dykes and a steep streamline slope in the vicinity of the gauging station (Davies et al. 1995). The pre-mining differences can be seen from monthly plots of the two treated catchments against Waterfall Gully (Figs 2 & 3). During the mining period, the Seldom Seen catchment retained its low summer baseflows (Fig. 2) while More Seldom Seen (Fig. 3) developed an elevated baseflow like that of Waterfall Gully. Once revegetation within More Seldom Seen was complete (1994), the baseflow returned to a low level and even ceased in the summers of 2000–01 and 2001–02 (Fig. 3).

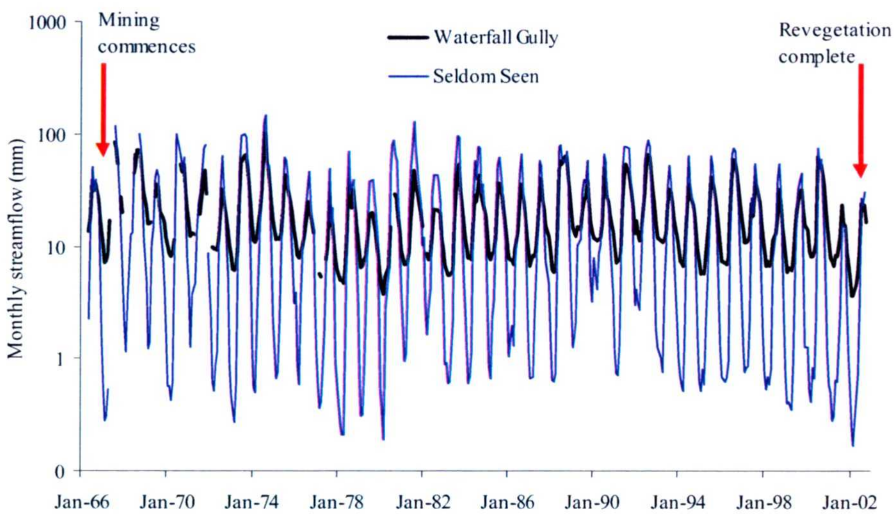

Figure 2. Monthly streamflows of the Seldom Seen and Waterfall Gully catchments

Table 2 gives the flow ratios of Waterfall Gully with the other two catchments for August, December and the whole year over the following periods: 1966–69 (nominal pre-treatment period), 1970–93 (nominal mining period), and 1994–2002 (nominal revegetation period). While these periods are not strictly accurate (e.g. revegetation in Seldom Seen was not fully completed until 2002) they indicate the differences in behaviour between the catchments. The ratios for both catchments increased during the mining period and declined during the revegetation period. There was a greater response from the More Seldom Seen catchment, probably due to the higher percentage of mining there (62% compared with 34% in Seldom Seen). Figure 4 shows the annual streamflows for the three catchments, and the differences discussed above are clearly evident. Figure 4 is based only on those daily flow records which are available and coincident: there is no filling of missing data. The plotted values are different from those in later graphs where they are compared with simulated flows and the missing records were filled for completeness.

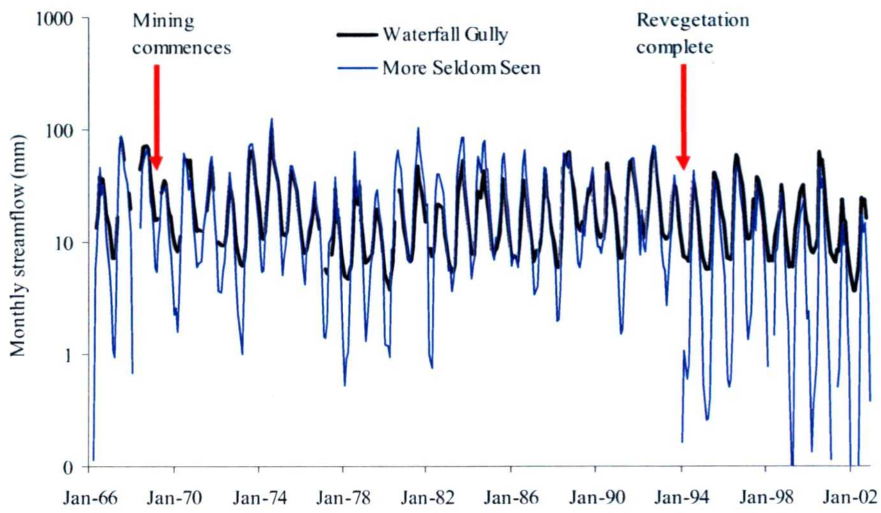

Figure 3. Monthly streamflows of the More Seldom Seen and Waterfall Gully catchments

Table 2. August, December and whole-year streamflow ratios of the Waterfall Gully catchment

Period	*August ratio*		*December ratio*		*Whole-year ratio*	
	Seldom Seen	More Seldom Seen	Seldom Seen	More Seldom Seen	Seldom Seen	More Seldom Seen
1966–69 (pre-treatment)	1.12	0.92	0.26	0.55	0.91	0.76
1970–93 (mining)	1.61	1.32	0.35	0.81	1.14	1.12
1994–2002 (revegetation)	1.22	0.74	0.20	0.25	0.82	0.56

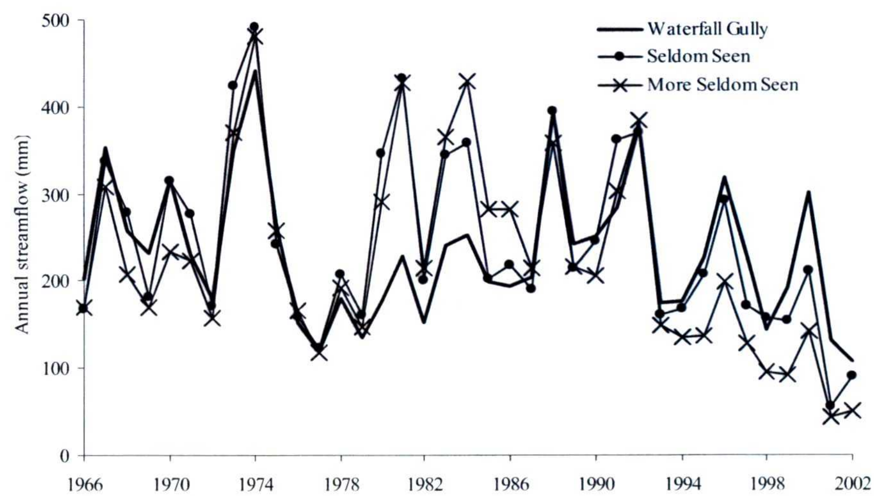

Figure 4. Observed annual streamflows of the Waterfall Gully, Seldom Seen and More Seldom Seen catchments

(Note: Only coincident daily records used with no filling of missing values, so some annual values are less than later graphs)

3.2 Paired-catchment study

The 'paired-catchment' method has previously been used for the Seldom Seen and More Seldom Seen catchments with Waterfall Gully as control (Loh et al. 1984; Davies et al. 1995; Bari & Ruprecht 2003). All used the nominal pre-treatment period 1966–69 to estimate a pre-mining relationship between the treated and control catchments. This study used the same approach.

The annual streamflow differences between this relation and the observed flows for Seldom Seen and More Seldom Seen are shown in Figure 5. The inaccuracy of this simple paired study is evident from the variations from zero in the nominal pre-treament period. Other issues with paired studies will be discussed later. For now, the interest is in the broad indications of such a study. The maximum annual streamflow difference for Seldom Seen was 230 mm (21% of rainfall), in 1981. The streamflow difference then declined rapidly and began an oscillation around zero. A similar pattern was observed in the More Seldom Seen catchment: the maximum annual streamflow difference was 247 mm (20% of rainfall), in 1981. However, the post-1994 differences were all negative, indicating a decline in flows compared with the pre-treatment period.

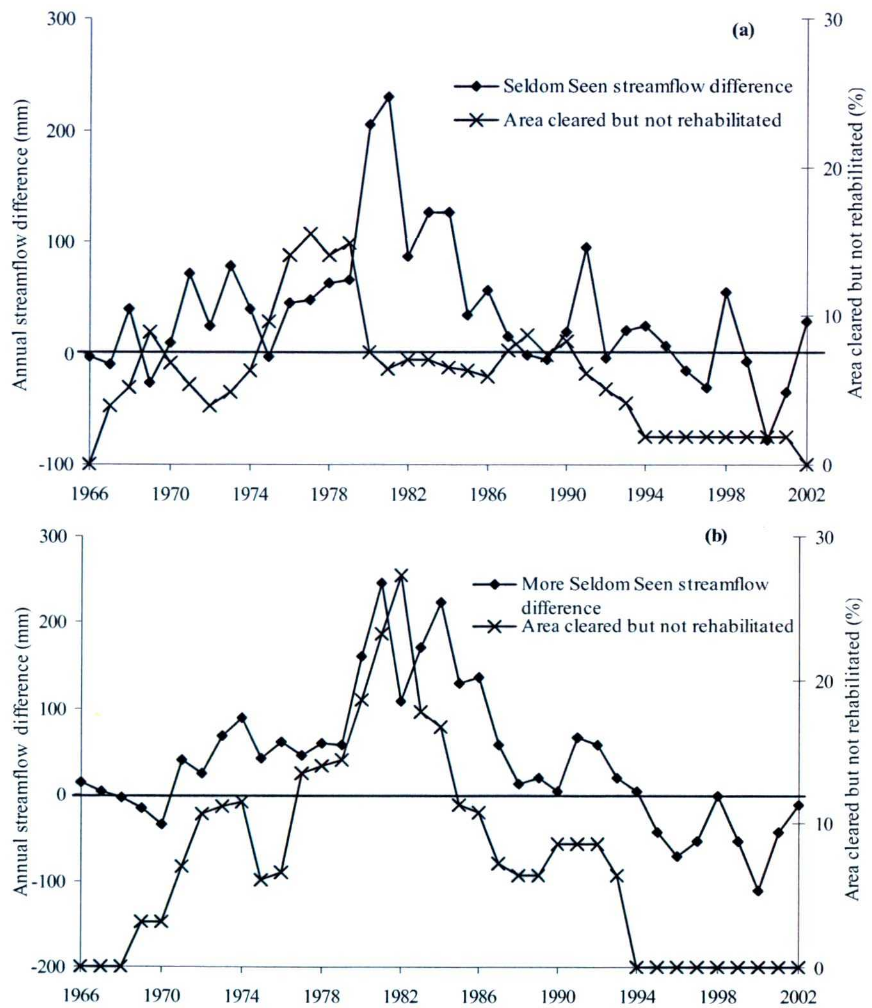

Figure 5. Difference plots of annual streamflow changes in a) Seldom Seen and b) More Seldom Seen, based on a paired-catchment regression with Waterfall Gully

4 The WEC-C model

WEC-C is a distributed deterministic catchment model of numerical form that simulates both water and solute movement within a catchment. Its form is especially useful where direct surface runoff is not the only streamflow generation process and below ground processes, that is, interflow and groundwater discharge, are significant contributors. The model has been described in detail by Croton and Barry (2001) and example applications to Darling Plateau catchments include those given by Bari and Croton (2000), Croton and Bari (2001), Bari and Croton (2002), Beverly and Croton (2002) and Croton (2004).

WEC-C employs a rectangular grid of uniform cell size in the lateral plane combined with a system of soil layers in the vertical to represent the regolith of a catchment (Fig. 6). A uniform grid was chosen for the lateral plane to simplify data input and output. For the same reason, the number of soil layers has been kept uniform across the model domain (this allows a layer to be connected laterally across all cells), although the thickness of any layer, or its elevation compared with the model datum, is flexible. This structure permits any soil layering and surface topography to be modelled. The top of the soil profile is defined by the soil surface while the bottom is defined by an impermeable basement surface (usually taken as the top of the parent rock if its permeability is low). The catchment is delineated by defining as active only those cells within the catchment divide; inactive cells are impermeable and act as solid boundaries to lateral flow within the model.

Subsurface lateral flows are simulated in each of the layers by a two-dimensional explicit finite-difference formulation. Vertical fluxes between model layers are handled by a dual continuum moisture model. This model includes, as boundary conditions, rainfall interception by a vegetation canopy and evaporation from the soil surface. Within the soil profile it includes flow to plant roots and plant transpiration as source/sink terms (Fig. 6). The vertical model solution is based on an explicit scheme applied to Richards' equation (Richards 1931) within each continuum. The dual continua are conceptualised as a system of preferred pathways, cylindrical in form, containing highly permeable material within a matrix of lesser permeability. The linkage between the matrix and preferred-pathway profiles is based on radial flow under both saturated and unsaturated conditions.

WEC-C considers overland flow via a nine-point finite difference solver that employs both a Manning's Equation-like algorithm and the kinematic wave equation. Channel flow can be either by simple reach summation, or by a channel-routing algorithm based on both Manning's Equation and the kinematic wave equation.

All parameters are defined locally in each model cell so that all available data on catchment variability can be directly incorporated into the model. WEC-C is particularly useful for mining studies in that it can incorporate soil excavation, and other profile changes, as inputs during the simulation. The unit of time for input of evaporation and rainfall data is daily; however, to maintain stability and accuracy the model operates on a much shorter internal time-step.

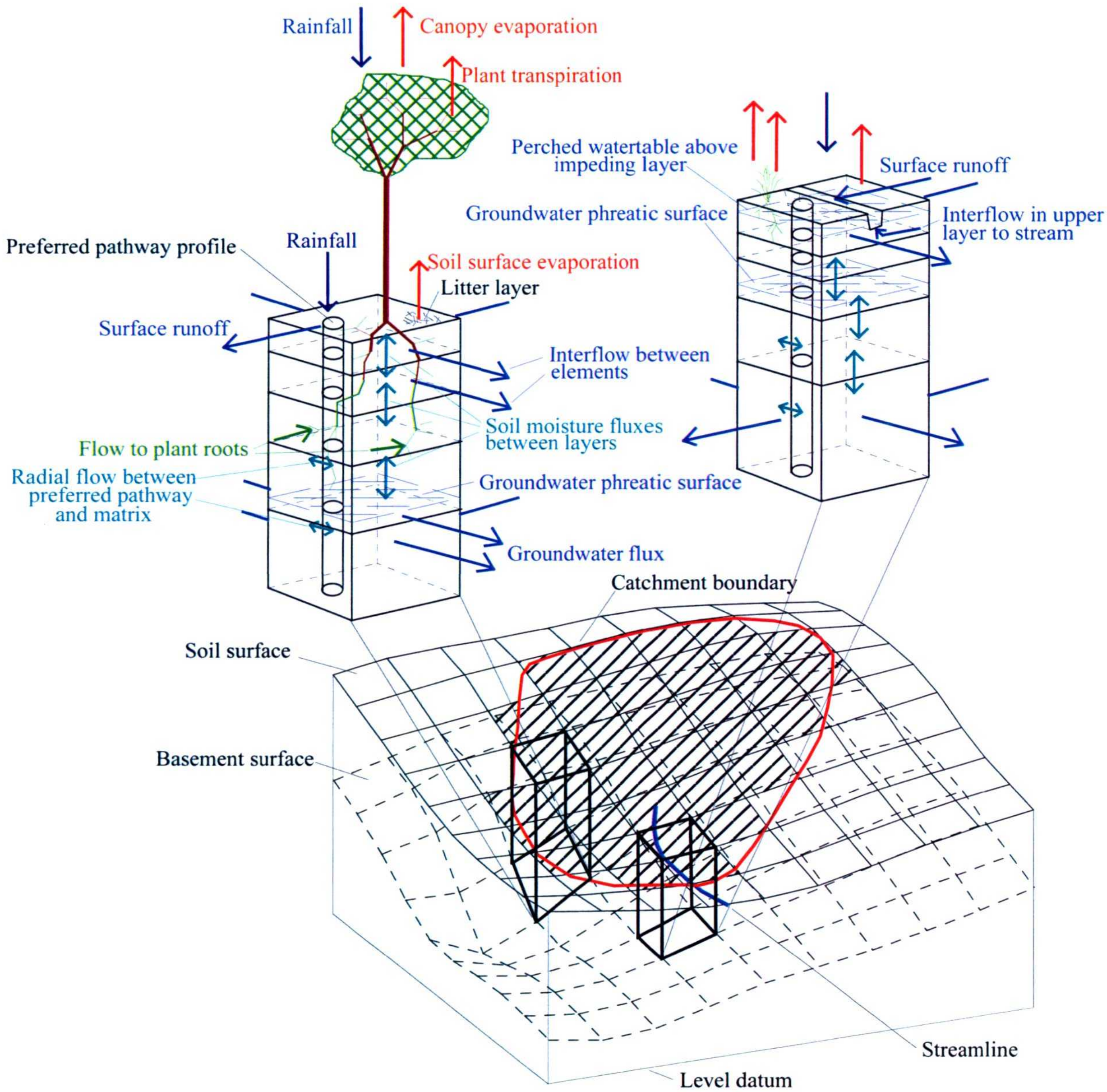

Figure 6. Schematic layout of WEC-C and the processes it models (after Croton & Barry 2001)

5 Data requirements and model set-up

5.1 Data requirements

The WEC-C model was run for 39 years from 1964 till 2002 on a daily time-step by the input of rainfall and evaporation data. Using these in combination with descriptive data such as estimates of LAI, orebody outlines and haul road alignments, the model creates a series of outputs that detail the simulated state of the catchments. Comparing the simulated outputs with measured data is the basis of the model calibration and validation processes.

For the Seldom Seen and More Seldom Seen catchments, groundwater level data was areally sparse and limited in duration. Stream salinity was not continuously measured for either catchment and the range of manually sampled salinities was small, 114–167 mg/L TDS on an annual flow weighted basis. Streamflow was therefore the sole variable for which comparisons were made between observed data and simulation output.

5.1.1 Rainfall and pan evaporation

Rainfall data were available from the rainfall gauges in each catchment from June 1974 till simulation end in 2002 (M509269 in Seldom Seen, M509270 in More Seldom Seen, and M509071 in Waterfall Gully). Rainfall data for the period 1964–74 was generated using records from Jarrahdale (M009023) and Wungong (M009044). Missing records for one station were filled in using data from the others. Daily pan evaporation was sourced from the CALM meteorological station at Dwellingup and was adjusted to the study location by application of the factor 1.109. This factor was based on Luke et al. (1988). Evaporation records were not corrected for the effects of the bird guard.

5.1.2 Streamflow

Continuous streamflow records were available from the gauging stations, Seldom Seen S616021 and More Seldom Seen S616022. The Seldom Seen gauge commenced operation on 13 April 1966 and the More Seldom Seen on 30 March 1966. Both are still operational.

5.1.3 Evapotranspiration

Evapotranspiration (ET) is the dominant component of the water balance of the Northern Jarrah Forest and far outweighs stream yields (Schofield et al. 1989). The average stream yield of both catchments over the study period was 22% of rainfall. The down-valley groundwater flow out of both catchments was estimated to be less than 1.0%. Neglecting storage effects, this left approximately 77% of the catchment water balances to account for. As most of this 77% was lost to ET its accurate simulation was essential to the successful simulation of catchment hydrology. In turn, the correct estimation of the vegetation cover and its temporal changes were essential to the estimation of ET.

The transpiration demand function used in WEC-C is described by potential transpiration (PT) per unit LAI *(Equation 1)*:

$$PT = A * \ln(E) + B \qquad \text{(Equation 1)}$$

where:

E = pan evaporation in mm/day
A and B are constants which, in this study, were: A = 0.6 and B = 0.6 for forest, and A = 0.9 and B = 0.6 for mine revegetation.

These values of A and B were from Croton (2004). Equation 1 is scaled by LAI to estimate total potential transpiration within the model.

5.1.4 LAI estimation

Because LANDSAT TM images were only available from 1988, while this study required estimates of LAI back to 1964, LAI estimations were based on interpretation of aerial photographs. A review of readily available photographs resulted in the selection of five for both catchments: 1969, 1979, 1984, 1990 and 2000; and one additional photograph from 1986, just for More Seldom Seen. This extra photograph was added as there were extensive FIRS activities in More Seldom Seen in 1985.

LAI estimation was based on a negative relationship with the red colour (R) from scans of the aerial photographs. A negative relationship with R from remotely sensed data has been used by other researchers to define LAI (Peterson & Running 1989; Price & Bausch 1995) due to the high absorption of R by leaf pigments (Coops et al. 1997). The relation used was a simple two-parameter equation *(Equation 2)*.

$LAI = a - b * R$ *(Equation 2)*

where:

R is the eight-bit scan value for red colour
a and *b* are parameters obtained by simultaneous solution for values of R.

The values of R used in Equation 2 were: bare areas, that is, LAI = 0.0; and stream zone areas, using an assumed LAI = 1.75. Table 3 lists the R-values for these along with the resultant values of *a* and *b*.

Table 3. Parameters a *and* b *used in Equation 2 for LAI estimation*

Year	Values of R estimated from aerial photographs			*a*	*b*
	LAI = 0	*Stream zone*	*Min value*		
1969	210	80	65	2.83	0.01346
1979	245	95	77	2.86	0.01167
1984	235	130	100	3.92	0.01667
1986	225	65	40	2.46	0.01094
1990 SS	230	50	40	2.24	0.00972
1990 MSS	240	70	40	2.47	0.01029
2000	240	115	30	3.36	0.01400

The LAI maps developed represent a historical estimate of the vegetation cover following activities such as mining and logging, and effects such as dieback. The Seldom Seen and More Seldom Seen catchments are not ideal sites for the study of the effects of bauxite mining, given the disturbance caused by these other factors. In addition, the records provided by Alcoa World Alumina Australia and CALM on their

DFR and FIRS activities within the catchments were accurate in areal extent but lacked information on the intensity of treatments or rates of post-treatment responses. Lastly, the CALM FMIS data on logging only provided information on the last recorded activity for a given area. The net result has been that, while it was possible to track vegetation density changes in the forest areas through interpretation of aerial photographs, it was not possible to assign the changes to any particular activity or effect. This would have been seen as a limitation if the primary objective were to understand the effects of particular DFR and FIRS treatments; but this is not the case, and therefore forest LAI changes are lumped together as a simple chronology of variation.

Figure 7 shows the estimated average LAIs for the study period. The catchments were divided into two areas: unmined forest and mine areas. For mine areas, the plotted LAIs were simple averages, without considering whether the areas were yet to be mined, were being mined, or were revegetated. In 1969, the LAIs for both catchments were similar, in the range 1.14 to 1.20 for the unmined forest and mine areas. The 1979 FIRS treatments within Seldom Seen show up clearly as a decline in unmined forest LAI to 1.04. There was then a steady growth in forest LAI until it was slightly above that of More Seldom Seen in 2000 (1.51 compared with 1.45). In the mined areas, the clearing can be seen as a dip in average LAI to minima of 0.65 for Seldom Seen and 0.62 for More Seldom Seen. The 2000 LAI estimates for both catchments in the mined areas had similar values: 1.50 for Seldom Seen and 1.53 for More Seldom Seen, which were similar to the unmined forest LAI in 2000. The developed LAI maps were consistent between catchments and areas and are consistent with the vegetation history.

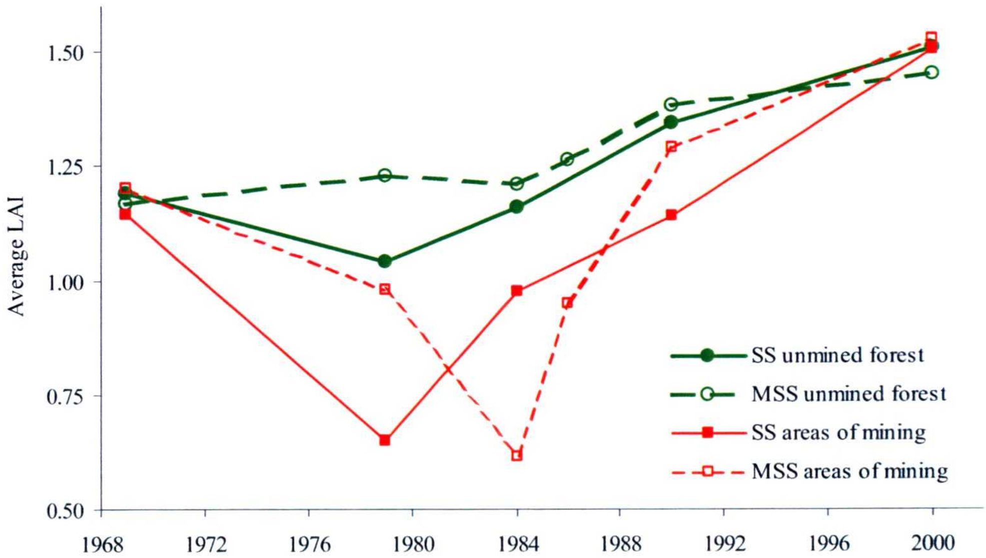

Figure 7. Average LAI estimates for the unmined forest and mine areas of the Seldom Seen (SS) and More Seldom Seen (MSS) catchments

To create a set of maps for the unmined scenario, the mine areas had to be filled with estimates of forest LAI in the post-mining period. This was accomplished by taking the last LAI estimate prior to mining and applying a growth factor estimated from the growth rates of 'undisturbed' areas of forest within the catchments. A second unmined scenario (the unchanged scenario) was also used in the study. In this unchanged scenario, for disturbed and undisturbed areas alike, the forest did not grow at all during the study period, and the initial LAI map from 1964 was used from simulation start to end (Table 4).

Table 4. LAI estimates and transpiration parameters for the four modelled scenarios

Scenario	*Land use*	*Value of A in Eq. 1*	*LAI description*
Mined – base scenario	Forest Mine Reveg.	0.6 0.9	LAI estimated from aerial photos for both forest and mined areas.
Mined – alternative scenario	Forest Mine Reveg.	0.6 0.6	LAI estimated from aerial photos for both forest and mined areas.
Unmined	Forest	0.6	LAI from aerial photos for forest, mine areas use last forest estimate plus growth curve.
Unchanged	Forest	0.6	1964 LAI map used for entire simulation. There is no growth of forest vegetation.

5.2 Model set-up

5.2.1 Catchment descriptions

The same model framework was used for Seldom Seen and More Seldom Seen catchments as for Del Park catchment by Croton (2004). It was based on a seven-layer model with the following layering. The first layer was the top soil, the second the duricrust on the valley flanks and a continuation of the topsoil in the valley floor. The third layer included the bauxitic and mottled zones, while the fourth to sixth layers were the pallid zone. The seventh layer was the weathering zone. The bedrock was assumed to be impervious and its surface was the model base.

Maps of soil profile depth were developed by Kriging on a 50-m grid the borehole depth data provided by the 11 drill holes in Seldom Seen and the three drill holes in More Seldom Seen (Table 9 in Appendix 2). The range of model soil profile depths were 5–30 m (average 17.9 m) for Seldom Seen and 8–24 m (average 17.4 m) for More Seldom Seen. The profile was divided into layer depths as follows: the first layer thickness was set to a uniform 0.4 m (Table 5); the second layer was assumed to be 1.5 m thick on the valley flanks thinning to 0.4 m in the valley floor; the third layer was set to 3.6 m on the valley flanks and to 0.8 m in the valley floor; the maximum thickness of the bottom (seventh) layer was 5.0 m, and layers four, five and six had depths equal to 33% of the remaining profile thickness.

Soil profiles of the entire catchment were divided into two: matrix and preferred pathways. For simplicity, only four soil types were used on the valley flanks for the matrix: a gravelly sand with a vertical saturated conductivity (K_{sat}) of 3000 mm/day for layer one, the duricrust with K_{sat} of zero for layer two, a loam with K_{sat} of 250 mm/day for layer three, and a clay with K_{sat} of 5 mm/day for the pallid and weathered zones (layers four to seven). Preferred pathways, occupying 5% of the profiles, had gravelly sand in all layers, with K_{sat} of 3000 mm/day (Table 5). The layering of the valley floors was similar to the valley flanks with two notable exceptions for layers two and four. In layer two, the duricrust was substituted by gravelly sand with K_{sat} of 3000 mm/day. Layer four, the top most layer of the pallid zone, had the properties of an impeding layer: clay with K_{sat} of 1.25 mm/day for the matrix, and a loam with K_{sat} of 125 mm/day for the preferred pathway. The percent occupancy of the preferred pathways was also reduced, from 5% to 1%, in layer four.

The form of the soil moisture characteristic curves, that is the ψ - θ and θ - K relations, have a marked effect on the outputs of the model. Raper and Croton (1996) reviewed all data for the Darling Plateau and curve forms were selected from their report that were similar to those of Campbell (1974) as modified by

Hutson and Cass (1987). These curve forms were preliminary though it should be noted that they have been successfully used in all Darling Plateau WEC-C modelling to date.

Regarding saturated lateral conductivity (K_{lat}) for the first three layers, a value of 15 m/day was used for everything except the duricrust which was assigned $K_{lat} = 0$. The value of 15 m/day was also used by Croton and Bari (2001), and, while it appears high, is considered reasonable. These values gave the best fit of the model output hydrograph shapes to the observed data. For the pallid zone a graduation with K_{lat} values of 0.0, 0.045 and 0.09 m/day for layers four, five and six respectively were used. These values, also applied by Croton and Bari (2001), were derived from Clarke et al. (2000) with the graduation of K_{lat} based on the observation by Martin (1988) that the lower section of the pallid zone appeared coarser and should be transitional. The weathering zone, layer seven, was assigned a K_{lat} value of 0.75 m/day (Clarke et al. 2000; Croton & Bari 2001).

Table 5. Assumed soil profiles for the valley flank and the valley floor soils of the catchments. The assumed profiles are the same as those used by Croton (2004). The units of K_{sat} are mm/day.

Layer	Thickness (mm)	Soil matrix		Preferred pathway		
		Type	K_{sat}	% Profile	Type	K_{sat}
Valley flank soils						
1	400	gravelly sand	3000	5	gravelly sand	3000
2	1500	duricrust	0	5	gravelly sand	3000
3	3600	loam	250	5	gravelly sand	3000
4	33% of balance	pallid clay	5	5	gravelly sand	3000
5	33% of balance	pallid clay	5	5	gravelly sand	3000
6	33% of balance	pallid clay	5	5	gravelly sand	3000
7	5000 maximum	weathering zone	5	5	gravelly sand	3000
Valley floor soils						
1	400	gravelly sand	3000	5	gravelly sand	3000
2	400 (1000)	gravelly sand	3000	5	gravelly sand	3000
3	800 (1600)	loam	250	5	gravelly sand	3000
4	33% of balance	Impeding layer	1.25	1	loam	125
5	33% of balance	pallid clay	5	5	gravelly sand	3000
6	33% of balance	pallid clay	5	5	gravelly sand	3000
7	5000 maximum	weathering zone	5	5	gravelly sand	3000

5.2.2 Initial conditions

The initial groundwater level map was derived from the measured groundwater level data. This map is subjective in nature, as there are only 11 piezometers within the Seldom Seen catchment and three piezometers within the More Seldom Seen catchment, and the record for all piezometers is limited (Table 9 in Appendix 2). To develop a soil moisture initial conditions map, a number of dummy simulations of the model were run with the vegetation cover left as a constant. The final simulations started in 1964 while the model outputs were compared to observed data from 1966 to 2002. This extra two years at the simulation outset helped buffer the effect of possible errors in the initial conditions.

5.2.3 Best parameter set

An infinite number of parameter sets are possible for complex, distributed, deterministic models such as WEC-C due to their many degrees of freedom. A successful model application must be based on experience and move forward through any parameter optimisation in a logical manner that considers not only the accuracy of gross outputs like streamflow, but also suitability of internal processes. A trial and error approach cannot be adopted.

The parameter set used was identical to that employed by Croton (2004) for the Del Park catchment. Del Park is a second-order catchment near Dwellingup and was mined for bauxite during the period 1976–89. The parameter set for Del Park was based on experience with WEC-C modelling of other catchments in the Darling Plateau. The use of the same parameter set for the three catchments (Del Park, Seldom Seen and More Seldom Seen) is not a definitive proof of its correctness; it does however indicate how robust it is and applicable as a generic parameter set for other, similar catchments in the Darling Plateau.

6 Comparison with observed data

As discussed in the previous section, the parameterisation used for the Seldom Seen and More Seldom Seen catchments was not an optimisation for them but rather a direct application to these catchments of the parameter set developed by Croton (2004) for the Del Park catchment. In this section, the performance of this parameter set is assessed by comparing simulated and observed streamflows. The comparison period was the 36 years 1966 to 2002 inclusive; and the results are presented in order of decreasing time scales, from annual to monthly to daily. The results for both catchments are given together, as the objective is to seek confirmation that the parameter set is applicable to both catchments and that there is commonality of response.

6.1 Annual streamflow

The general correspondence of the simulated to observed annual streamflows of the Seldom Seen catchment is good (Fig. 8), though there is some underestimation in some higher flow years. Figure 9 shows the data as an x-y plot of observed vs simulated, with the slope term of 0.87 and the general falling of the points below the 1 to 1 line highlighting the high flow underestimation. The $R^2 = 0.87$ does, however, still imply a reasonable correlation between simulated and observed.

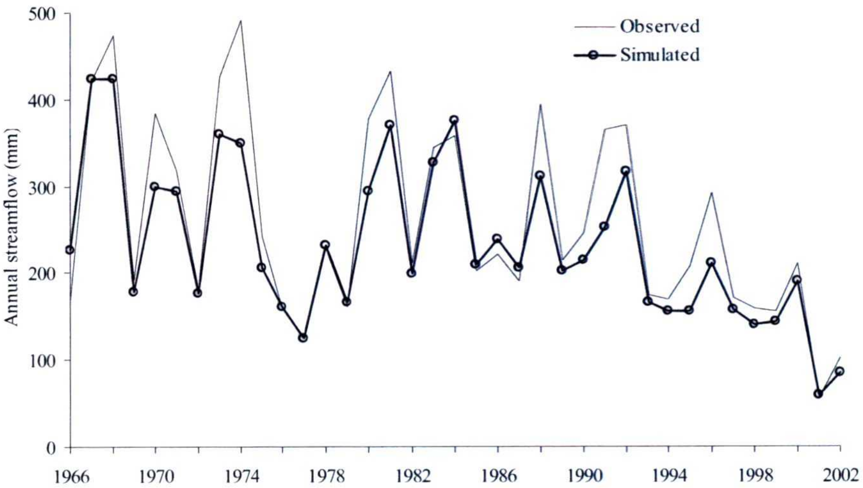

Figure 8. Time series comparison of observed and simulated streamflows for the Seldom Seen catchment

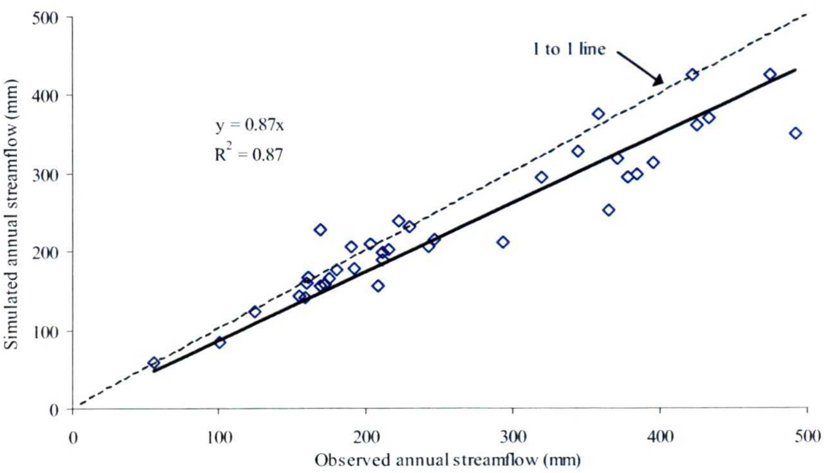

Figure 9. Comparison of observed and simulated annual streamflows for the Seldom Seen catchment

The correspondence of the simulated to observed annual streamflows of the More Seldom Seen catchment is very good (Fig. 10); while there is still some underestimation in the high flow years, this is significantly less than for Seldom Seen. Figure 11 is an x-y plot for More Seldom Seen and the slope term is closer to 1.0, that is 0.93. The $R^2 = 0.91$ implies a strong correlation between simulated and observed.

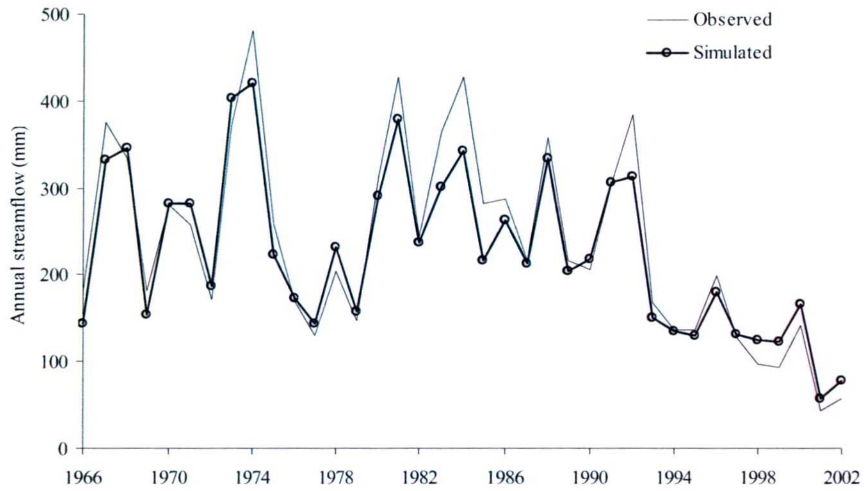

Figure 10. Time series comparison of observed and simulated streamflows for the More Seldom Seen catchment

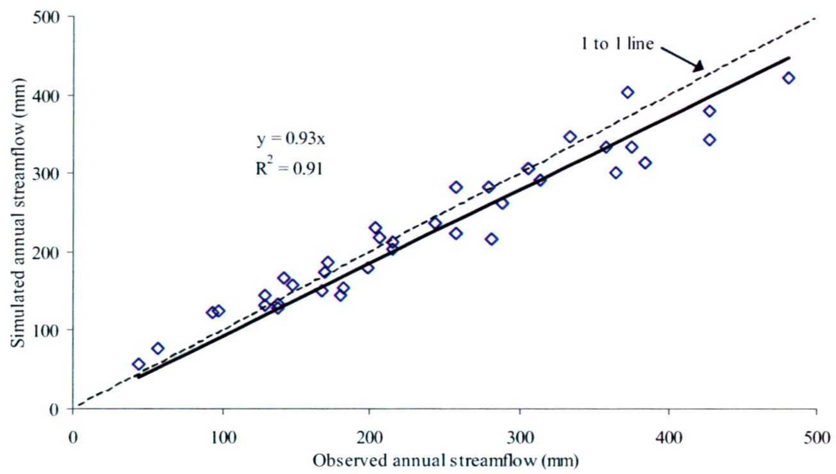

Figure 11. Comparison of observed to simulated annual streamflows for the More Seldom Seen catchment

6.2 Monthly streamflow

The correspondence of the simulated to observed flows for both catchments is better for monthly than for annual (Figs 12 & 13). This is expected as the Mediterranean-type climate of the Darling Plateau creates highly seasonal flow variations which tend to swamp the variation between observed and simulated. Sometimes, though, monthly statistics are useful and, for this study, they shed light on the underestimated high flows. Figure 12, an x-y plot of monthly flows for Seldom Seen, shows that the underestimation was caused primarily by the model's peak flows being lower than the observed flows. For flows above 40 mm/month, the simulated has dropped below the 1 to 1 line in almost all cases. Figure 13 is the corresponding plot for More Seldom Seen; the slope term at 0.94 is close to 1.0 and the points scatter about the 1 to 1 line rather than plotting below it.

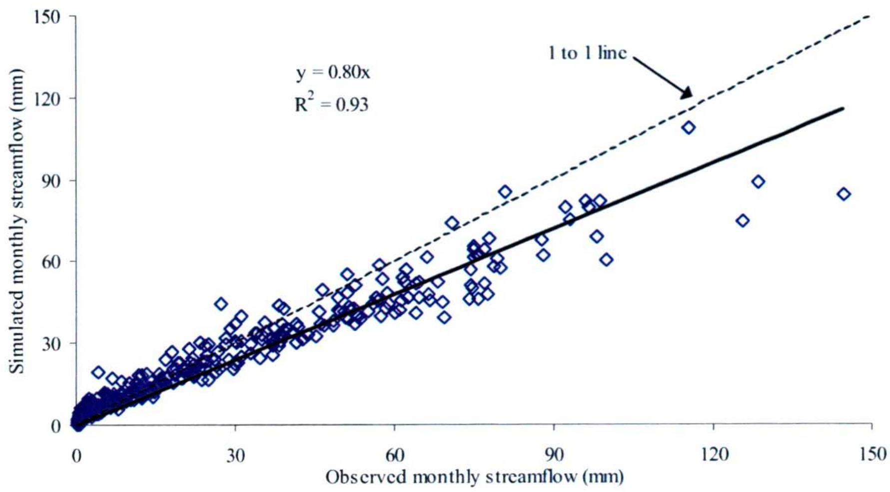

Figure 12. Comparison of observed and simulated monthly streamflows for the Seldom Seen catchment

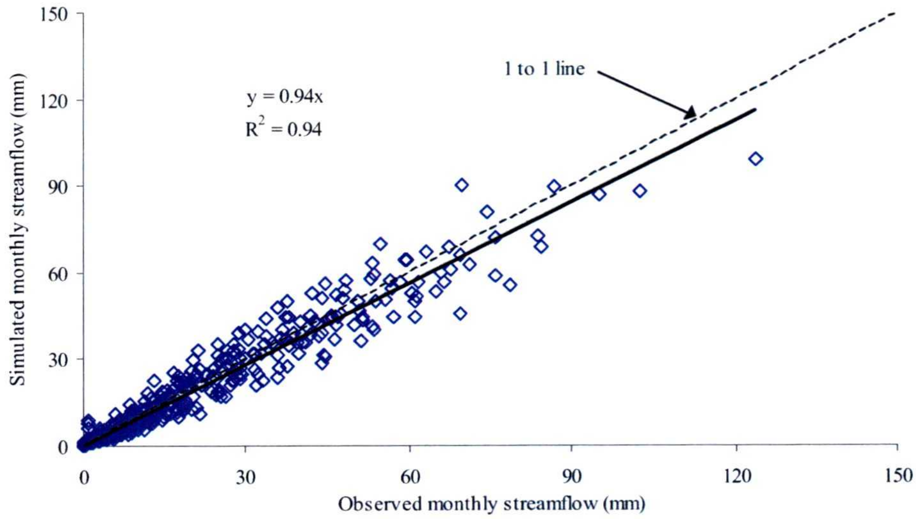

Figure 13. Comparison of observed and simulated monthly streamflows for the More Seldom Seen catchment

6.3 Daily streamflow

Two daily hydrographs for Seldom Seen are presented in Figure 14: one for the highest flow and worst fitted year, 1974 (Fig. 14a); and one for the best fitted year and third lowest flow, 1977 (Fig. 14b). The differences in scale are important when viewing these graphs. For 1974, the simulated flow tracks the observed well until late July when the simulated fails to follow the observed into a period of elevated streamflow, much of which is above 4 mm/day. The plot for 1977 shows that, when such a period of high flows was absent, the model tracked the observed over the whole year. Figure 15 shows the flows of the More Seldom Seen catchment for the same two years. For 1974, it can be seen that the observed peak flows did not rise as high for More Seldom Seen as they did for Seldom Seen and the model trace therefore remained closer to them, though there is still underestimation in the second half of the winter flow period. The fit for 1977 is very good, with accurate tracking of flows across the range; such a fit approaches the limit of daily time-step modelling.

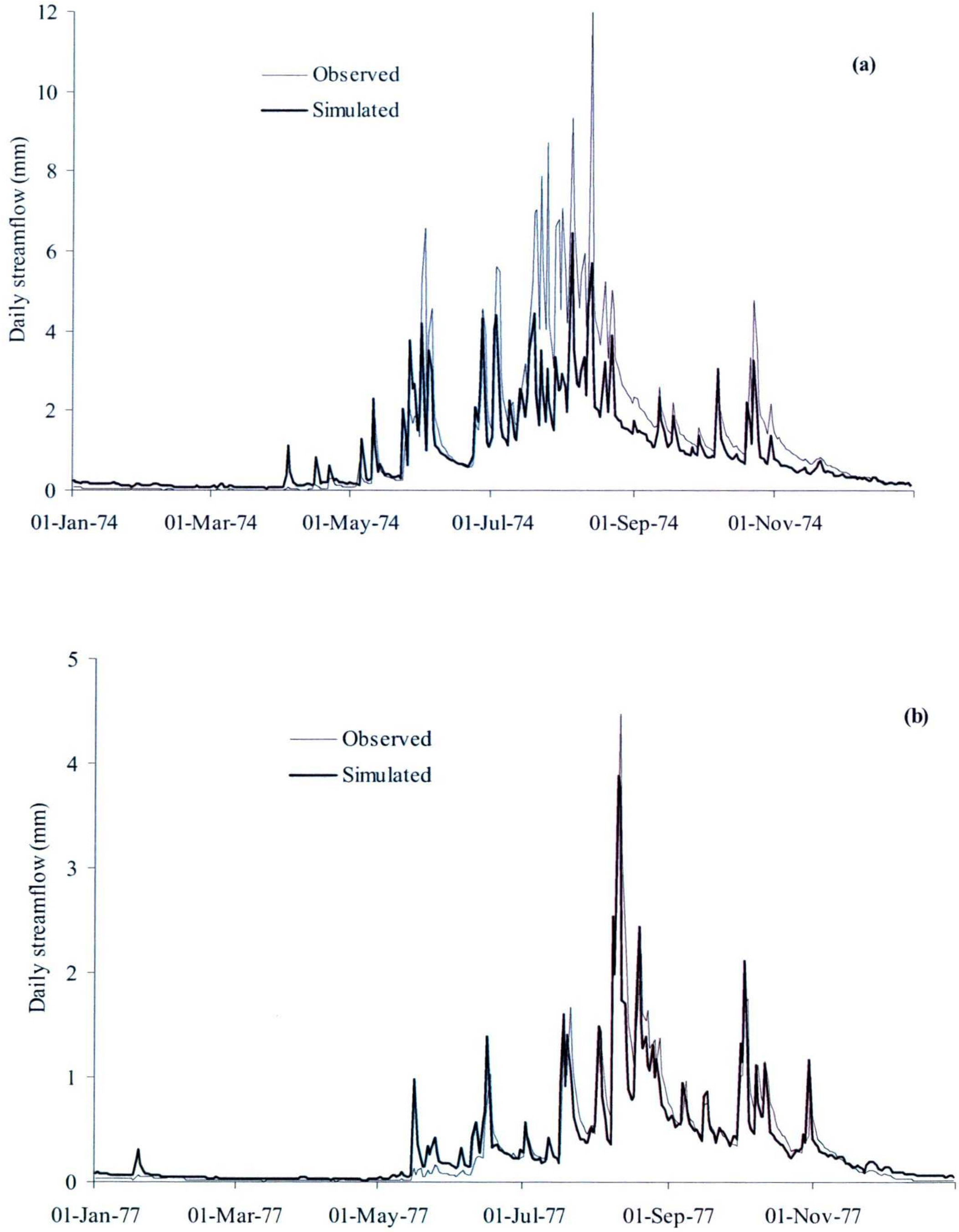

Figure 14. Comparison of observed and simulated daily streamflows for the Seldom Seen catchment for a) 1974 and b) 1977

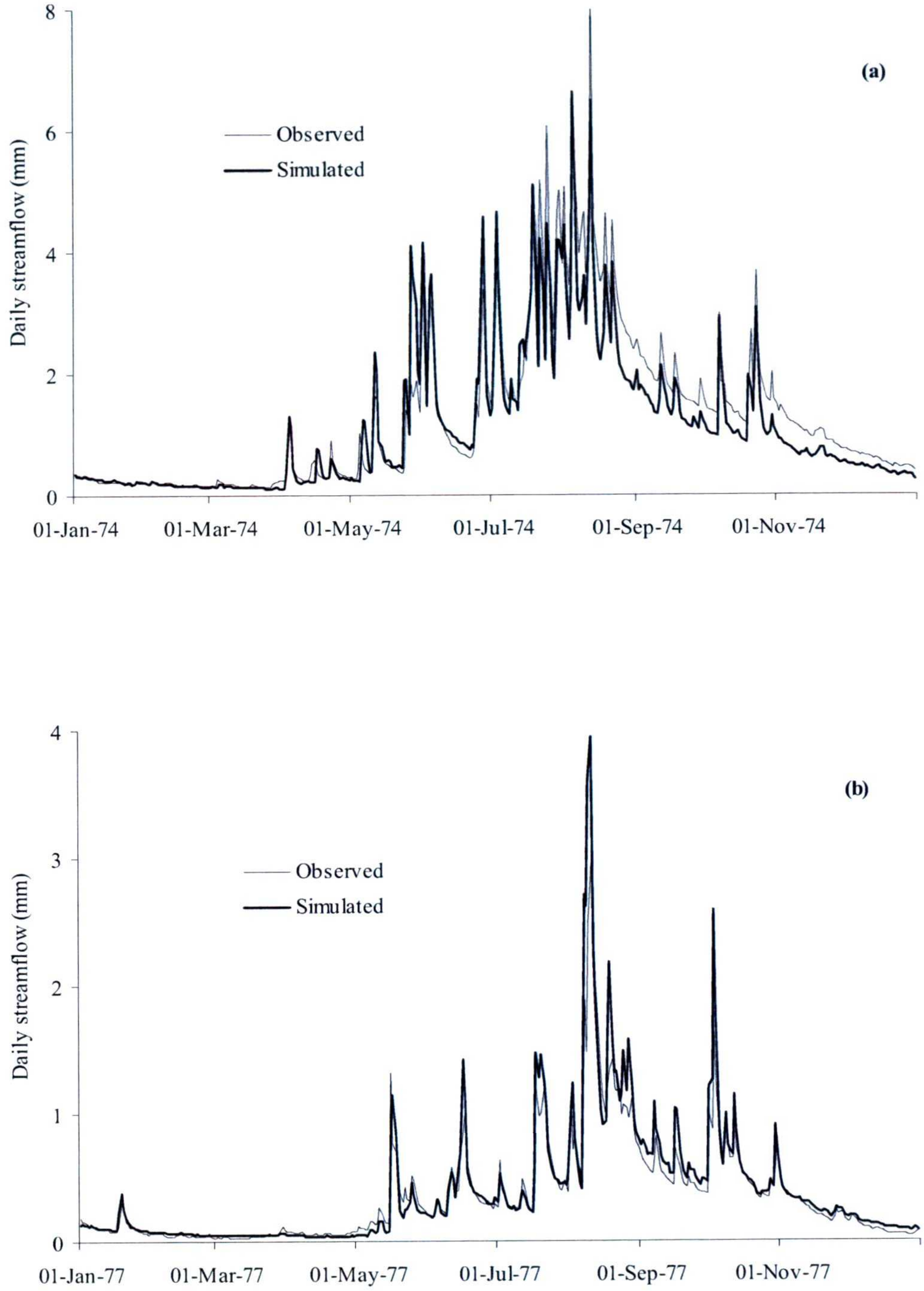

Figure 15. Comparison of observed and simulated daily streamflows for the More Seldom Seen catchment for a) 1974 and b) 1977

Figures 16 and 17 show x-y plots for the daily observed and simulated streamflows for the Seldom Seen and More Seldom Seen catchments. As expected, the Seldom Seen values above about 4 mm/day tend to plot below the 1 to 1 line, while the More Seldom Seen values are scattered around the 1 to 1 line through the whole range.

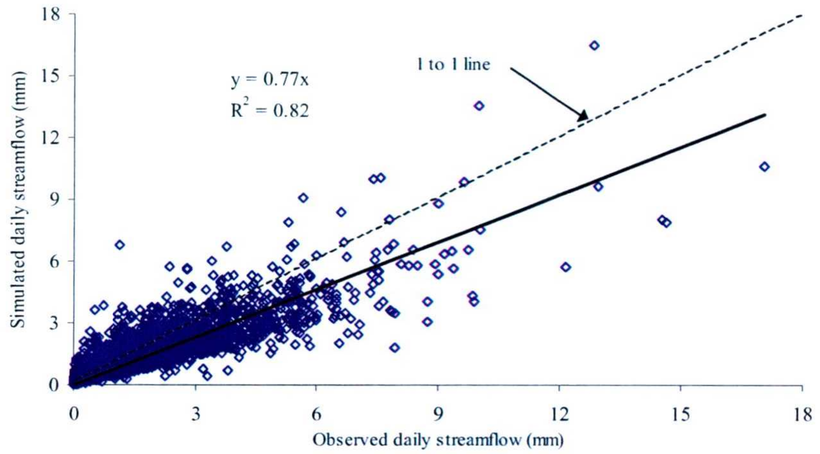

Figure 16. Comparison of observed and simulated daily streamflows for the Seldom Seen catchment

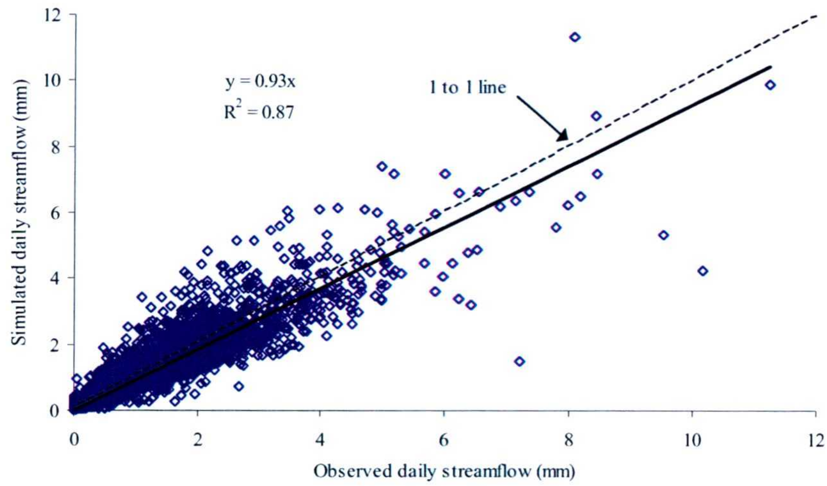

Figure 17. Comparison of observed and simulated daily streamflows for the More Seldom Seen catchment

6.4 Summary

Model performance in terms of streamflows is summarised in Table 6 using five statistical measures: mean, the coefficient of correlation (R^2), coefficients of efficiency (E_1 & E_2), and index of agreement (d_2) (Lagates & McCabe 1999). By all measures, the More Seldom Seen simulations have outperformed those for Seldom Seen. It has already been proposed that the primary cause of this is underestimation of flows in the later part of high flow years. Were the present modelling for Seldom Seen being undertaken in isolation, it would be necessary to optimise the model parameters for this catchment and obtain a better fit. However, the exercise being undertaken is constrained in two ways. Firstly, a new parameter set is not being developed but rather an established parameter set by Croton (2004), developed on the Del Park catchment, is being applied. Secondly, the modelling of Seldom Seen and More Seldom Seen is a combined exercise, and, as a close match to observed data has already been obtained for More Seldom Seen, there is little justification for embarking on a new parameter optimisation exercise. The present period of below-average rainfalls, and resultant below-average streamflows, favour remaining with the present parameter set. As these are the conditions for a good match with observed data, the predictions of present day flows are better than implied by the statistics in Table 6.

In conclusion, while there are limitations concerning the high flow year simulations for the Seldom Seen model, these should not impede the model fulfilling the study objective of assessing the effects of bauxite mining on streamflows to Perth's water supply reservoirs. However, it must be kept in mind that the present Seldom Seen model is underestimating flows above about 4 mm/day, and this model should not be used in future studies where this could be important — such as flood flow estimation.

Table 6. Summary of statistics for simulated streamflows vs observed streamflows

Catchment		*Daily*	*Monthly*	*Annual*
Seldom Seen	Observed mean streamflow (mm)	0.711	21.3	260
	Simulated mean streamflow (mm)	0.634	19.2	233
	R^2	0.82	0.93	0.87
	E_2	0.81	0.89	0.81
	E_1	0.69	0.76	0.61
	d_2	0.94	0.96	0.94
More Seldom Seen	Observed mean streamflow (mm)	0.665	20.0	234
	Simulated mean streamflow (mm)	0.635	19.1	223
	R^2	0.87	0.94	0.91
	E_2	0.86	0.94	0.91
	E_1	0.71	0.78	0.72
	d_2	0.96	0.98	0.97

Note: The R^2 values are for constrained regressions, that is $y = m*x$.

7 Simulation of streamflow changes

The mined base scenario, which in Section 6 was compared with observed streamflows, is an attempt to model the real-life situation of the catchments, that is, the streamflows when mining takes place and the forest changes in LAI due to treatments and natural growth. It is also assumed in this simulation that potential transpiration (PT) per unit LAI of mine area revegetation was greater than the PT per unit LAI of the unmined forest (Table 4). This was necessary to obtain a match between observed and simulated streamflows throughout the study period. In this section three other 'what-if' scenarios will be introduced and compared. These 'what-if' scenarios, and how they will be compared, are as follows:

- The unmined scenario (Table 4) where mining is assumed not to take place but the forest still changes in LAI due to treatments and natural growth. This scenario will be compared with the mined base scenario to show the effects of mining.
- The unchanged scenario (Table 4) where it is assumed that neither mining nor changes in forest LAI take place. This will be compared with the unmined scenario to show the effects of forest changes in LAI due to treatments and natural growth.
- An alternative mined scenario (Table 4), where the PT of the mine revegetation is the same as that for the forest. This scenario will be compared with the mined base scenario to show how this change in PT affects predicted streamflows.

7.1 Effects of mining (mined base scenario vs unmined scenario)

Figure 18 compares the unmined and mined scenario annual streamflows with the observed streamflows for the Seldom Seen catchment. From 1967, streamflows in the unmined scenario fall below those of the mined and this situation remains until 1999 when the mined starts to dip below the unmined. Figure 19 is the same plot but for More Seldom Seen. For this catchment, the unmined streamflows drop below those of the mined in 1970 and cross above in 1993.

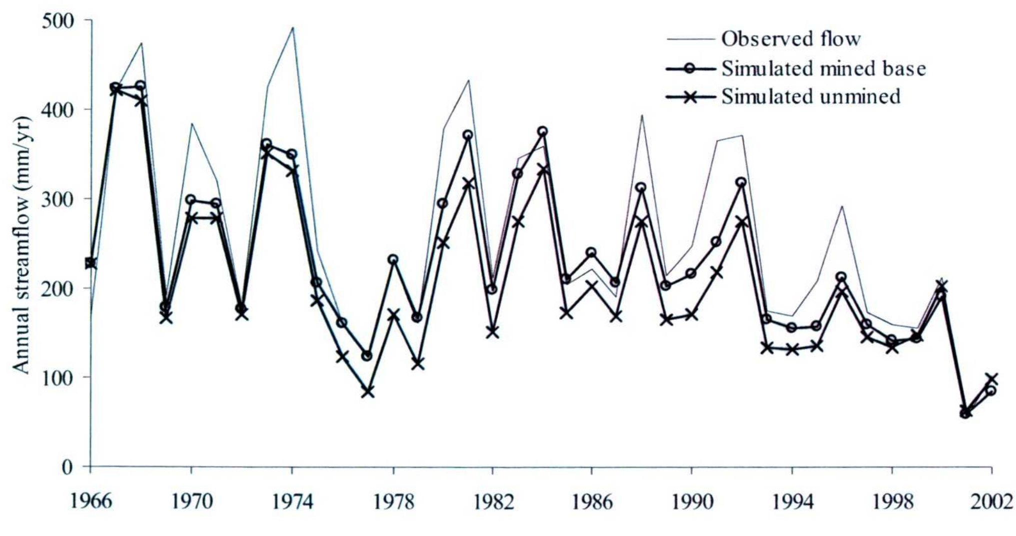

Figure 18. Comparison of observed and mined and unmined scenario streamflows for the Seldom Seen catchment

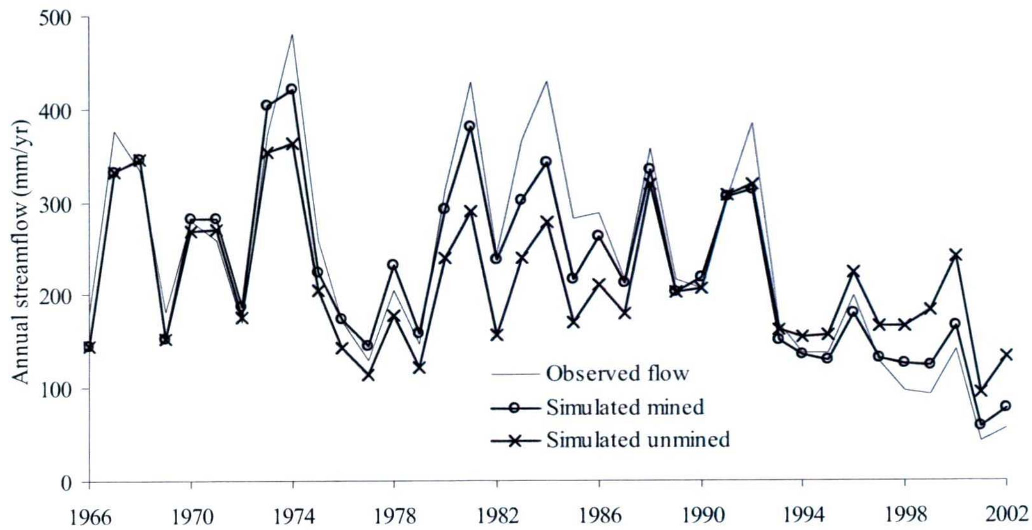

Figure 19. Comparison of observed and mined and unmined scenario streamflows for the More Seldom Seen catchment

To allow a clearer picture of the relative differences between the mine and unmined scenarios, Figures 20 and 21 are difference plots between the mined and unmined scenarios also showing the area cleared for mining but not revegetated. (These differences have been created by subtracting the unmined scenario flows from those of the mined scenarios and therefore represent the changes in streamflow due to mining). For both catchments, the streamflow difference due to mining follows the percentage area-cleared curve and the peaks in flow difference are close to when the areas cleared for mining are at their maximum. Once the cleared areas pass their peaks, there is a steady decline in the streamflow differences and the simulations end with both streamflow differences dropping below the zero line. These reductions relate to the mine area revegetation growing and its evapotranspiration (ET) becoming a significant factor in the catchment water balance.

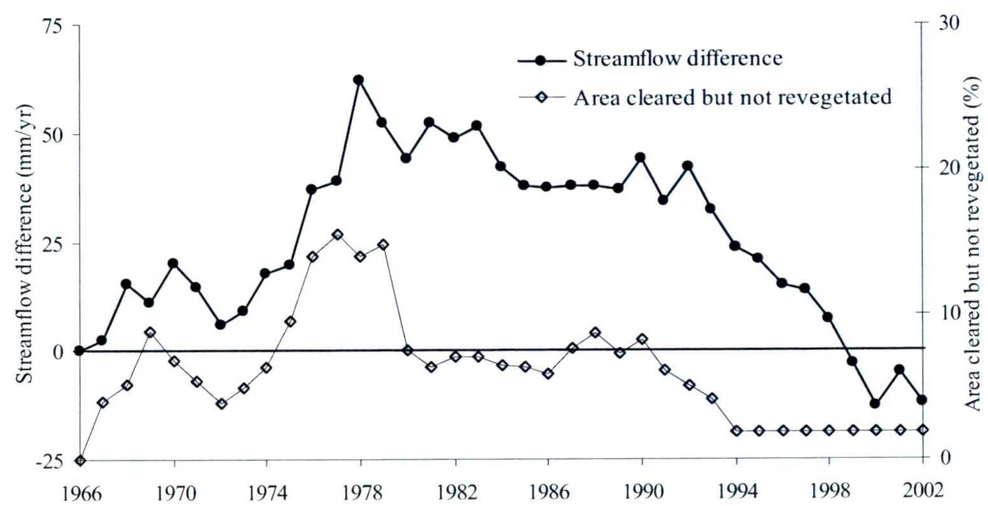

Figure 20. Difference between mined and unmined simulated streamflows for the Seldom Seen catchment. Area cleared but not rehabilitated is plotted for comparison.

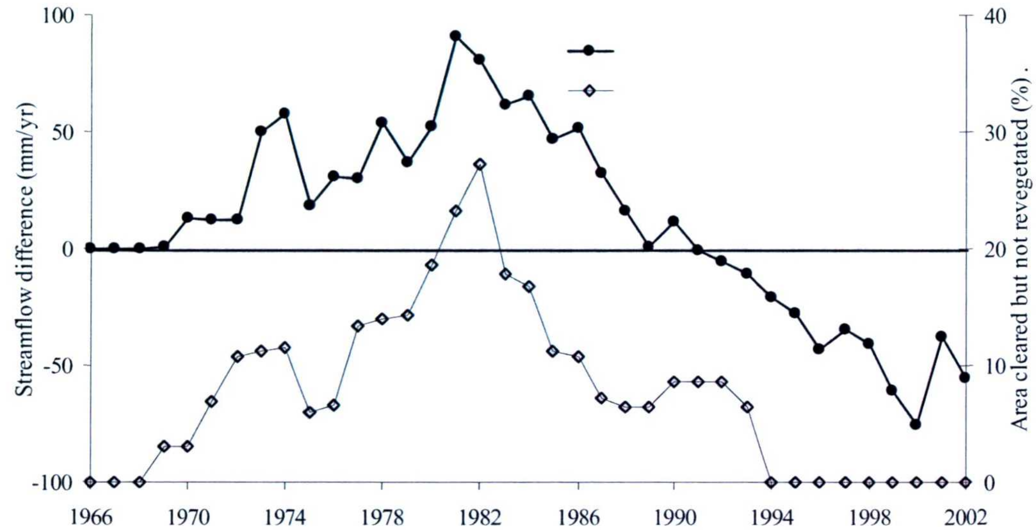

Figure 21. Difference between mined and unmined simulated streamflows for the More Seldom Seen catchment. Area cleared but not rehabilitated is plotted for comparison.

To make the water balance issues in Figures 20 and 21 clearer, Figures 22 and 23 are water balance difference plots for the mined and unmined scenarios for the two catchments. Three components are graphed; ET, streamflow and soil water storage. The ET and streamflow traces are simple annual differences between the mined and unmined scenarios, that is they are the difference for any given year. The soil water storage difference, which includes both unsaturated and groundwater storages, is a running total from 1966 and therefore presents the cumulative difference, or how much water has been gained or lost by the mined scenarios compared with the unmined scenarios.

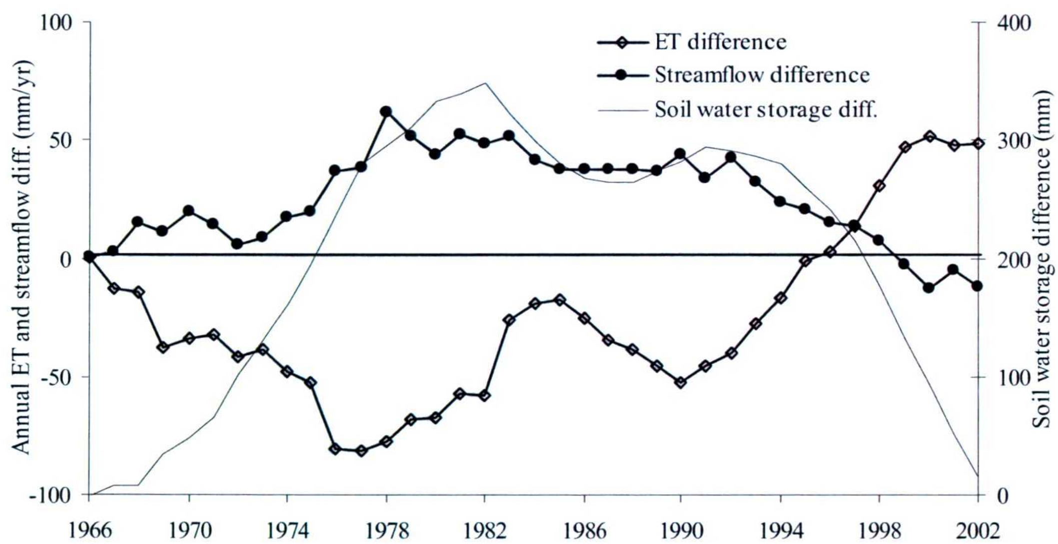

Figure 22. Water balance difference traces for the Seldom Seen catchment between the mined and unmined scenarios

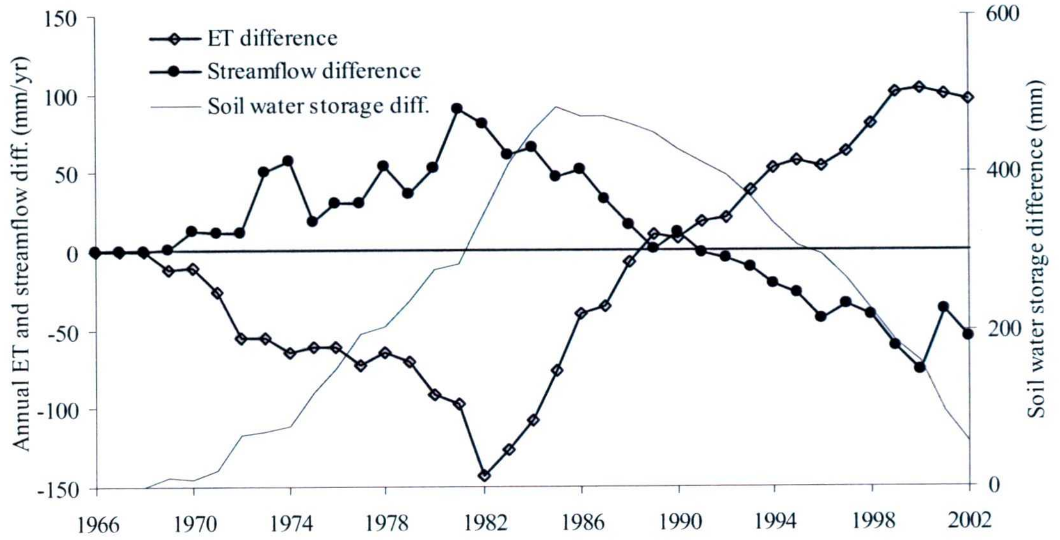

Figure 23. Water balance difference traces for the More Seldom Seen catchment between the mined and unmined scenarios

As shown in Figure 22, in the Seldom Seen catchment, the commencement of clearing in 1967 causes the difference in ET to drop below the zero line and it does not intersect it again until 1995. At first, this reduction in ET goes to increases in both soil water storage and streamflow; however, by 1982, the storage has reached a maximum of 348 mm and the reductions in ET are going into streamflow alone. From 1994, the mine area revegetation starts to predominate causing the ET difference to become positive and thereby cause both the storage and streamflow differences to decline. At simulation end, the ET difference has plateaued at about 50 mm/yr and the sum of the streamflow and storage differences is declining at an equal rate to maintain the water balance. It is expected that the storage difference can only decline so far, and were the simulations extended beyond their 2002 end point, the difference in ET would become balanced just by streamflow reductions.

The story is similar in More Seldom Seen, though more obvious due to the greater percentage of the catchment mined and the shorter duration of mining. The ET difference plot declines steadily to a minimum of –143 mm/yr in 1982. The additional water due to the negative difference in ET is divided between streamflow and soil water storage changes; the storage difference reaches a maximum of 482 mm in 1985. The increasing percentage area of mine revegetation starts to predominate after 1982 and the ET difference increases steadily until it passes through the zero line in 1988. It plateaus at about 100 mm/yr by simulation end. Like the Seldom Seen catchment, both soil water storage and streamflow of the More Seldom Seen catchment go into decline to balance the increases in ET. The simulation ends with both the soil water storage and streamflow differences still declining.

7.2 Forest growth (unmined scenario vs unchanged scenario)

The previous comparison was between the mined and unmined scenarios. The following comparison is between two unmined scenarios. The first is the unmined scenario which has already been used in the previous section and includes changes in forest LAI due to treatments and natural growth. The second is the unchanged scenario where the forest vegetation is kept in its original state during the whole simulation (Table 4), that is, there is no growth or other change in the density of the forest cover. The difference between these two scenarios gives the reduction in streamflow due to forest growth. Figures 24 and 25 show the unmined and unchanged simulated annual streamflows. For both catchments forest growth brings a decline in streamflow. The reduction for Seldom Seen catchment for the last year of simulation is 56 mm/yr (37% of flow) and for More Seldom Seen catchment is 54 mm/yr (29% of flow).

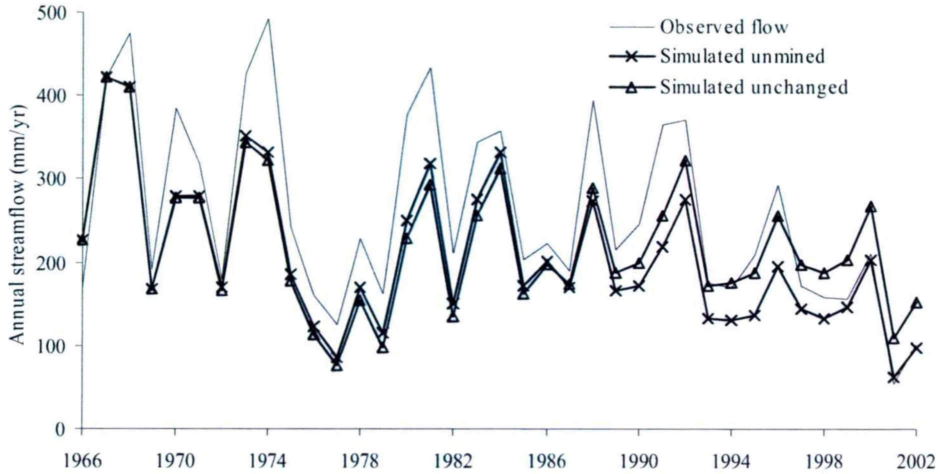

Figure 24. Seldom Seen catchment simulated streamflows for the unmined and unchanged scenarios with observed flow plotted for comparison

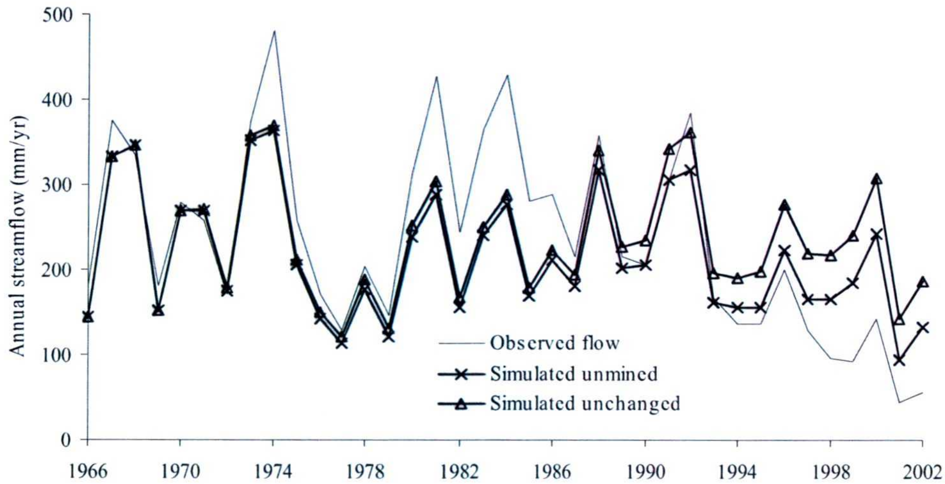

Figure 25. More Seldom Seen catchment simulated streamflows for unmined and unchanged scenarios with observed flow plotted for comparison

7.3 Sensitivity to PT of mine revegetation (mined base scenario vs mined alternative scenario)

The mined base scenario assumed significantly higher potential transpiration (PT) for revegetation after mining (Table 4). In the mined alternative scenario, the PT of mine revegetation was the same as the PT of undisturbed forest (A = 0.6 in *Equation 1*). This section presents the comparison of these two mined scenarios.

The simulated annual streamflows for both mined scenarios for Seldom Seen show many similarities (Fig. 26). The main differences were a better fit to observed flow for the simulated mined alternative (A = 0.6) scenario up to 1998, after which flow of the mined alternative scenario rose above observed streamflow, and the mined base scenario with increased PT for mine revegetation (A = 0.9) became the better fit to observed streamflow.

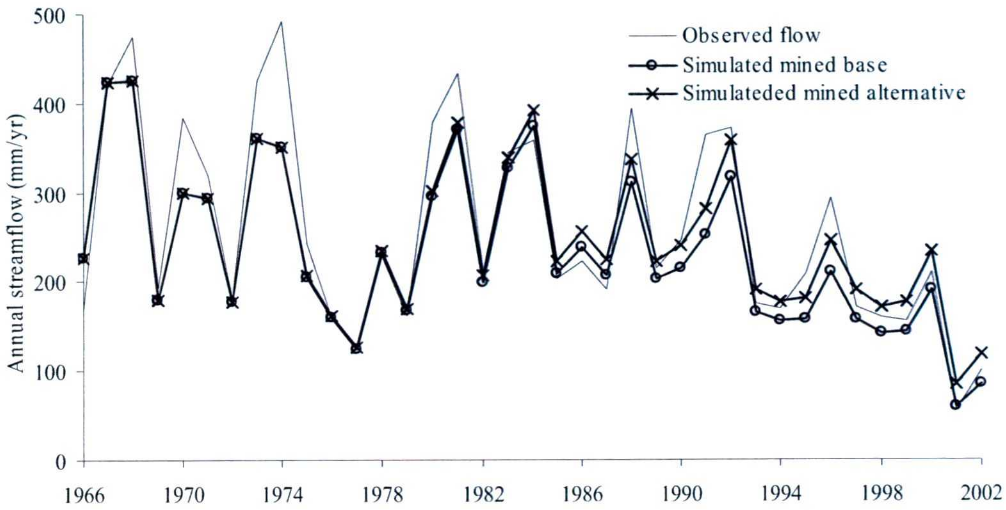

Figure 26. Comparison of the Seldom Seen catchment observed and simulated streamflows for mined base scenario and mined alternative scenario

A similar comparison for More Seldom Seen (Fig. 27) shows a very different situation. For this catchment, streamflow for the mined alternative (A = 0.6) scenario rose strongly above the observed from 1993 while that of the mined base scenario (A = 0.9) closely tracked it.

The difference in these two catchment responses may be explained in terms of the timing and extent of the revegetation. For the Seldom Seen catchment the last, small area was rehabilitated in 2002, while for the More Seldom Seen catchment all revegetation was completed by 1994. The areas mined and subsequently revegetated were very different: 34% of the Seldom Seen catchment and 62% of the More Seldom Seen catchment. The result is that the differences in water use by the mine revegetation between the mined base scenario and the mined alternative scenario are more obvious for the More Seldom Seen catchment than for the Seldom Seen catchment. Expressed as a difference between the mined base scenario and mined alternative scenario for the last year of simulation, Seldom Seen had a reduction of 34 mm/yr (29% of flow) and More Seldom Seen had a reduction of 52 mm/yr (40% of flow).

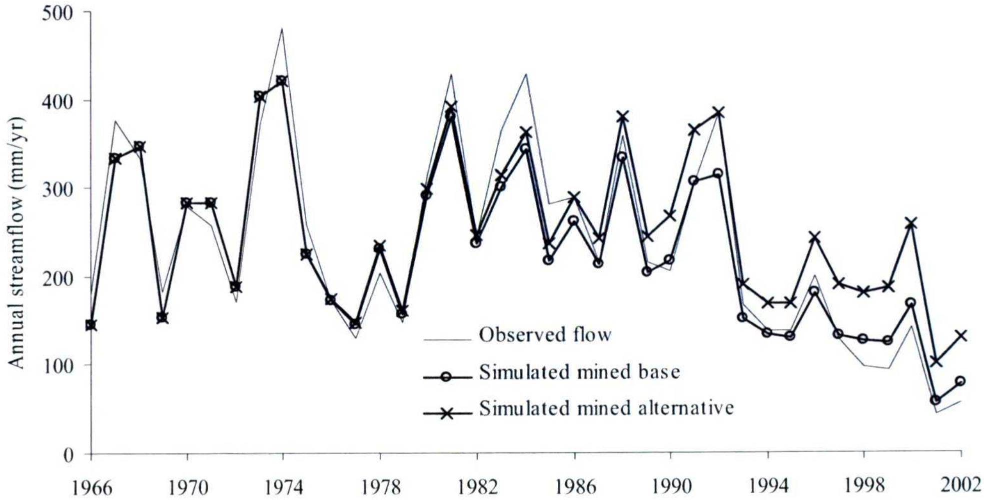

Figure 27. Comparison of the More Seldom Seen catchment observed and simulated streamflows for mined base scenario and mined alternative scenario

7.4 Summary of simulated streamflow changes

The preceding subsections outlined the four simulation scenarios undertaken for each catchment and the differences in streamflow between them. The key points are listed below and summarised in Table 7:

- Clearing for mining creates a transient increase in streamflow. The maximum increases in annual streamflow due to clearing were estimated to be 62 mm/yr for Seldom Seen (36%) in 1978, and 90 mm/yr for More Seldom Seen (31%) in 1981.
- Mine revegetation appears to have a higher annual evapotranspiration than unmined forest thus reducing streamflow. The reductions at simulation end in 2002 were estimated to be 12 mm/yr for Seldom Seen (13%) and 55 mm/yr for More Seldom Seen (42%). The water balances indicated that both soil water storage and streamflow were still reducing. Whether the reductions in streamflow are permanent or transient is unknown.
- The forest in the unmined sections of the catchments grew during the study period and caused reductions in streamflow additional to those due to revegetation of mine areas. The reductions at simulation end in 2002 were estimated to be 55 mm/yr for Seldom Seen (36%) and 54 mm/yr for More Seldom Seen (29%).

Table 7. Summary of simulated streamflow changes

	Mining		**Forest growth**		**Revegetation**	
	Increase in streamflow		*Reduction in streamflow*		*Reduction in streamflow*	
	(mm/yr)	(%)	(mm/yr)	(%)	(mm/yr)	(%)
Seldom Seen	62	36	55	36	12	13
More Seldom Seen	90	31	54	29	55	42

8 Discussion

8.1 Comparison with paired-catchment study

The long duration of streamflow monitoring, 1966 to 2002 (37 years), make the Seldom Seen and More Seldom Seen catchments some of the oldest experimental catchments on the Darling Plateau. It is unfortunate, however, that a number of issues have limited the utility of the Waterfall Gully catchment to act as a control: partial clearing for grazing and agriculture; recurrent silting problems with the streamflow-gauging-station stilling well; landform markedly different from the treated catchments; and different rates of change in forest cover due to dieback. These were compounded by short pre-treatment records for the catchments: one incomplete year for Seldom Seen and three years (one incomplete) for More Seldom Seen. The net result has been that, for estimating the effects of bauxite mining, the paired-catchment study method has been of limited value and really can only act as a qualitative confirmation of the modelling results.

Table 8 lists the changes in streamflow due to mining, estimated by both modelling and a paired-catchment study using Waterfall Gully as control. The peak streamflow increases, in the first column of Table 8, are very different between the methods, with the modelling increases a small fraction of the control catchment study values. The reasons for this large difference seem to be two-fold. Firstly, it appears to be, in part, due to the model underestimating streamflow for higher flow years. Secondly, the Waterfall Gully catchment appears to have below-normal streamflows during the peak mining periods in the Seldom Seen and More Seldom Seen catchments. Figure 28 shows the five-year moving averages for both Waterfall Gully streamflow and rainfall. The axes for these two traces have been subjectively adjusted to cause the traces to overlay. It can be seen that for the period 1980–89 streamflow is well below rainfall. The cause of this is not clear; it may relate to the rainfall–streamflow relation of Waterfall Gully being too complex to be represented by a simple graph like that in Figure 28, or it could even relate to a monitoring issue. Whatever the reason, it calls into question the utility of Waterfall Gully as a control and implies that the peak streamflow increases given in Table 8 using the control catchment method are almost certainly a significant overestimate.

Interestingly, the values in the second column in Table 8, average reductions in streamflow for the period 1998–2002, are very close between methods. As possible long-term reductions in streamflow are of more interest in a water resources context than are short-term increases, this agreement between methods adds weight where it is most needed to the validity of the model predictions.

Table 8. Streamflow changes due to mining, estimated by modelling and the paired-catchment study using the Waterfall Gully catchment as control

	Peak streamflow increase (mm/yr)	*Average reductions in streamflow 1998–2002 (mm/yr)*
	Seldom Seen	
Modelling	62	–5.2
Paired-catchment study	230	–7.8
	More Seldom Seen	
Modelling	90	–54
Paired-catchment study	247	–44

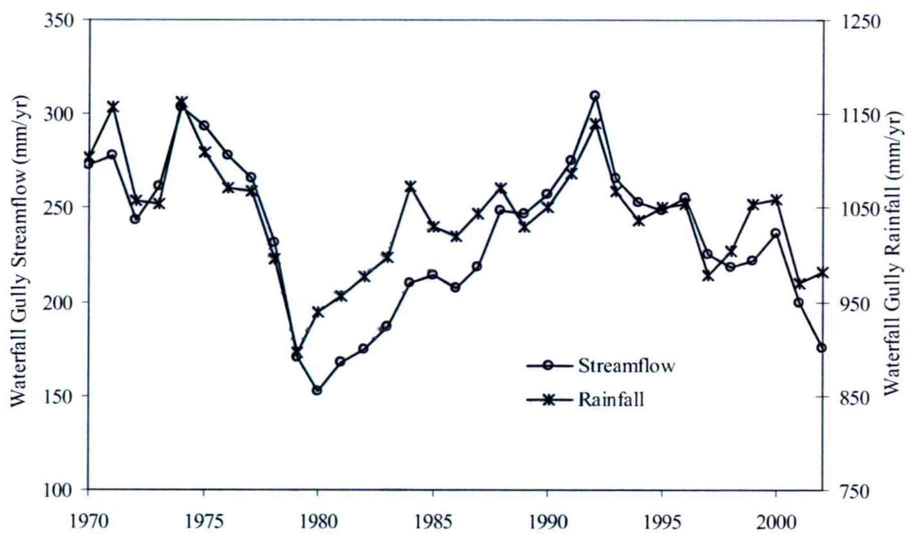

Figure 28. Five-year moving averages for both Waterfall Gully catchment streamflow and rainfall

8.2 Comparison with previous studies

Loh et al. (1984) did the first review of streamflows for the Seldom Seen and More Seldom Seen catchments, using Waterfall Gully as a control in a paired-catchment study. Davies et al. (1995) undertook a second paired-catchment study. They concluded, that while the separation of the effects of mining from forest management activities was difficult, the effects of forestry were negligible and the changes in observed streamflow were solely due to mining. This finding is consistent with the present study in that Davies et al. (1995) only had data up to 1994 and it can be seen from Figures 24 and 25 that the significant response in streamflow due to changes in forest cover was only starting to appear as their study period ended.

Davies et al. (1995) estimated that the annual maximum increases in streamflow due to mining were 23% of rainfall for Seldom Seen catchment and 21% of rainfall for More Seldom Seen catchment, with both occuring in 1981. These are very similar to the present study's estimates from paired-catchment analysis which unfortunately are probably erroneous due to the lack of a stable rainfall-streamflow relation for Waterfall Gully. Davies et al. (1995) also found that, by 1994, when revegetation of mine areas was largely complete, streamflow had returned to close to pre-mining levels. This is consistent with the present study: it was not until the late 1990s that flow reductions below pre-mining levels became obvious.

8.3 Accuracy compared with observed streamflows

The accuracy of the models was considered sufficient for the yield estimates made as part of this study. Significant underestimation of higher flows were noted for the Seldom Seen catchment model, so this model should not be used where this would be an issue, such as in flood studies. The underestimation seems to be caused by inaccuracy in representing mine runoff during high flow years. This was probably related to haul road runoff, and its discharge via sediment settling sumps located along the roads: the effect was absent in early high flow years when there was little mining in the catchment. For instance, 1967 was the second highest flow year with a complete record (there has been significant filling of record for 1968 due to lost data from instrument malfunction) and the daily streamflow hydrographs for observed and simulated are given in Figure 29. While a peak early in the 1967 flow season has been underestimated by the model, there is no evidence of the late season underestimations seen in Figure 14(a). The effect is also largely absent for More Seldom Seen catchment where less of the haul road network discharges to the stream.

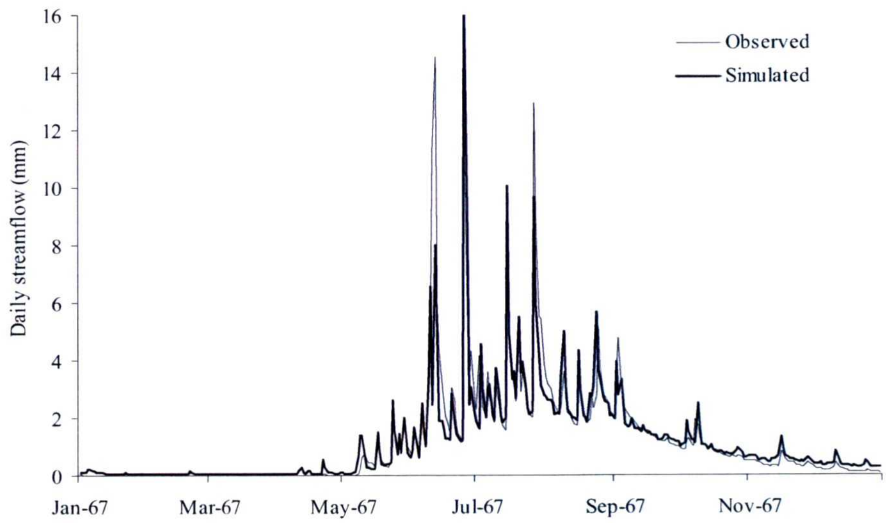

Figure 29. Comparison of observed and simulated daily streamflows for the Seldom Seen catchment for 1967

8.4 Simulated effects of mining

A number of points can be made regarding the effects of mining. Firstly, clearing for bauxite mining creates a transient increase in yield: the peak annual values were estimated to be 62 mm/yr for Seldom Seen and 90 mm/yr for More Seldom Seen. This additional streamflow is due to the reduced ET of the mine areas caused by removal of the vegetation. While the total additional flow was large — estimated to be 957 mm for Seldom Seen and 824 mm for More Seldom Seen — it is not the full reduction in ET, as some water goes into storage. The soil water storage of Seldom Seen was estimated to have increased by 351 mm due to mining; for More Seldom Seen it was 482 mm. These changes in storage partially buffered the effects of mining on streamflows with the buffering operating both ways, that is, both limiting increases and delaying reductions.

Water balance difference calculations showed that the simulated storages for the mined scenarios are now declining compared with the unmined scenarios. These declines mean that the mined scenarios are moving towards drier states than the unmined scenarios. As the storage differences widen so should the capacity to generate streamflow, and further reductions in streamflows would be expected if the simulations were extended.

Figure 30 shows the simulated effects of mining on peak daily flows. In Figure 30 are comparison plots for the two catchments between unmined and mined simulated streamflows for the 52 highest daily flows for the period 1969–94 (26 years, so an average of two plotted values per year). The period 1969–94 was chosen as it is the period when both catchments have areas cleared for mining. It can be seen that there has been an increase in streamflows due to mining with all but a few points plotting above the 1 to 1 line. The regressions in Figure 30 imply that there has been an increase of 14% in peak daily streamflows for Seldom Seen and 16% for More Seldom Seen.

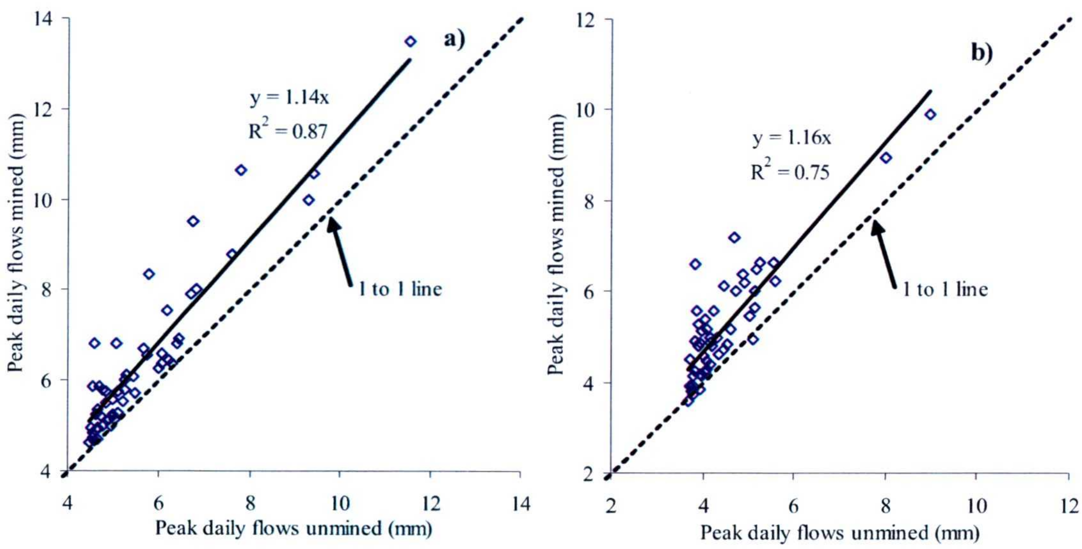

Figure 30. Comparison of maximum daily simulated streamflows for a) Seldom Seen and b) More Seldom Seen during 1969–94

Figure 31 shows comparison plots of minimum monthly flows for the unmined and mined simulations for the same period as Figure 30, that is 1969–94. Minimum monthly flows are good indicators of changes in summer baseflow. As in Figure 30, the plot shows that active mining caused streamflow increases though the regressions imply much larger average rises: 60% for Seldom Seen and 45% for More Seldom Seen.

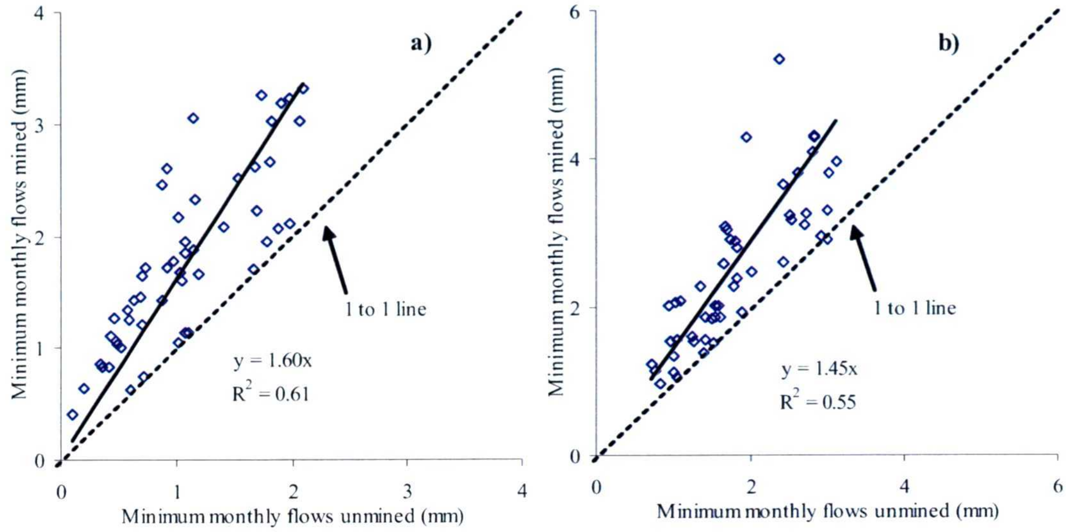

Figure 31. Comparison of minimum monthly simulated streamflows for a) Seldom Seen and b) More Seldom Seen during 1969–94

Figure 32 shows comparison plots of minimum monthly flows for the unmined and mined simulations for the end of simulation period, that is, 1998–2002. For Seldom Seen, it can be seen that the baseflows of the mined and unmined scenarios are similar, and, while the regression has a slope of 1.13 and implies 13% greater flows for the mined scenario, the reality is that this slope term is strongly controlled by a single high value from the year 1998, and if this value is neglected the slope becomes 1.02, essentially one. For More Seldom Seen, the regression slope is 0.59 implying a 41% reduction in streamflow. Figure 32(b) also implies a proportionately greater reduction in flows for the mined scenario at the lower end of the graph. This indicates the non-linearity of the response to mining.

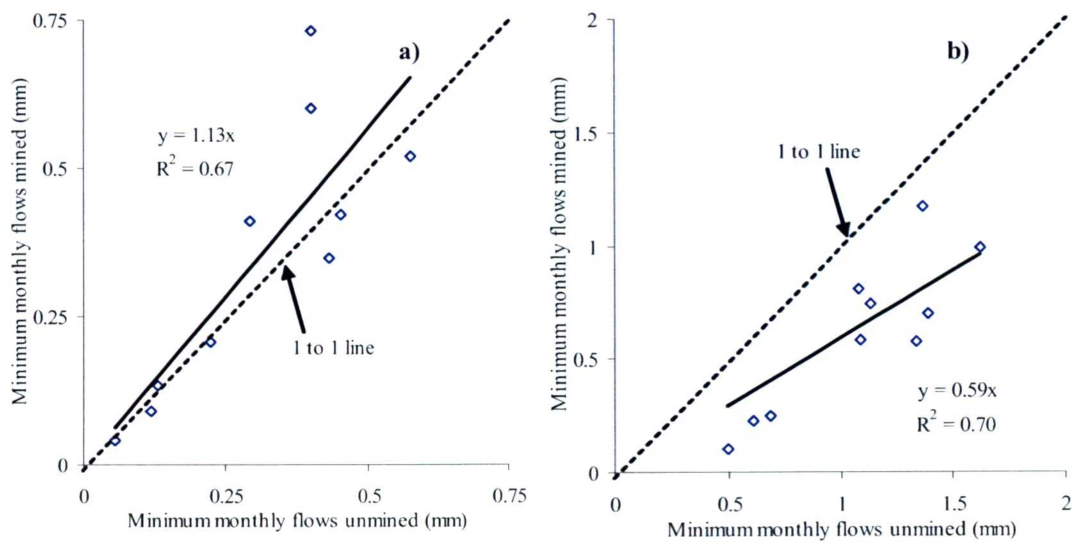

Figure 32. Comparison of minimum monthly simulated streamflows for a) Seldom Seen and b) More Seldom Seen during 1998–2002

8.5 Evapotranspiration by mine revegetation

The modelling difference between the mined base scenario and the mined alternative scenario is a simple adjustment of one parameter resulting in an increase in potential transpiration (PT) for the revegetation. The indications from Seldom Seen, More Seldom Seen and Del Park (Croton 2004) are that this alteration in PT is required to obtain a history match to observed data; it is still an open question as to whether this additional transpiration is required in the long term. The additional transpiration may be required by the revegetation to support an elevated rate of wood production compared with the native forest. If so, as the revegetation matures the rate of wood production would slow and the transpiration should reduce. Alternatively, it could relate to an excess of available soil water (Figs 22 & 23) and may reduce as this excess is depleted. However, with revegetation on the catchments commencing in 1971 for Seldom Seen and 1970 for More Seldom Seen, there is now some revegetation more than 30 years old and there was no implication from the study that there was any reduction in potential transpiration by the older revegetation.

Croton's studies on Del Park imply that other factors, such as alterations to the soil profile by mining, may make more water available to mine revegetation. If so, the elevated transpirations may be permanent. Additional research is required to assess the effects of bauxite mining on long-term water yields.

8.6 Vegetation densities and LAI estimation

The forest cover across the Seldom Seen and More Seldom Seen catchments was sparse compared with that for typical High Rainfall Zone jarrah forest (Bartle 1976), and the pre-mine streamflows were probably elevated compared with other forested catchments. Therefore, the reductions in yield due to mine revegetation may be a return to the more normal situation. This is obviously simplistic and neglects those site-specific factors that control revegetation densities. For instance, Croton (2004) found for the Del Park catchment that, by 2000, the LAIs in the forest and revegetated areas were all in the relatively small range of 2.0 to 2.2. This was 40% higher than forest and revegetation LAI estimates in Seldom Seen and More Seldom Seen, which were also in a small range, 1.45 to 1.53 in 2000 (Fig. 9). However, the closeness of LAI values for a given catchment could be driven as much by the method to measure them as by any true similarity. LAI estimation by remote means such as aerial photographs or Landsat TM is difficult in even highly controlled situations such as uniform crops. The calculation of LAI for a mosaic of forest and mine revegetation with widely varying ages must be considered tentative at best. As this problem is further compounded by the apparent growth of the undisturbed forest, LAI estimation was probably the weakest component of this study.

9 Conclusions

WEC-C models were successfully developed for the Seldom Seen and More Seldom Seen catchments and applied to study the effects of bauxite mining and forest management on streamflows. Mine clearing caused a transient increase in streamflow; the maximum increases in annual streamflow due to clearing were estimated to be 62 mm/yr for Seldom Seen (36%) and 90 mm/yr for More Seldom Seen (31%). Elevated streamflow lasted 32 years for Seldom Seen and 20 years for More Seldom Seen.

Young mine revegetation appears to have a higher evapotranspiration (ET) than unmined forest and to be thus reducing streamflow. The reductions at the simulation end in 2002 were estimated to be 12 mm/yr for Seldom Seen (13%) and 55 mm/yr for More Seldom Seen (42%). Water balance calculations indicated that soil water storages in the catchments were still reducing and that further reductions in streamflow could be expected. Whether the reductions in streamflow are permanent or transient could not be determined in this study.

The unmined forest was found to have grown during the study period, reducing streamflows beyond the reductions due to mine revegetation. At simulation end in 2002, the reductions due to forest growth were estimated to be 55 mm/yr for Seldom Seen (36%) and 54 mm/yr for More Seldom Seen (29%).

10 Recommendations

Four recommendations are being made for future work:

- Continue the streamflow monitoring of the catchments. The study determined that the catchments were at a key point in their hydrology at the end of 2002 and that both their soil water stores and streamflows were likely to reduce further.

- Improve the estimates of LAI. The present study used five aerial photographs to define the LAI history for Seldom Seen and six for the history of More Seldom Seen. These are small numbers given the 37 years of simulation. Many more photographs are available and could improve the quality of the vegetation history (the present study was limited to the few by difficulties with sourcing photographs in the time available). While additional photographs are likely to improve the accuracy of the history matches between observed and simulated streamflows, they are unlikely to significantly alter the present study findings.

- Improve the sophistication of the models, particularly regarding the representation of mining in the Seldom Seen catchment. The study established that problems with history-matching high flow years were likely to be related to haul-road runoff: the haul road networks input to the present models may be inhibiting runoff where it was occurring in reality. As with LAI estimation, such improvements in the model layouts are likely to improve the accuracy of history matching to streamflows, but are unlikely to significantly alter the present estimates of mining related effects, other than to give increases in flows during the wetter years of active mining.

- Model the Waterfall Gully catchment. This modelling study was necessary due to the apparent lack of a stable rainfall–streamflow relation for Waterfall Gully. Whether this was because the rainfall–streamflow relation of Waterfall Gully is too complex for simple analysis; or whether it related to other issues like accuracy of monitoring or catchment disturbance, could not be determined. It is recommended that the Waterfall Gully catchment be modelled using WEC-C to define its hydrological behaviour and shed light on these issues.

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Appendix 1 - Vegetation history

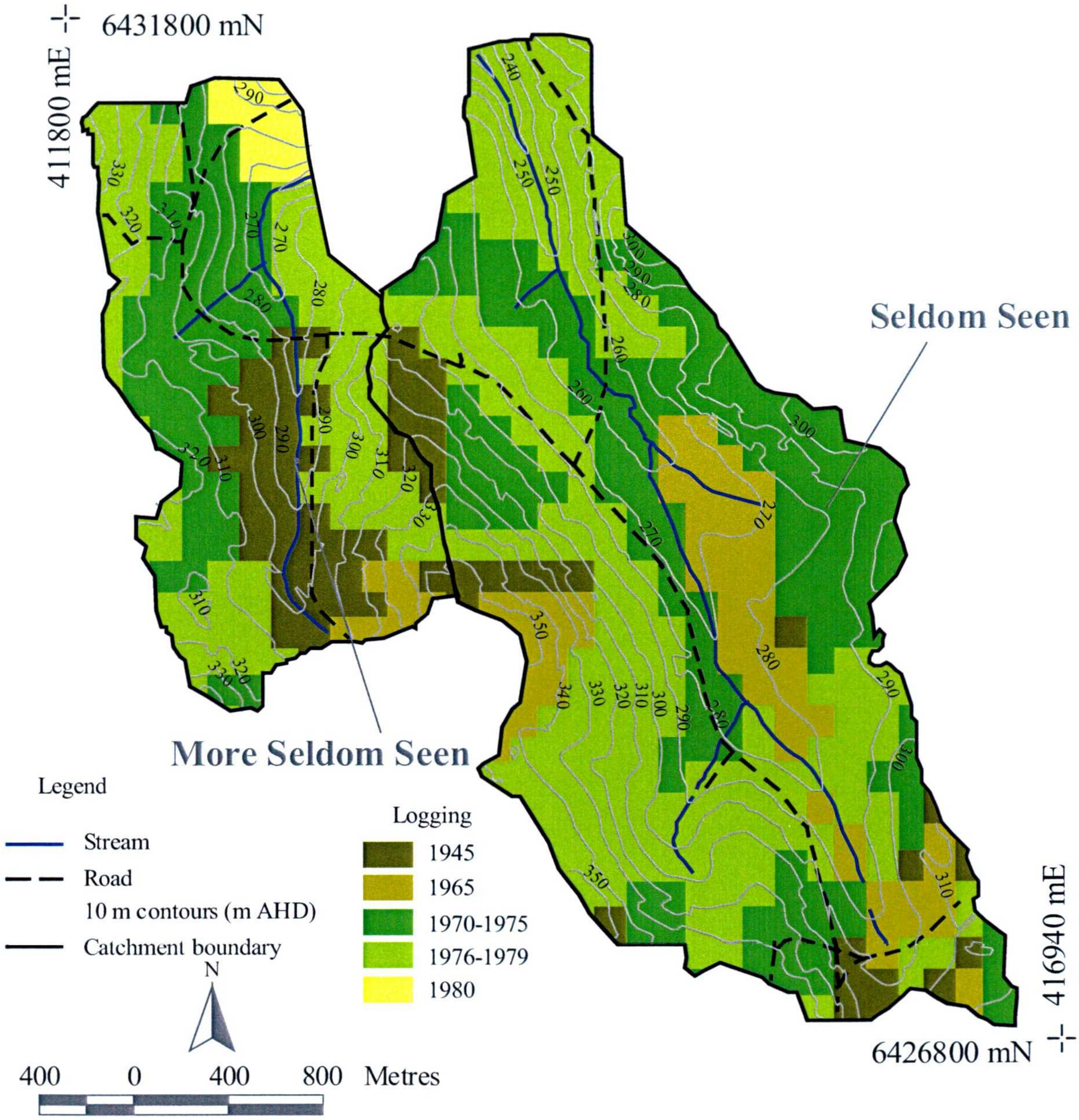

Figure 33. CALM FMIS history of forest logging in the Seldom Seen catchments

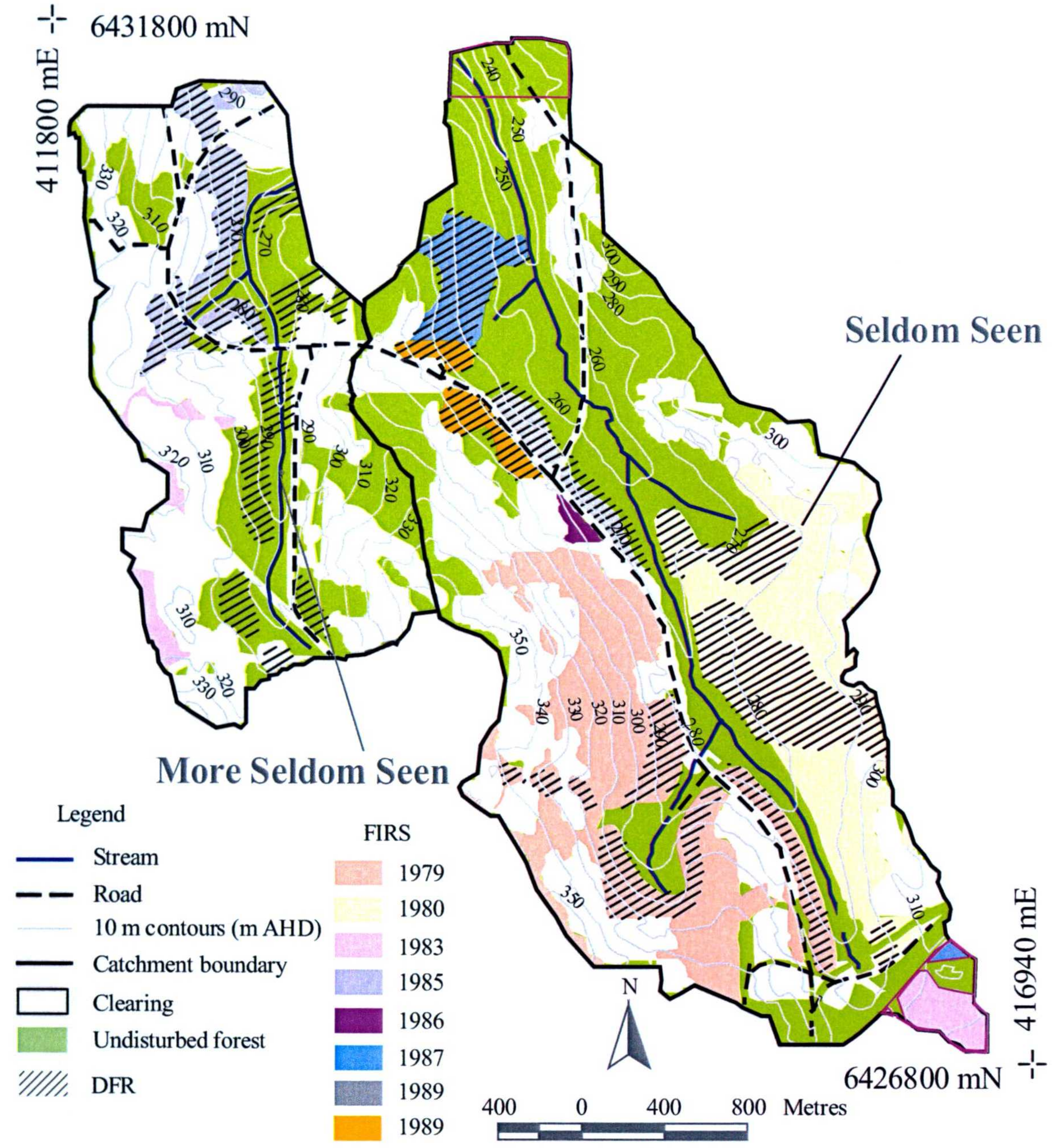

Figure 34. Forest Improvement and Rehabilitation Scheme (FIRS) and Dieback Forest Rehabilitation (DFR) in the Seldom Seen catchments

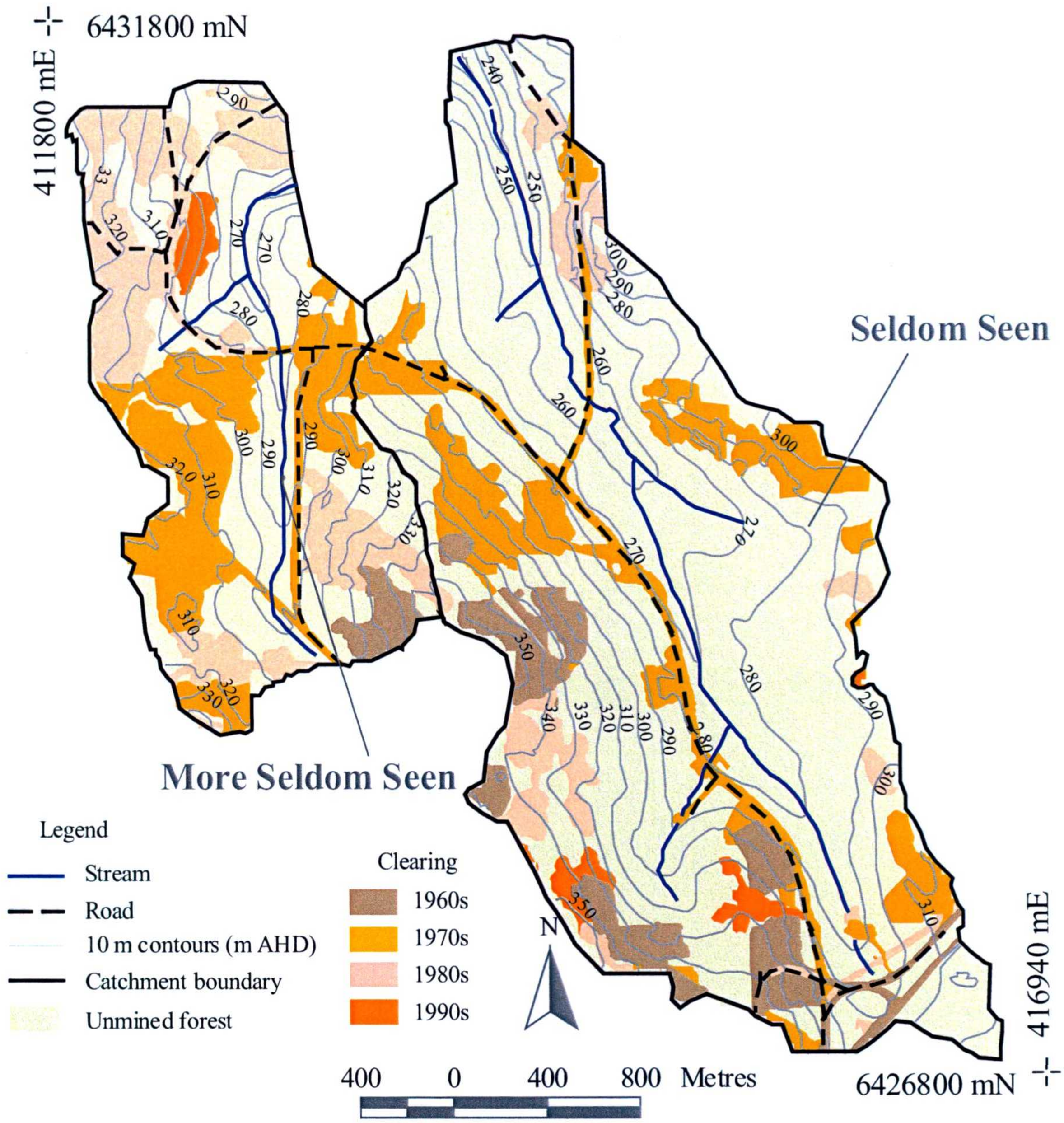

Figure 35. History of clearing for mining in the Seldom Seen catchments

Appendix 2 - Piezometer details

Fourteen piezometers were established in the catchments between 1975 and 1980 (Fig. 37 & Table 9). There are not many groundwater level observations available and only two piezometers, G61612799 and G61612794, which were part of a study into the groundwater responses due to FIRS, have a record of more than a few readings.

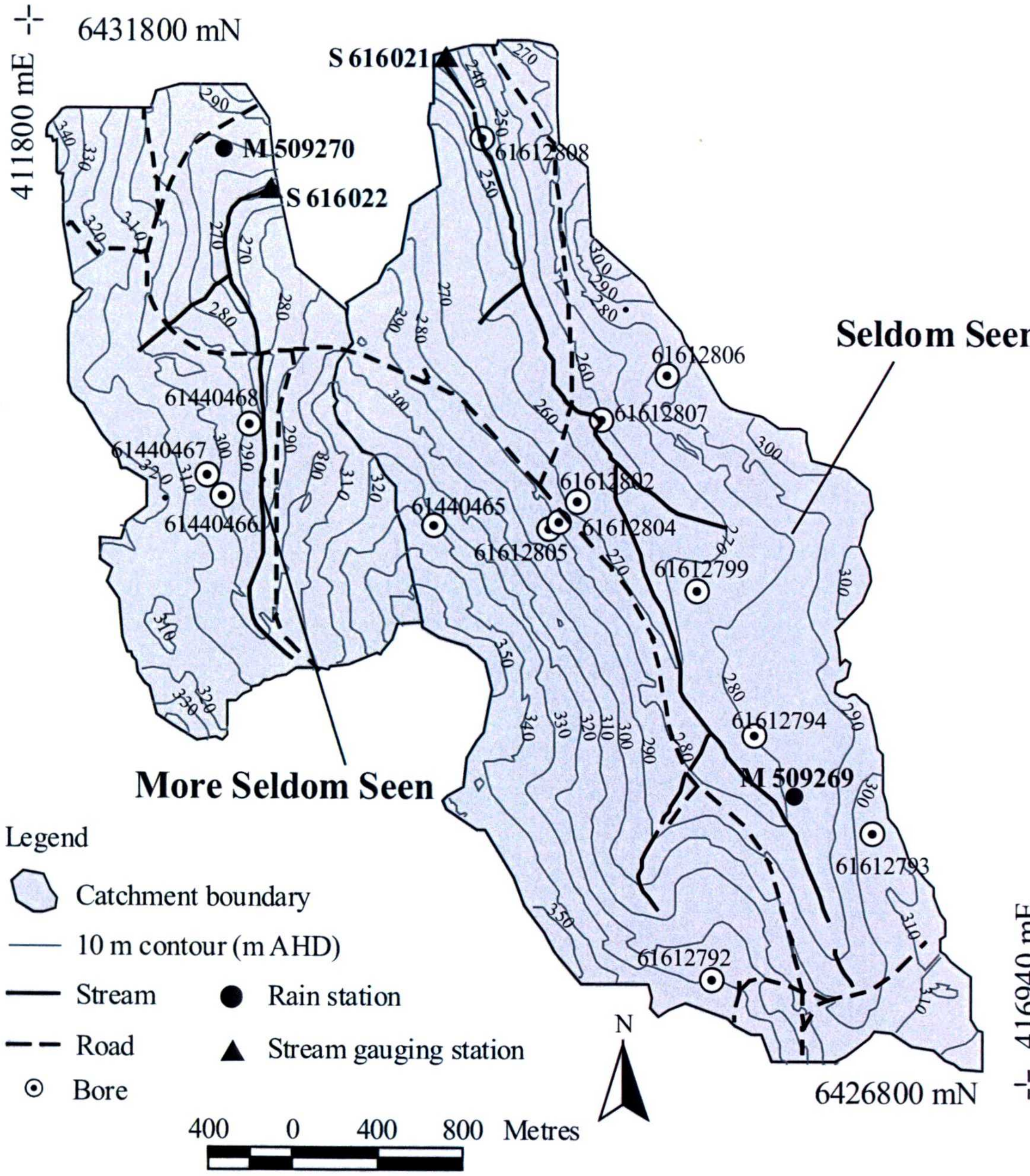

Figure 36. Topography and piezometer locations

Table 9. Details of the piezometers

DoE ID	Easting	Northing	Depth drilled (m)	Initial depth to water (m)	Topographic location	Monitoring period	Number of readings
			Seldom Seen				
G61440465	414137	6429468	27.3	5.9	Upslope	1979	4
G61612808	414356	6431269	5.00	4.8	Valley	1975–76	2
G61612807	414917	6429963	7.6	1.1	Valley	1979	3
G61612806	415232	6430168	21.7	16.7	Upslope	1979	2
G61612805	414677	6429454	30.6	5.7	Midslope	1980	1
G61612804	414724	6429490	23.8	3.0	Midslope	1980	1
G61612802	414811	6429584	22.5	6.0	Midslope	1980	1
G61612799	415371	6429170	10.7	5.5	Midslope	1975–79	27
G61612794	415648	6428499	9.3	3.2	Valley	1975–79	26
G61612793	416191	6428051	15.2	8.9	Upslope	1979	4
G61612792	415447	6427362	27.1	9.5	Upslope	1979	4
			More Seldom Seen				
G61440466	413130	6429609	17.9	N/A	Midslope	N/A	N/A
G61440467	413065	6429704	24.4	N/A	Midslope	N/A	N/A
G61440468	413262	6429943	8.0?	N/A	Valley	N/A	N/A

Note: N/A means the data was not available.

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