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Recommended environmental water requirements for the Daly River, Northern Territory, based on ecological, hydrological and biological principles

WD Erskine, GW Begg, P Jolly, A Georges, A O'Grady, D Eamus, N Rea, P Dostine, S Townsend & A Padovan

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Executive summary

Flow regimes and environmental water requirements of the Daly River must be understood to set appropriate environmental flows and water licence conditions for large scale agricultural development and associated vegetation clearing. The Daly River provides a unique opportunity to address these issues before significant agricultural development impacts on streamflow regimes and to protect its long recognised wild river status.

Environment Australia and the Northern Territory Government, therefore, as part of the National River Health Environmental Flow Initiative, funded the following five projects:

- Modelling Dry-season flows and predicting the impact of water extraction on a flagship species — the pig-nosed turtle (*Carettochelys insculpta*);
- Tree water use and sources of transpired water in riparian vegetation along the Daly River, Northern Territory;
- Environmental water requirements of *Vallisneria nana* in the Daly River, Northern Territory;
- Periphyton and phytoplankton response to reduced Dry season flows in the Daly River;
- Inventory and risk assessment of water dependent ecosystems in the Daly Basin.

The aim of these projects was to provide recommendations on environmental flows consistent with maintaining the biota and wider ecosystem values of the Daly River. Eight of the nine species of freshwater turtles found in the Northern Territory are present in the Daly River. Furthermore, at least two nationally threatened species of elasmobranchs, the Freshwater whipray (*Himantura chaophraya*) and the Freshwater sawfish (*Pristis microdon*), are also present. According to Pogonoski et al (2002), these species are critically endangered and vulnerable, respectively.

The recommendations derived from work undertaken for the five projects are given in table A. They need also to be accompanied by the following actions:

- Northern Territory Government introduces integrated natural resource management for the Daly River catchment and a robust method for determining water allocations;
- Natural estuarine biophysical processes and aquatic habitats are maintained;
- Groundwater-dependent ecosystems are identified and protected;
- High quality data are collected at all river gauging stations for both low and high streamflows;
- A benchmarking and monitoring (including biomonitoring) program is designed and implemented;
- An adaptive ecosystem management approach is implemented along with the environmental water allocations and the benchmarking and monitoring programs.

Table A Final environmental water allocations recommended for the Daly River

	Environmental Issue	Recommended Water Allocation and/or Restriction on water extraction
1	Interdependence of streamflow, groundwater discharge and groundwater and surface water quality	Groundwater and streamflow quantity and quality must be managed holistically and supported by an integrated natural resource management approach. Dry season streamflows must continue to be sourced from karst aquifers with bicarbonate dominance and very low nutrient concentrations.
2	Protection of critical streamflows that cue various biotic responses	Environmental water allocations can be partly addressed by adopting a flexible and variable approach to agricultural water allocations. Flood peaks and minimum streamflows must be maintained unchanged. Agricultural extraction can be permitted from less ecologically sensitive streamflows, as outlined below.
3	Protection of flood peaks for channel maintenance, reworking of sand bars for pig-nosed turtle nesting sites, lateral connection of floodplains, natural disturbance events for riparian vegetation regeneration	• No water extraction on rising stage and peak of flood hydrographs during Wet season. • Water extraction of up to 20% of the streamflow allowed when flood stage has dropped at least 1 m below peak during the Wet season.
4	Maintenance of groundwater levels and spring inflows to the Daly River	No groundwater extraction allowed within 3 km in a straight line from the Daly River. This condition is to be verified by modelling of aquifers and detailed monitoring of bore levels and revised, as needed. The assessment criterion should be based on a series of bores situated next to the Daly River and at various distances (up to about 5 km) away from the channel. Control bores next to the river must be outside the cone of depression in groundwater level caused by pumping from bores further from the river.
5	Maintenance of minimum streamflows to protect *Vallisneria nana*, *Spirogyra* and pig-nosed turtle	Agricultural water extraction allowed from the Daly River and aquifers providing spring input must be managed so that the cumulative impact on flows is < 8% when streamflows reach the following thresholds at the stated locations: Claravale Crossing – 6.2 m^3s^{-1} Oolloo Crossing – 12 m^3s^{-1} Mt Nancar – 12 m^3s^{-1} At discharges greater than the above thresholds, no more than 20% of the streamflow greater than the above thresholds (ie 16 m^3s^{-1} when streamflow is 80 m^3s^{-1} but only 3 m^3s^{-1} when streamflow is 15 m^3s^{-1}) can be extracted.
6	Maintenance of turtle and fish passage	Same conditions as outlined for point 5 plus: All road crossings should be built according to Erskine & Harris's (2003) principles for unimpeded fish passage Water quality barriers (such as irrigation return flows, drain discharges, etc) to faunal passage should be prohibited.
7	Maintenance of groundwater levels for periodic/episodic use by riparian vegetation	No extraction of groundwater within 3 km of the Daly River. All of the riparian vegetation water use can be met by maintaining a streamflow of less than 2 m^3s^{-1} during the Dry season, assuming that there is no loss of streamflow to regional aquifers. Therefore, groundwater levels next to the Daly River must not be lowered below river levels.
8	Maintenance of existing water quality	Apply ANZECC and ARMCANZ (2000) water quality guidelines so that trigger values for pH, electrical conductivity, bicarbonate, total nitrogen, total phosphorus, soluble reactive phosphorus and selected metals are derived and applied to the Daly River and groundwater. Exceedances of trigger values must induce a to-be determined response from government and agricultural industry.
9	Maintain existing structure and function of all wetlands	No dam or regulatory structure to be built on any river without an EIS.
10	Assessment of the adequacy of imposed licence conditions and discharge thresholds with appropriate revision based on monitoring results	Adopt an adaptive ecosystem management approach supported by appropriate licensing, auditing, stream gauging, groundwater level measurements, water quality monitoring, biomonitoring and benchmarking programs. There must be feedback from the monitoring/auditing results to the licence conditions.

There are many significant potential threats to the health of the Daly River from further agricultural development and associated vegetation clearing. Such threats, should they occur, will modify the environmental water allocations recommended in table A and will necessitate future revisions, depending on the results of monitoring under an adaptive ecosystem management approach. The presently identified threats from future agricultural development and consequential land clearing are:

- altered soil and catchment hydrology, including increased runoff (Mott et al 1979; Bridge et al 1983a; 1983b; Dilshad & Jonauskas 1992; Dilshad et al 1996);
- accelerated soil erosion and sediment delivery to rivers (Dilshad et al 1996, Elliott et al 2002);
- reduced groundwater recharge and baseflow discharge;
- increased incidence of fish kills.

Acknowledgments

We thank Steve Tickell and Danuta Karp (NT Department of Infrastructure Planning and Environment), Joan Mount and Ann Webb (Supervising Scientist Division), and the project teams and presenters at the September 2002 workshop for their assistance with, and constructive comments on, this report. Dr Helen Larson constructively reviewed the fish aspects of the report.

Recommended environmental water requirements for the Daly River, Northern Territory, based on ecological, hydrological and biological principles

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Introduction

The Daly Basin has been selected by the Northern Territory Government for major agricultural development which will intensify the current pastoral use by land subdivision, large scale clearance of native vegetation and land modification (Price et al 2002). The Daly River is the most significant wildlife feature in the Daly Basin because the perennial streamflow creates a variety of lotic habitats not found in any other river in the Northern Territory (Price et al 2002). Eight of the nine species of freshwater turtles found in the Northern Territory are present in the Daly River. Furthermore, at least two nationally threatened species of elasmobranchs, the Freshwater whipray (*Himantura chaophraya*) and the Freshwater sawfish (*Pristis microdon*), which are classified as critically endangered and vulnerable respectively (Pogonoski et al 2002), are also present. The Daly River is also an important recreational fishery (fig 1) for Barramundi (*Lates calcarifer*).

Flow regimes and environmental water requirements of the Daly River and its tributaries (fig 2) must be understood to set appropriate environmental flows and water licence conditions for large scale agricultural development. The Daly River provides a unique opportunity to address these issues before significant agricultural development impacts on streamflow regimes (O'Grady et al 2002a&b, Rea et al 2002) and to protect its long recognised wild river status (Deacock 1982).

Environment Australia and the Northern Territory Government, as part of the National River Health Environmental Flow Initiative, funded the following five projects on the Daly River:

- Project 23045 — Modelling Dry-season flows and predicting the impact of water extraction on a flagship species (Georges et al 2002);
- Project 23086 — Tree water use and sources of transpired water in riparian vegetation along the Daly River, Northern Territory (O'Grady et al 2002a);
- Project 23087 — Environmental water requirements of *Vallisneria nana* in the Daly River, Northern Territory (Rea et al 2002);
- Project 22963 — Periphyton and phytoplankton response to reduced Dry season flows in the Daly River (Townsend et al 2002);
- Project 23088 — Inventory and risk assessment of water dependent ecosystems in the Daly Basin (Begg et al 2001).

The aim of these projects was to provide recommendations on environmental flows consistent with maintaining the biota and wider ecosystem values of the Daly River, given competing demands of agriculture, recreation and tourism, conservation and Aboriginal culture (Georges et al 2002). The general objective of the Environmental Flow Initiative was to assist state and territory water resource agencies meet the Council of Australian Governments (COAG) Water Reform requirements for making environmental water allocations.

The focus of the Daly River studies was generally the reach between Claravale and Beeboon crossings (fig 3). In this river section, streamflow is perennial and characterised by persistent Dry season baseflows originating from springs (fig 4) supplied from regional karst aquifers (Jolly 1984, 2001, 2002, Jolly et al 2000, Tickell 2002, Cook & Tickell 2002). The middle reaches of the Daly River are listed on the National Estate as an important wetland area in the Daly Basin bioregion, and are a major breeding and Dry season habitat for a variety of flora and fauna (Rea et al 2002).

The purpose of this report is to:

- Provide a concise overview of the work completed for the five projects listed above;
- Record the outcomes of a workshop on the environmental water requirements of the Daly River that was required under the funding arrangements for the above National River Health Environmental Flow Initiative projects;
- Recommend principles for determining environmental water allocations for the Daly River catchment, based on the knowledge gained from the main study reach; and
- Recommend environmental water requirements for the Daly River between Claravale and Beeboon crossings.

Background information, which is essential for understanding the results and recommendations of these studies, is presented first.

Figure 1 Combining science and recreation on the Daly River. Note abundant large woody debris in the channel (photograph: Steven Tickell).

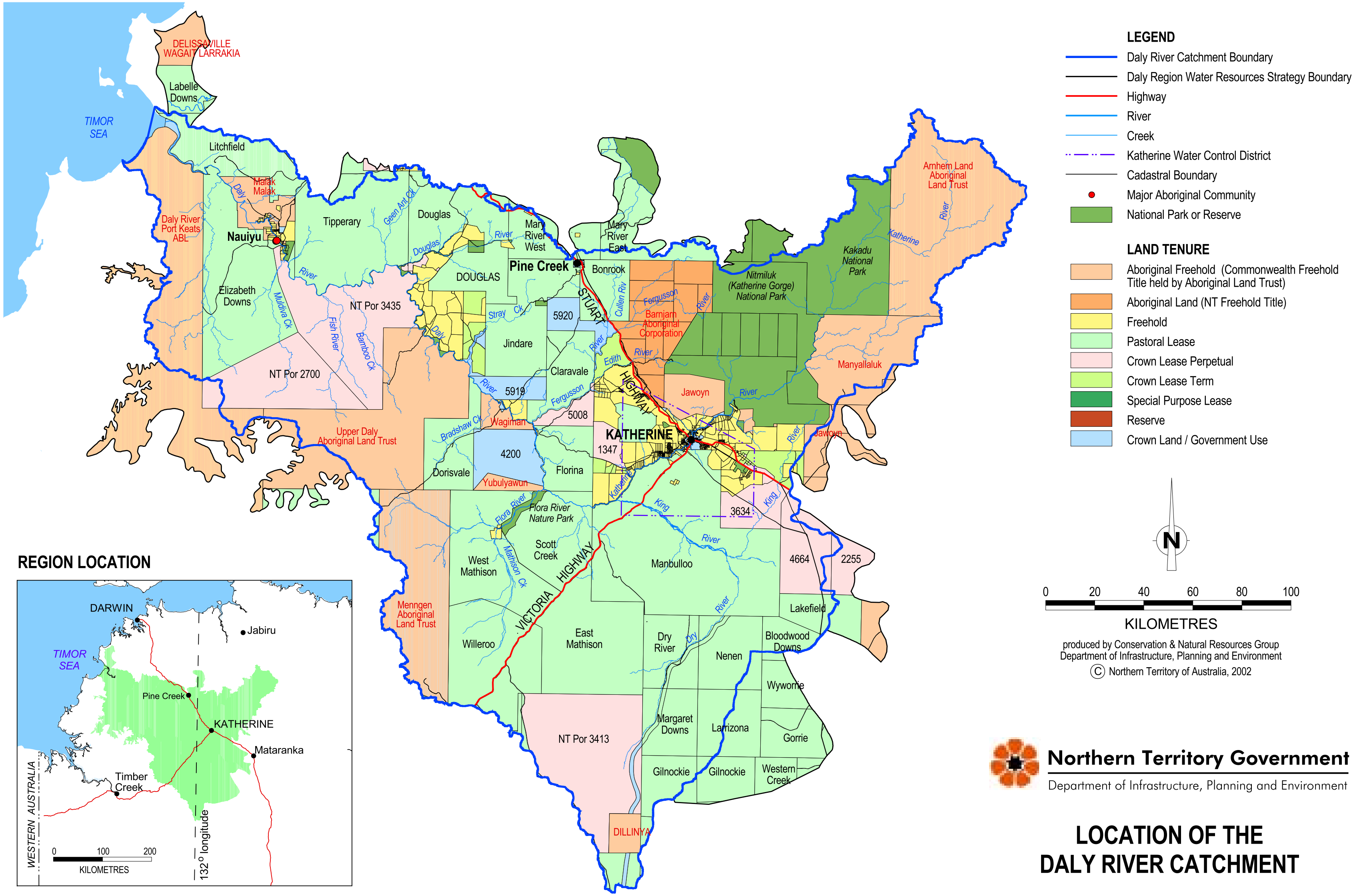

Figure 2 The Daly River Catchment (figure provided by the Conservation and Natural Resources Group, DIPE, NT Government)

Daly River Catchment

The Daly River is a large (52 577 km^2 catchment area) perennial river located about 200 km south of Darwin (fig 2). Faulks (1998a, 1998b) has comprehensively described the biophysical characteristics of the catchment as well as stream and wetland condition at many sites.

Rainfall is distinctly seasonal throughout the catchment. Low mean monthly rainfall (<10 mm) is recorded at Katherine (1888/89 to 1988/89) between May and September (peak of the Dry season), high mean monthly rainfall (>100 mm) is recorded between December and March (Wet season) and intermediate values are recorded in both the lead up to, (29 to 85 mm average in October and November respectively) and at the end of, the Wet season (31 mm average in April) (Mollah et al 1991). Daily rainfall totals rarely exceed 200 mm (fig 5).

Mean annual rainfall increases generally from south-east to north-west across the Daly River catchment from 690 mm at Willeroo to 1300 mm at Daly River (Fitzpatrick 1965). Mollah (1986) found that mean annual rainfall for the common period, 1961/62 to 1983/84, varied from 1017 mm at Katherine to 1375 mm at Wooliana (fig 2). However, mean annual rainfall at Katherine for the period 1888/89 to 1988/89 was 947 mm (Mollah et al 1991). Annual rainfall variability for stations in the catchment increases from the coast inland (coefficients of variability increase from 17.3% to 27.5%) and is relatively low by Australian standards (Christian & Stewart 1953, Fitzpatrick 1965, Slatyer 1960, Mollah et al 1991).

As shown in fig 6, annual rainfall at Katherine is temporally variable, exhibiting repetitive cycles of persistently high and low rainfall (Mollah et al 1991, Jolly 2001, 2002). Jolly (2001, 2002) found that lowest annual rainfall at Katherine was 364 mm in 1951/52 and that the highest was 1990 mm in 1897/98. Above average annual rainfall was recorded for the Wet seasons before and during the National River Health Environmental Flow Initiative studies on the Daly River.

Jolly (2001, 2002) constructed an approximate water balance for the Daly River catchment. He found that mean annual runoff varied across the catchment from 119 to 294 mm, except for the Dry River where it was only 23 mm. At the most downstream gauge (Mt Nancar), the mean annual runoff of the Daly River is 148 mm of which 135 mm is surface runoff and 13 mm is regional groundwater discharge. Sustained baseflow of about 7 to 20 m^{3}s^{-1} persists right through the Dry season at Mt Nancar (Chappell & Bardsley 1985).

The inter-annular variability of runoff is much greater than for rainfall (Chappell & Bardsley 1986, Jolly 2001, 2002). Figure 7 shows that annual discharge between 1960/61 and 1998/99 ranged over three orders of magnitude at three gauging stations on the Katherine and Daly Rivers. The maximum annual range in water level at the same stations varied between about 4 and 22 m over the same time period (fig 8). As a result, the inter-annular range in maximum instantaneous discharge varied by up to three orders of magnitude (fig 9) which is much less than the six orders of magnitude on the highly flood variable rivers of southeastern Australia (Erskine 1994a, 1996a, Erskine & Livingstone 1999, Erskine & Warner 1999).

Many rivers in the Daly catchment exhibit persistent streamflow right through the Dry season due to groundwater inflows from significant aquifers (Jolly 1984, 2001, 2002, Jolly et al 2000). Those contained in carbonate rocks of the Daly Basin are the most significant (Jolly 1984, 2001, 2002, Jolly et al 2000). Annual recharge of aquifers varies from 0 mm in dry years to 300 mm in wet years with an average of 90 mm (Jolly 2001, 2002). The inter-annular variation in minimum instantaneous discharge at three gauging stations on the Katherine and Daly rivers only ranged over two orders of magnitude and cease-to-flow conditions never occurred between 1961 and 2000 (fig 10). Groundwater levels vary greatly during the year (figures 11 & 12) reflecting the duration and magnitude of the Wet season (recharge) and the discharge of groundwater to rivers and transpiration losses by trees during the Dry season (Jolly 2001, 2002). For an average year, 23% of rainfall is converted to runoff but this varies from 10% for the year of minimum catchment rainfall to 36% for the year of maximum catchment rainfall (Jolly 2001 2002). Pumping for water supply purposes is very small and currently uses less than 0.2% of mean annual runoff (Jolly 2001, 2002).

In the upper reaches of the catchment, Dry season streamflows originate predominantly from aquifers within Cretaceous sediments (fig 13). With groundwater inflow from the carbonate rocks of the Daly Basin (fig 13), the conductivity of the Daly River increases 20–30 fold, pH and the carbonate buffering capacity increase at least an order of magnitude, whilst soluble phosphorus and nitrate concentrations more then double (Townsend et al 2002).

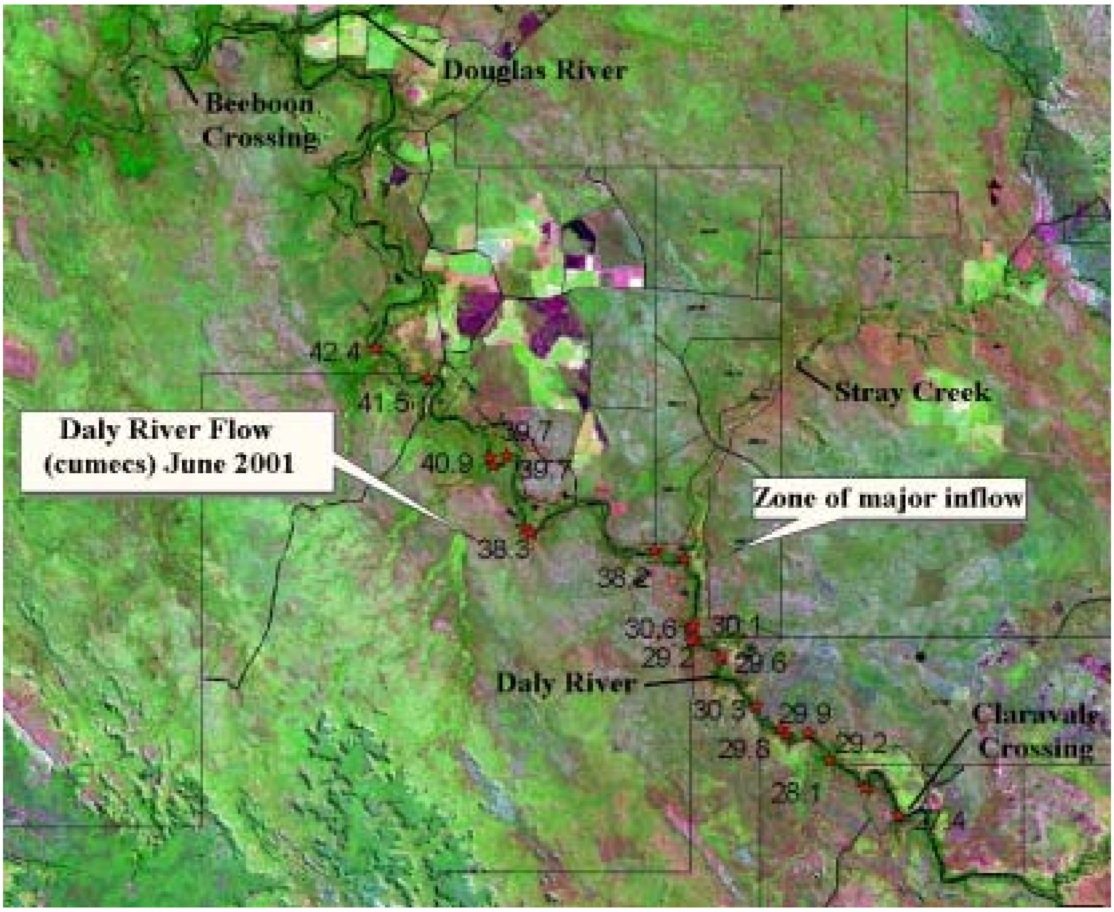

Figure 3 False colour image of the Daly River between Claravale and Beeboon crossings with flows shown for various locations in June 2000 (flow data provided by Arthur Georges)

The carbonate rocks in the Cambro-Ordovician Daly Basin are part of the Daly River Group and host the most productive aquifers (fig 13) in the Daly River catchment (Jolly 1984, Kruse et al 1990; Jolly et al 2000; Jolly 2001; 2002). The Daly River Group and its component formations were first formally defined by PD Kruse (Kruse et al 1990) although the stratigraphic unit had been recognised since 1949 (Noakes 1949). Daly River Group sediments are 708.5 m thick in the type section but possibly attain 740 m in the thickest part of the Daly Basin (Kruse et al 1990). The constituent formations, in ascending order, are Tindall Limestone, Jinduckin Formation and Oolloo Dolostone (Randal 1962; Kruse et al 1990). The Tindall Limestone and Oolloo Dolostone contain the major aquifers contributing spring flow (fig 4) to the Daly River. The Jinduckin Formation contains only minor aquifers and does not contribute significantly to flows in the Daly River.

River water chemistry differs markedly between seasons (Rea et al 2002). Surface runoff dominates streamflow during the Wet season and is characterised by low electrical conductivity but relatively high nutrient and organic matter levels. Groundwater inflow, mainly from limestone/dolostone aquifers, maintains streamflows during the Dry season and is dominated by bicarbonate. Groundwater inflow from the Oolloo Dolostone aquifer has very low nutrient concentrations (nitrate-nitrite 0.001–0.01 mg/L, nitrate 0.004-0.04 mg/L, reactive phosphorus <0.005 mg/L) and hence the Daly River is extremely sensitive to small increases in nutrients during the Dry season (Rea et al 2002). The transition period between Wet and Dry seasons is characterised by a steady increase in electrical conductivity and light, with a corresponding decrease in suspended solids, turbidity, iron, nitrate-nitrite and total phosphorus. An abrupt decrease in turbidity during the early Dry season was explained by flocculation of the suspended sediment due to the input of bicarbonate-dominated groundwater which rapidly became the dominant source of streamflow at discharges of about 70-80 m^3s^{-1} in 2000 (Rea et al 2002). This discharge threshold varies interannually according to the timing and rate of groundwater input which is, in turn, dependent on aquifer recharge during preceding Wet seasons (figures 11 & 12). Low turbidity permits light for plant growth (Rea et al 2002).

Figure 4 Spring inflow to the Daly River (photograph: Steven Tickell)

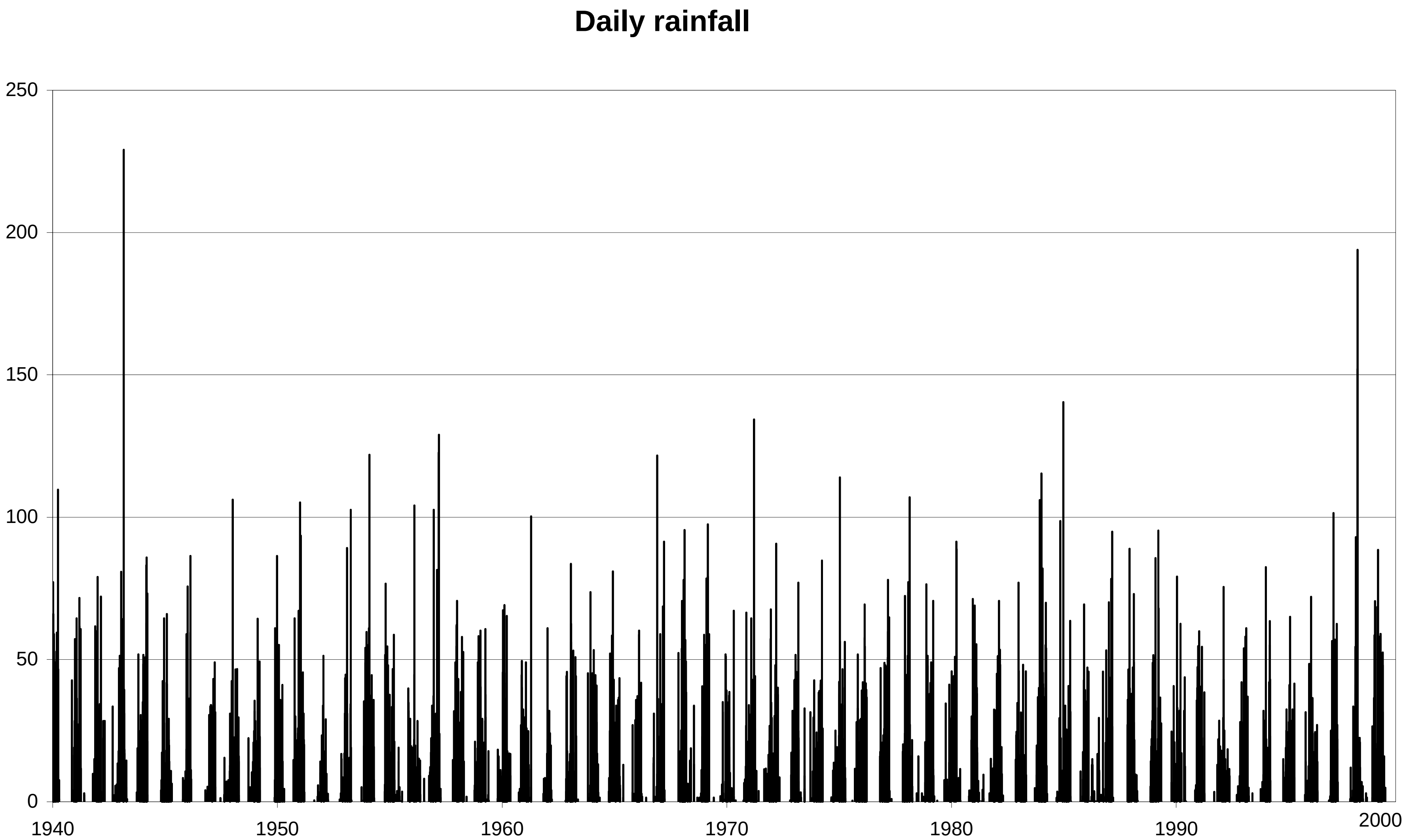

Figure 5 Daily rainfall at Katherine PO DR014902 between 1940 and 2000 (from Jolly 2001)

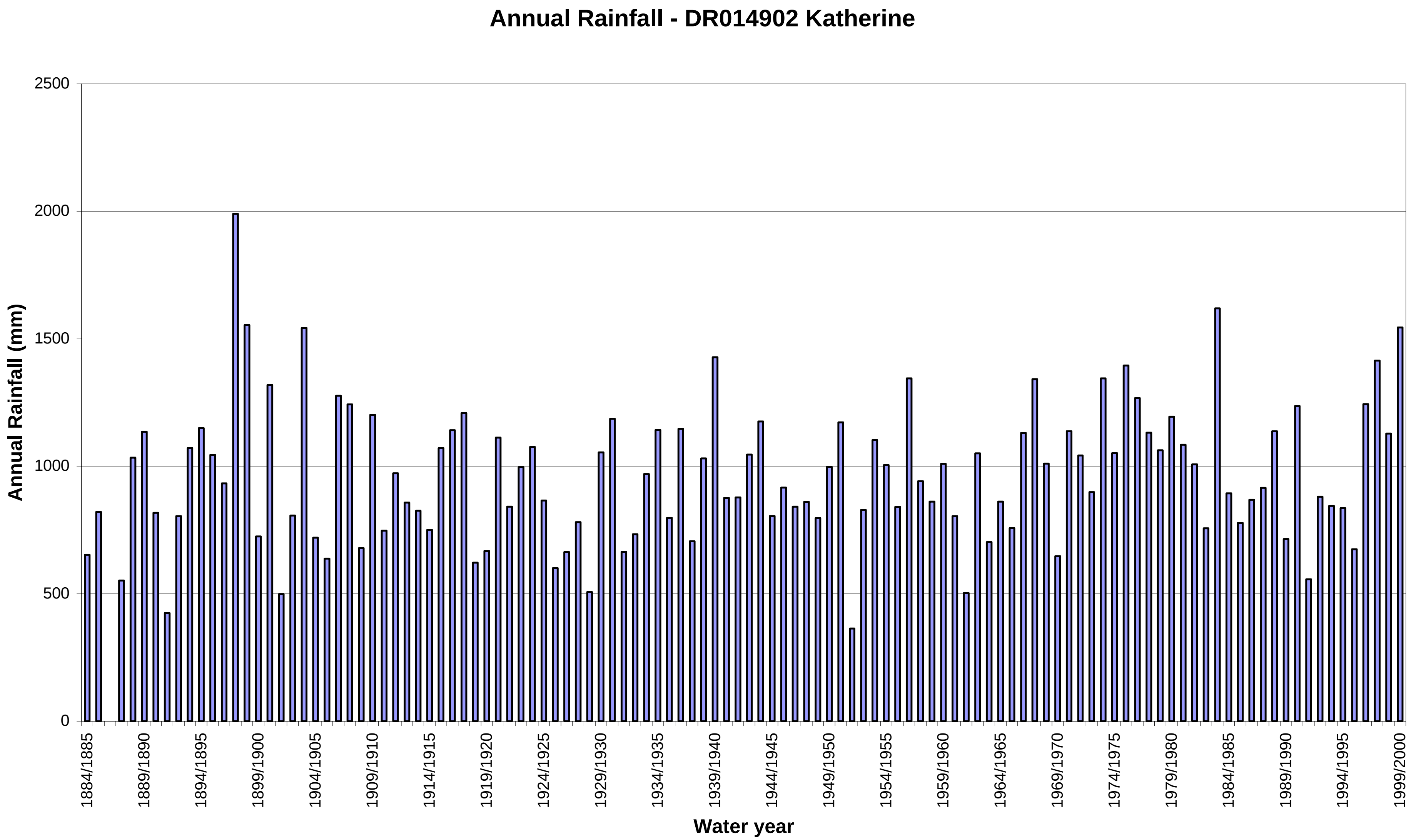

Figure 6 Annual (Oct–Sep) rainfall at Katherine PO DR014902 between 1884/85 and 1999/2000 (from Jolly 2001; 2002)

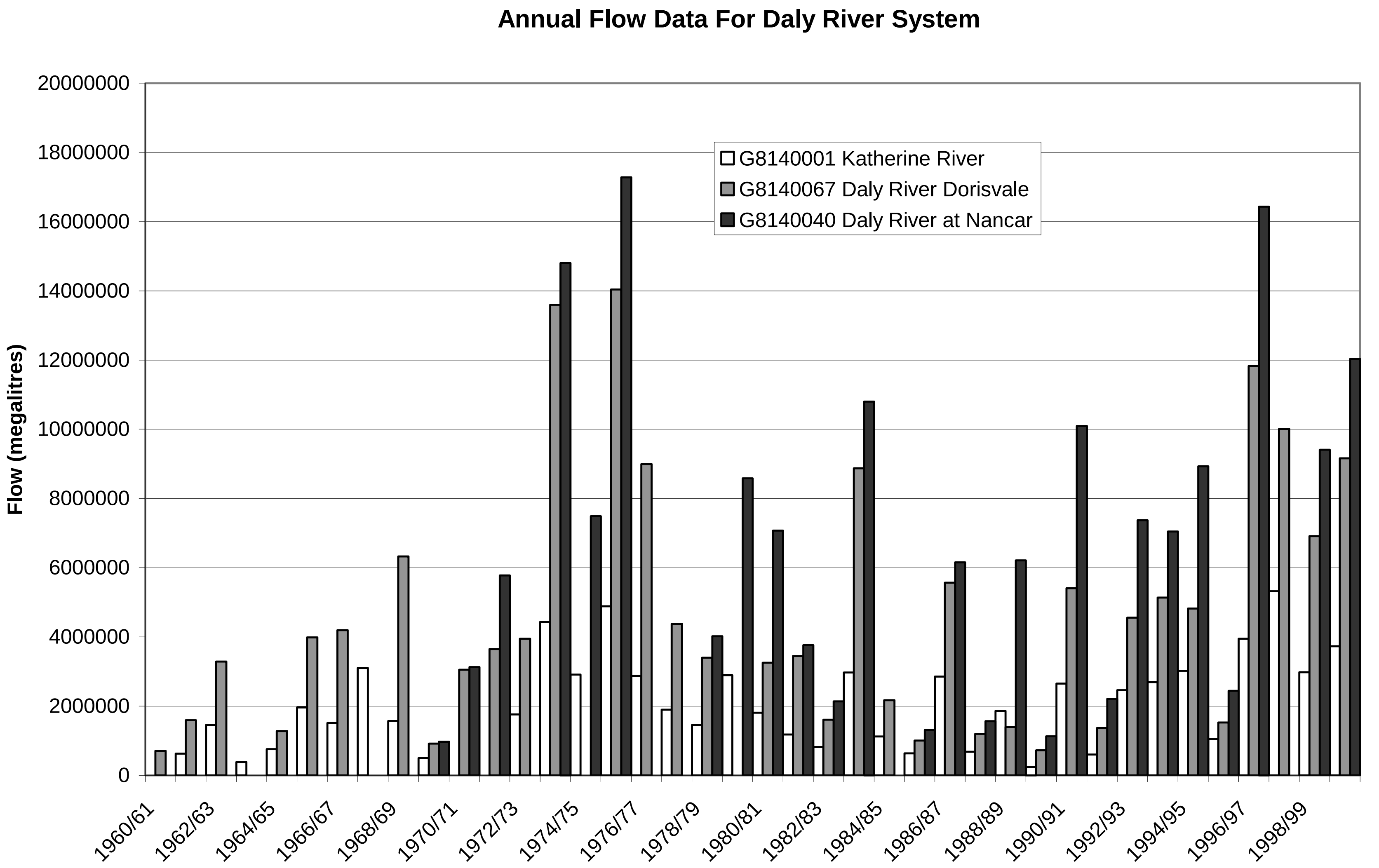

Figure 7 Annual discharge at gauging stations G8140001, G8140067 and G8140040. Note that no data are shown for years with incomplete records (from Jolly 2001; 2002).

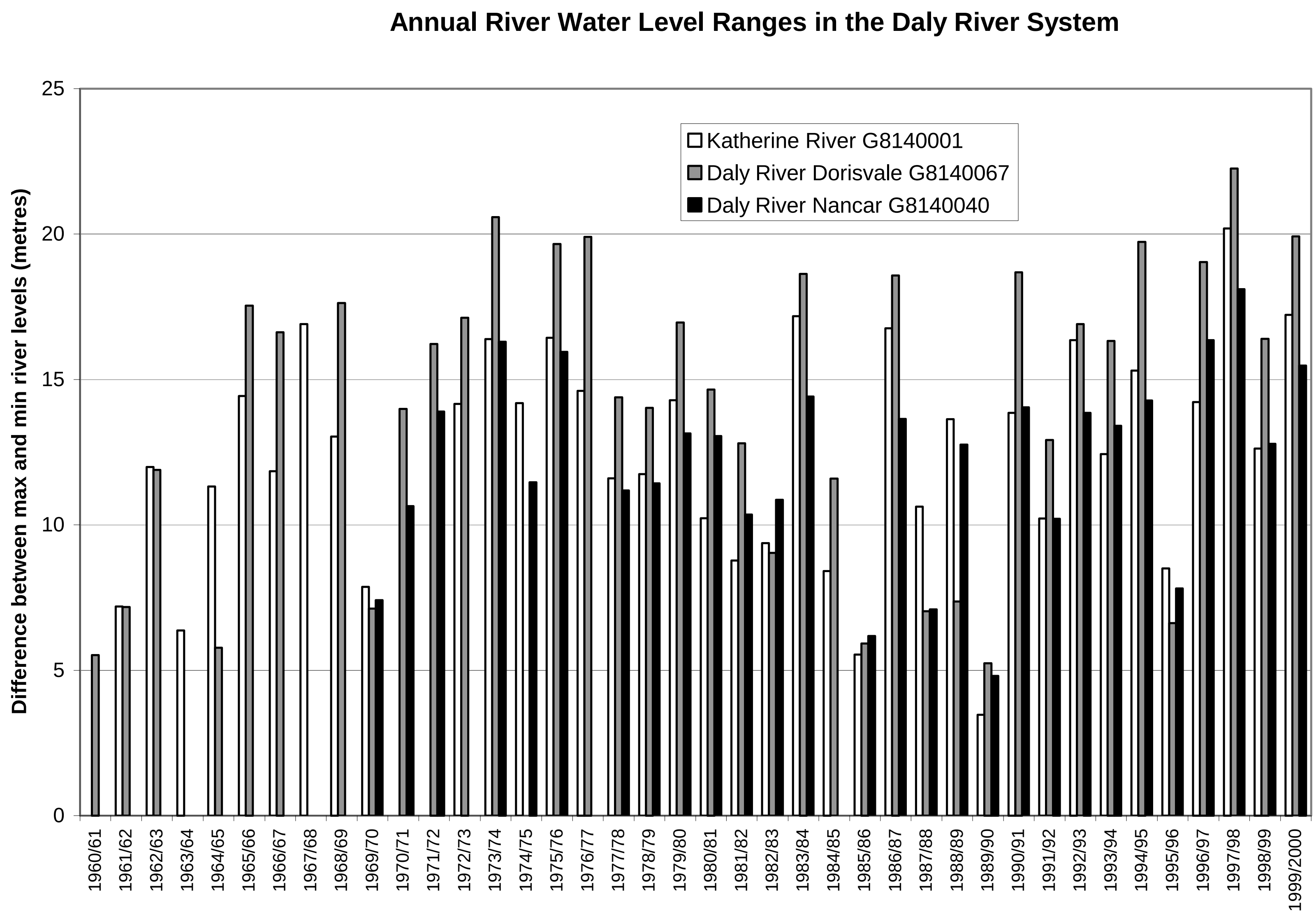

Figure 8 Variation between highest and lowest river water level at gauging stations G8140001, G8140067 and G8140040 for each year. Note that no data are shown for years with incomplete records (from Jolly 2001; 2002).

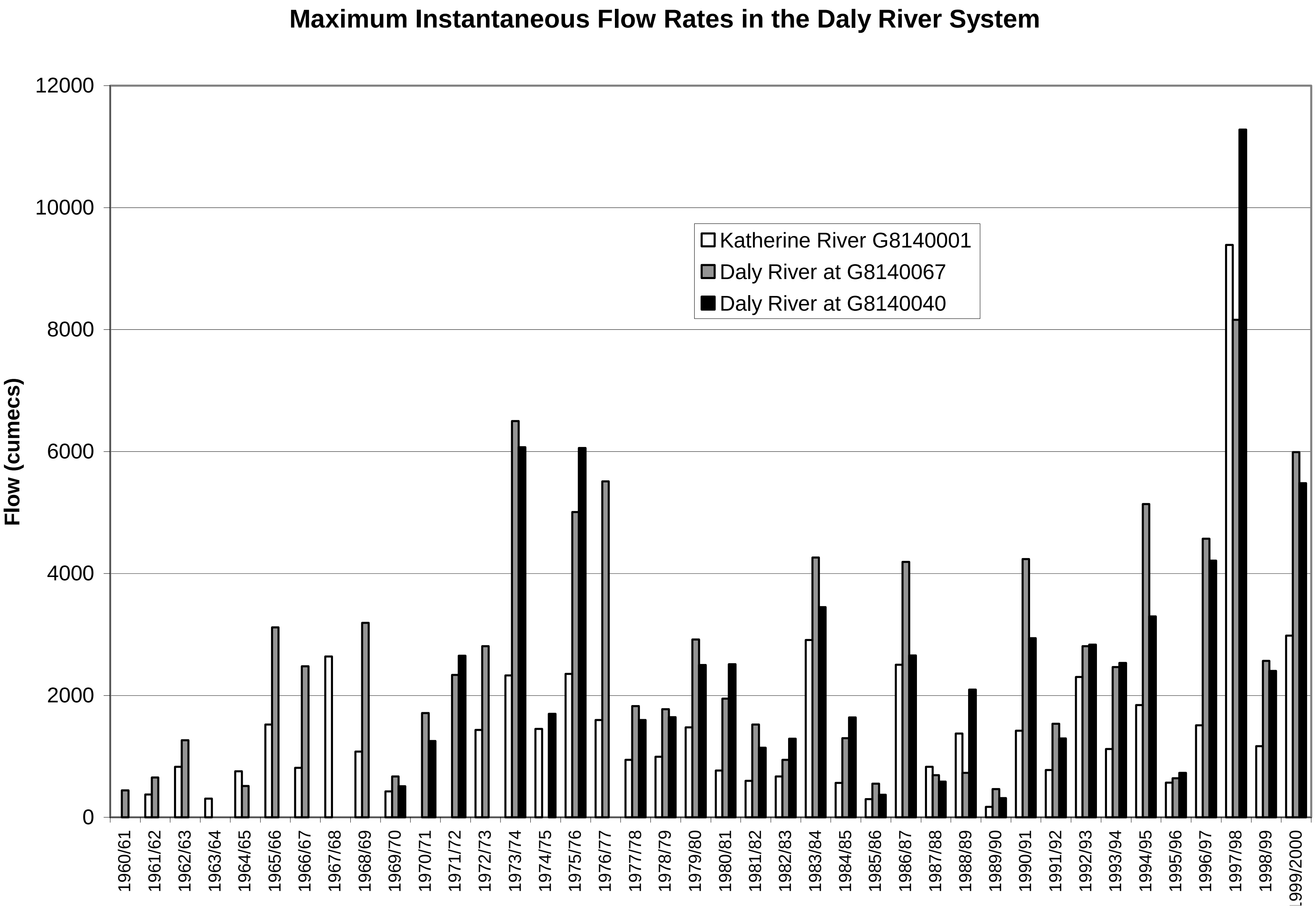

Figure 9 Maximum instantaneous discharge at gauging stations G8140001, G8140067 and G8140040 for each year of record. Note that no data are shown for years with incomplete records (from Jolly 2001; 2002).

The Lowest Instantaneous Flow Rates at G814001, G8140067 and G8140040 for the years 1961 to 2000

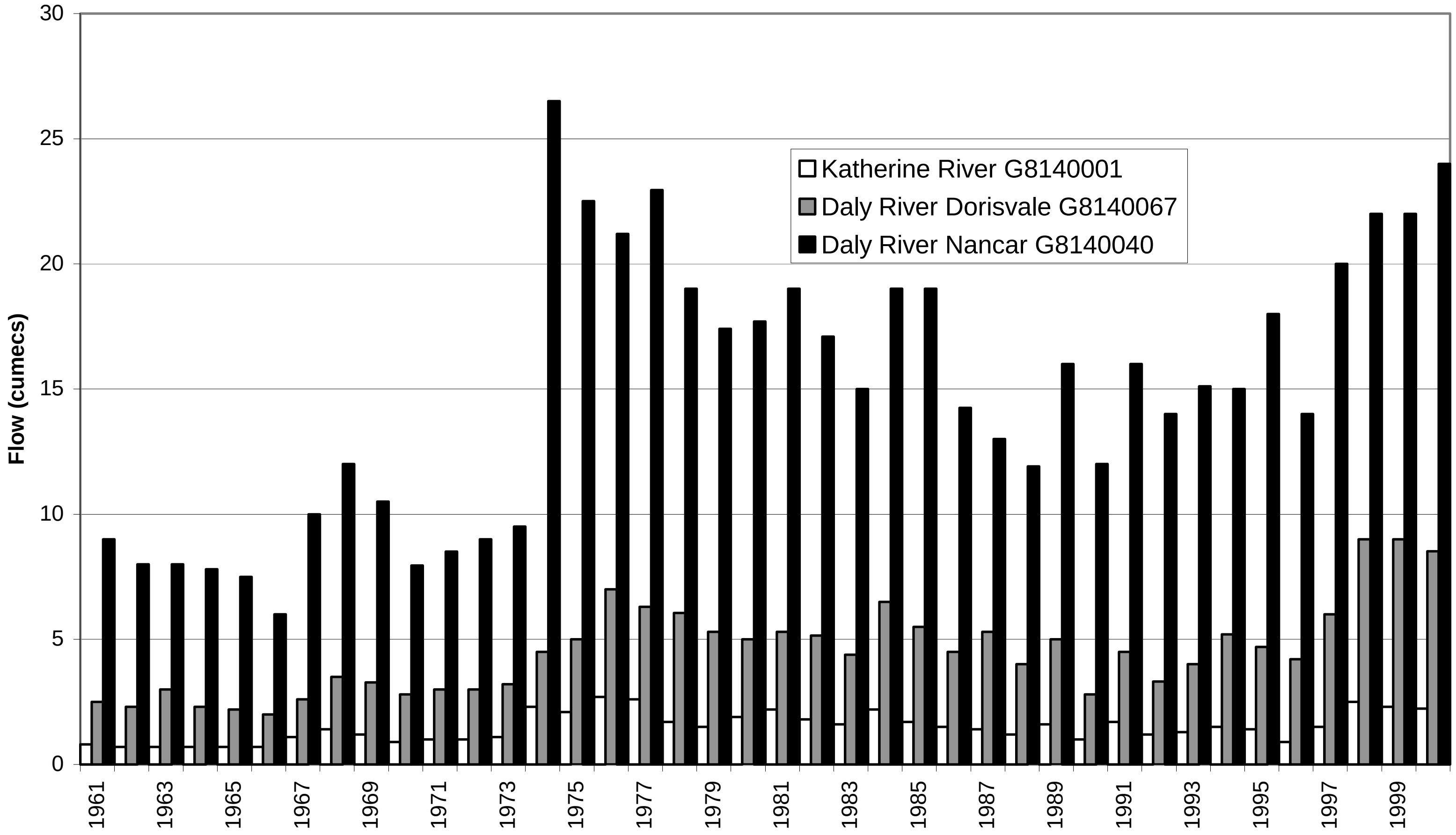

Figure 10 Minimum instantaneous discharge at gauging stations G8140001, G8140067 and G8140040 for each year of record. Note that data for G8140040 for years 1961 to 1966 have been derived from G8140041(Daly River at Gourley)(from Jolly 2001; 2002).

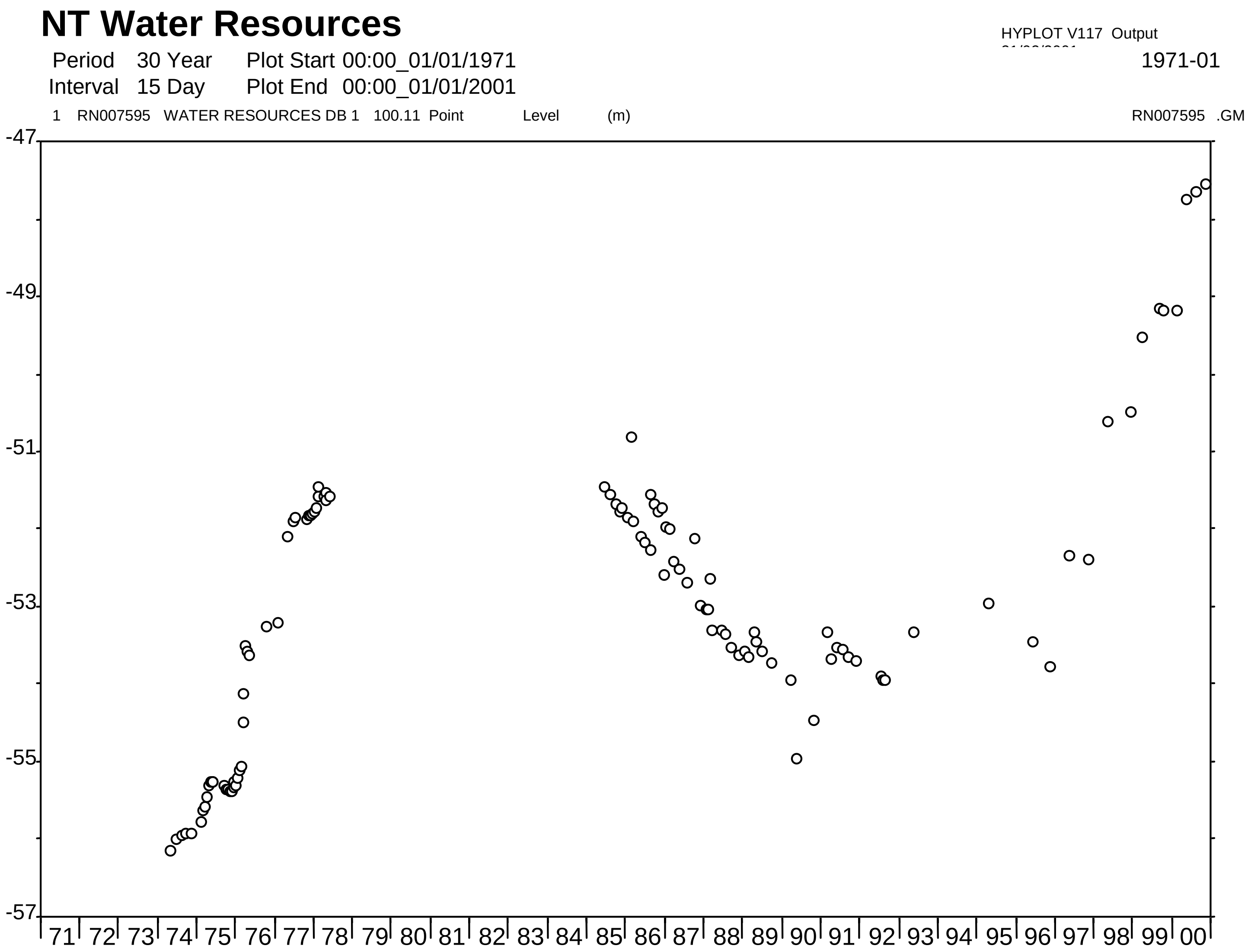

Figure 11 Temporal variations in groundwater levels in bore RN7595 which monitors water levels in the Oolloo Dolostone (overlain by Cretaceous sediments) aquifer near Claravale Crossing (from Jolly 2001; 2002)

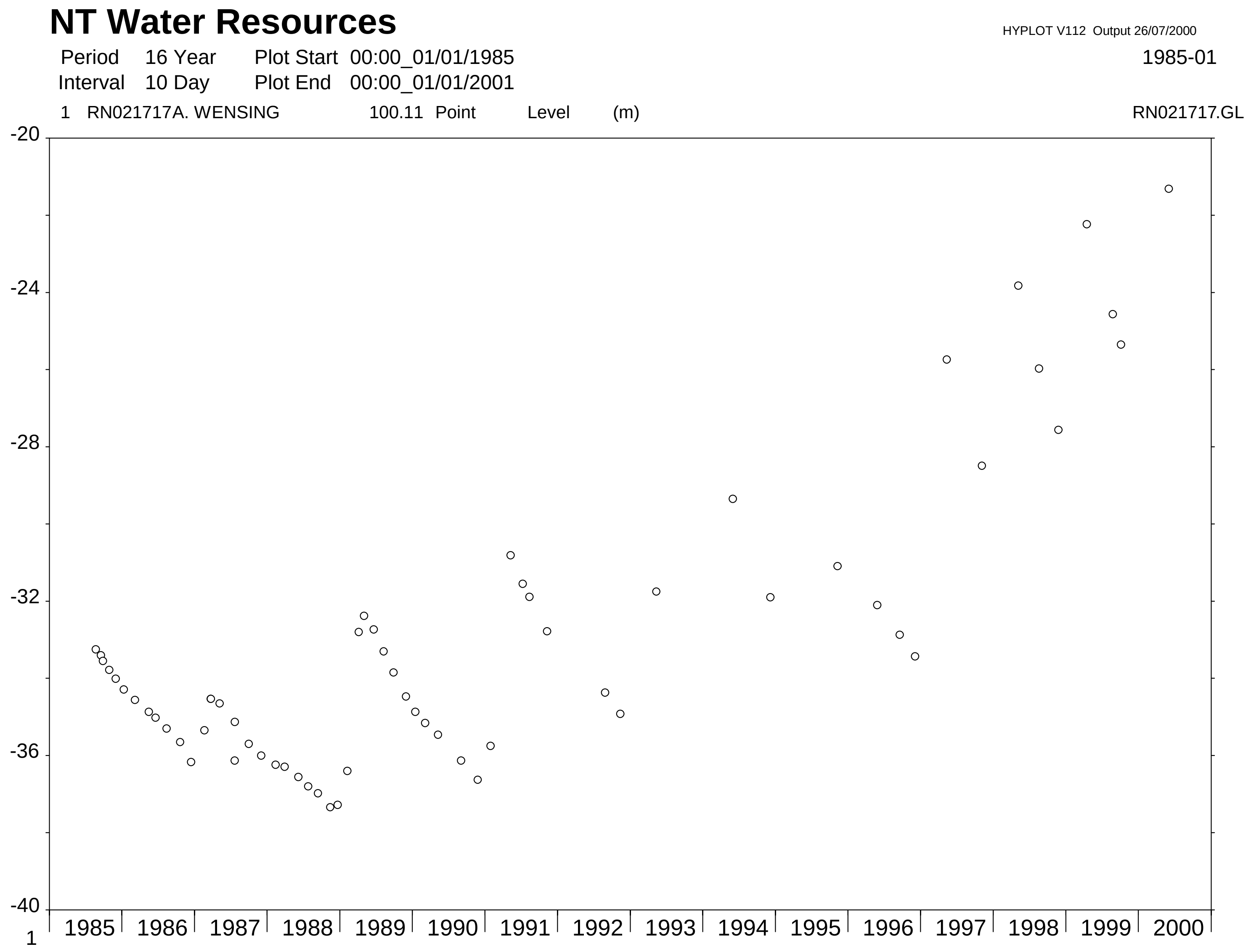

Figure 12 Temporal variations in groundwater levels in bore RN21717 in the Oolloo Dolostone aquifer near Oolloo Crossing where the dolostone exhibits surface outcrop (from Jolly 2001; 2002)

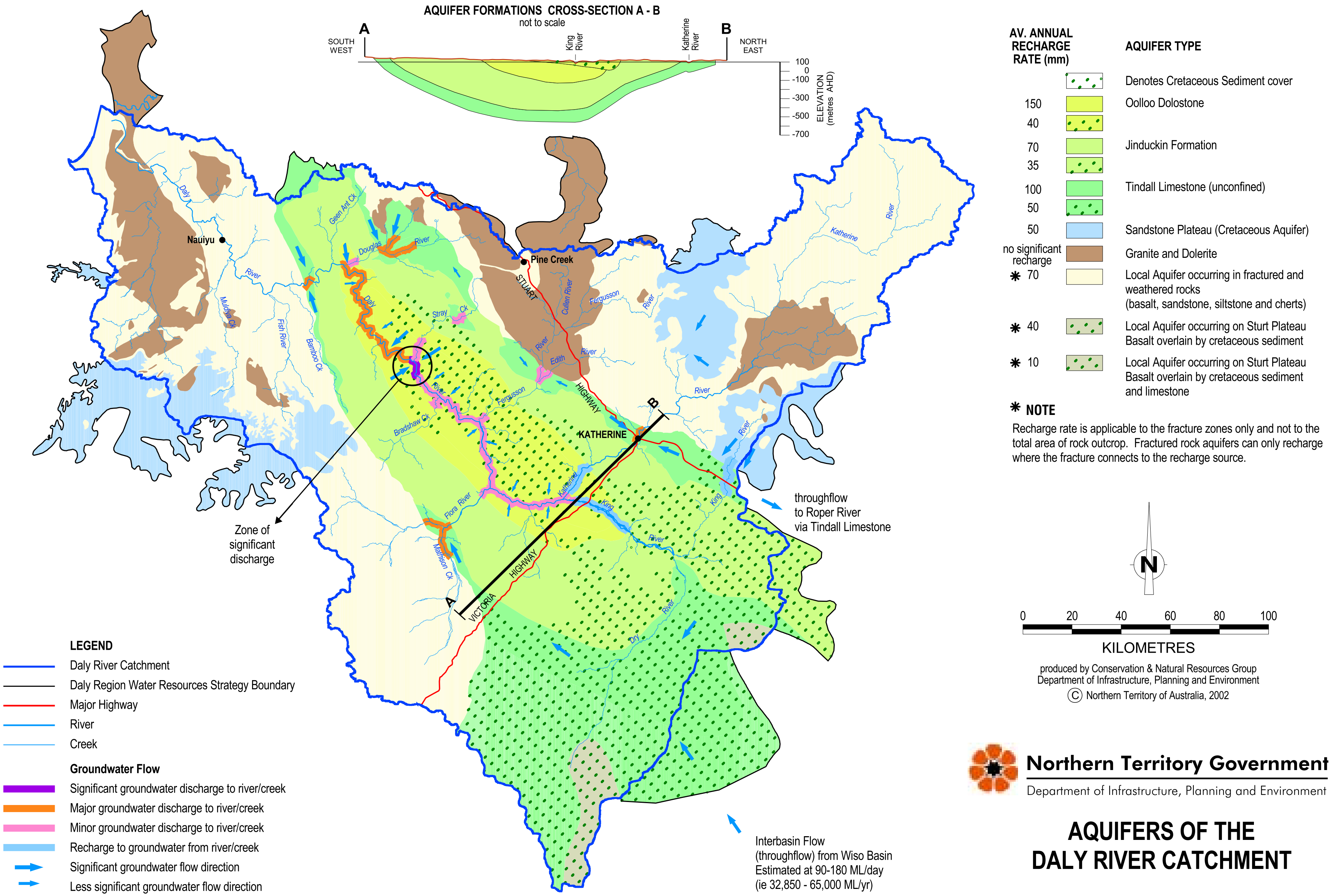

Figure 13 Aquifers of the Daly River Catchment (figure provided by the Conservation and Natural Resources Group, DIPE, NT Government)

Modelling Dry season flows and predicting the impact of water extraction on a flagship species

Georges et al (2002) present the results of Project 23045. The Pig-nosed turtle (*Carettochelys insculpta*) is a high profile flagship species (fig 14) because it is of considerable international concern, being the sole remaining member of a once widespread Family, and because the best Australian populations of the species are found in the Daly River. Furthermore, the Daly River also contains eight of the nine species of freshwater turtles present in the Northern Territory (Price et al 2002). Protecting the pig-nosed turtle will likely conserve a number of other species whose biological, ecological and environmental requirements are less stringent and hence it can be regarded also as an umbrella species.

Figure 14 Pig nosed turtles (*Carettochelys insculpta*) (photograph: John Cann)

According to Georges et al (2002), the Pig-nosed turtle is a freshwater turtle that has temperature-dependent sex determination. During the Dry season, gravid females move extensively to find fluvially reworked, clean sand banks with direct connection to water where they deposit clutches of 4 to 19 eggs in shallow chambers 0.3 to 2 m from water. Pig-nosed turtles have limited mobility out of water because they cannot walk easily. Nesting sites are either sandy lee-side shadow deposits behind large woody debris or boulders, sandy point bars on the inside of bends or sandy tributary-mouth bars where sand-bed tributaries debouch into the main stream (Benn & Erskine 1994). There is approximately one suitable nesting site per km of channel in the study reach. Pig-nosed turtles nest twice every second year but asynchronously so there is a dual nesting period each Dry season. Linear home range for females extended between 2.5 and 13.9 km and for males, between 1.5 and 4.5 km. Timing of nesting depends on water temperature. The eggs incubate rapidly over 50-90 days to maturation depending on date laid and incubation temperature. The trigger for hatching is flooding or torrential rain and hydrological mismatching with egg development leads to high mortality. Embryos only have sufficient resources to carry them through about 60 days at 30°C on reaching maturity. Pig-nosed turtles are omnivorous but, during the Dry season, rooted macrophytes, principally *Vallisneria nana* and associated macrophytes, are the dominant food source. There was no *V. nana* in the first 32 km of channel downstream of Claravale Crossing in 2001 (Rea et al 2002).

The 73.7 km long study reach of the Daly River extended from Claravale Crossing to the confluence with Cattle Creek which is located downstream of Beeboon Crossing (fig 3). The maximum recorded streamflow at Dorisvale gauge between 1960 and 2002 was 8100 m^3s^{-1} in January 1998. Dry season streamflows at the Daly River at Dorisvale gauging station (G8140067) and at Oolloo Crossing gauging station (G8140038) are closely related with the least squares linear regression equation being:

$$Q_O = 3.74199 + 1.457Q_D \quad (1)$$

$$R^2 = 0.92; F = 599.95; \rho < 0.0001$$

where Q_O is mean daily discharge at Oolloo Crossing and Q_D is mean daily discharge at Dorisvale.

On the basis of detailed streamflow gaugings on 3 June and 3 September 2001, the spring and surface water inflows to the Daly River were determined. A total of 46–63% of the net inflow in the 66.9 km between Claravale and Oolloo crossings occurred from springs in the 9 km adjacent to the Stray Creek development area. Bradshaw and Stray creeks also contributed significant surface streamflows in June although Bradshaw Creek had ceased flowing in September.

Populations of many species of aquatic organisms depend on their ability to move freely through the stream channel network. Increasing the frequency and duration of baseflows and extreme low streamflows will compromise turtle life history through limited access to resources, which are essential for reproduction (eg nesting banks) and feeding (eg *Vallisneria* meadows). To determine passage through the study reach by the pig-nosed turtle and aquatic habitat connectivity, the one-dimensional, standard step, steady state, backwater model, HEC-RAS, was used for ten subcritical streamflows using 1028 cross sections and 12 streamflow change locations. *Breakpoints* were defined as points which would restrict the movement of pig-nosed turtles along the river longitudinal continuum. They equate to areas of river bed where the maximum flow depth immediately upstream of a hydraulic control is less than 0.5 m. *Pools* were then defined as lengths of channel between successive breakpoints.

For the lowest recorded streamflow of 2 m^3s^{-1} at Dorisvale gauge, there were 35 breakpoints defining 34 pools, none of which were less than 300 m long. On average 77% of turtles would be successful in nesting at a discharge of 2 m^3s^{-1} at Dorisvale gauge. The average number of *V. nana* beds per pool was less than four.

For a discharge of 4.8 m^3s^{-1} at Dorisvale gauge, there were 20 breakpoints defining 19 pools. On average 87% of turtles would be successful in nesting at a discharge of 4.8 m^3s^{-1} at Dorisvale gauge. The average number of *V. nana* beds per pool was 7.4.

For a discharge of 7.6 m^3s^{-1} at Dorisvale gauge, there were 13 breakpoints defining 12 pools. For discharges greater than 7.6 m^3s^{-1} at Dorisvale gauge, all pools have 100% chance of having a nesting site. The average number of *V. nana* beds per pool was about 15.

For a discharge of 10.5 m^3s^{-1} at Dorisvale gauge, there were 8 breakpoints defining 7 pools. Under such flow, 5.5 km of the study reach was fragmented into small pools whereas 51.2 km formed very large or continuous pools which are the main refuges for riverine biota. The average number of *V. nana* beds per pool was about 20.

For a discharge of 13.3 m^3s^{-1} at Dorisvale gauge, there were 4 breakpoints defining 3 pools. Under such flow, only 1.8 km of the study reach was fragmented into a small pool. The average number of *V. nana* beds per pool was still about 20.

At streamflows greater than 16.1 m^3s^{-1} at Dorisvale gauge, the maximum flow depth always exceeded 0.5 m and hence there were no barriers to the free movement of pig-nosed turtles and other aquatic biota in the study reach.

A model was developed to predict water temperatures in the Daly River in the study reach in response to changes in weather, water depth and streamflow so as to estimate the effects of irrigation extraction on river water temperatures. However, the changes predicted are much lower than those caused by natural weather variations and shifts in nesting time in response to other factors.

Impacts of flow reduction due to agricultural extraction on the life history of the pig-nosed turtle were assessed and classified as ‘boom’, ‘bust’ or ‘catastrophic’. In terms of population dynamics, a ‘boom’ period occurs when conditions are such that reproductive output not only ensures that current population levels are sustained, but is also sufficient to fully offset low recruitment that that would have otherwise resulted in population decline in preceding ‘bust’ periods. Boom years may well be infrequent, and it is to be expected that the bust years would numerically dominate the boom years. Changing the frequency of boom relative to bust periods through streamflow alteration is likely to have substantial long-term impact on the population levels sustained locally. Minimum streamflows greater than 9.1 m^3s^{-1} at Dorisvale gauge were classified as ‘boom’ conditions because:

- river fragmentation did not greatly restrict home range;
- access to nesting banks was unrestricted;
- there was good access to feeding grounds; and
- there was no appreciable thermal impact.

Boom conditions occur naturally in about 20% of years. Minimum streamflows less than 6.2 m^3s^{-1} at Dorisvale gauge were classified as ‘bust’ conditions because of significant impacts on at least one of the above factors. Such conditions occur naturally three out of five years. ‘Catastrophic’ conditions were defined as zero streamflow which has not been recorded to date. Minimum streamflows have to be protected to ensure the viability of the pig-nosed turtle.

Tree water use and sources of transpired water in riparian vegetation along the Daly River

O’Grady et al (2002a, 2002b) present the results of Project 23086. The banks of the Daly River are stepped due to the presence of in-channel benches below the floodplain (Erskine & Livingstone 1999) and the riparian vegetation (fig 15) exhibits distinct vertical zonation from the river bed across the benches to the levee crest of the floodplain (Faulks 1998a&b). O’Grady et al (2002a&b) found 43 tree species including three introduced species during their riparian vegetation surveys at five sites. Mean basal area was 71 ± 13.1 m^2 ha^{-1} and mean stocking rate was 1219.6 ± 164.7 stems per ha. Six species (*Melaleuca argentea*, *Melaleuca leucadendra*, *Eucalyptus bella*, *Cathormion umbellatum*, *Nauclea orientalis* and *Casuarina cunninghamiana*) contributed 82% of the standing basal area. *M. argentea* and *M. leucadendra* trees form a linear strip along the lower bank (fig 15) with a closed monsoon forest community of *C. cunninghamiana*, *N. orientalis*, *Barringtonia acutangula*, *Ficus* *racemosa*, *Cat. umbellatum* and *Strichnos lucida* behind on benches. Eucalypt woodland is present on the levees with *E. bella*, *E. tectifica*, *Erythrophloem chlorostachys*, *Planchonia careya* and *Terminalia ferdinandiana* dominating. *Acacia auriculiformis* and *C. cunninghamiana* are found in all zones.

Figure 15 Riparian vegetation on the Daly River (photograph: Steven Tickell)

Water use by five *E. bella* and five *M. argentea* trees at each of three sites (Claravale Crossing, downstream of Oolloo Crossing and the confluence of the Douglas and Daly Rivers) at three times (July 2000, September 2000 and May 2001) over four days was measured by the compensation heat pulse technique. At the same time, leaf water potential on three leaves from each tree for which water use was measured and soil matric potential for three replicate soil samples at multiple depths were also determined. There was no difference in daily tree water use between sites or seasons. Mean water use normalised by sapwood area in *E. bella* was 2.7 ± 0.2 $m^3 m^{-2} d^{-1}$ and in *M. argentea* was 2.3 ± 0.2 $m^3 m^{-2} d^{-1}$. The lower water use of *M. argentea* may reflect different microclimatic conditions (greater shading and a lower vapour pressure deficit) within the river channel than on the levee. Daily tree water use for each species was related to diameter at breast height (DBH) by a highly significant power function, despite pooling results for a large number of trees over a range of times and locations. The lack of a distinct seasonal pattern of water use appears to be a feature of tropical evergreen trees. Pre-dawn leaf water potentials remained close to zero during all seasons for both species at all sites. Midday leaf water potentials declined compared to pre-dawn values at all sites for all seasons in both species but this decline was greater in *E. bella* than in *M. argentea*. Both *E. bella* and *M. argentea* had pre-dawn leaf water potentials that were less than the soil matric potentials in the upper 1 m of soil, suggesting that the trees were accessing water at depths greater than 1 m. In May 2001 pre-dawn leaf water potentials were similar to soil matric potentials at a depth of 3 m. Neither species developed significant water stress during the Dry season based on the pre-dawn leaf water potentials. River margin soils were very shallow and often saturated at 1 m. Levee soils were heavier textured than river margin soils and, as a result, held more moisture within the unsaturated zone of the very deep (>9 m) soil profiles. Trees, even on the levees, did not develop significant water stress during the Dry season.

Samples of river water, soil water, groundwater and xylem water for a number of tree species were collected at the Douglas/Daly and Oolloo sites in September 2000 and August 2001 to determine the stable isotope composition of potential water sources that could be compared to xylem water. There is no fractionation of hydrogen/oxygen isotopes during water uptake by plant roots allowing the identification of water sources where there is a clear difference in isotopic composition between each source. Riverside trees (*M. argentea*) had deuterium signatures (-48.3 to -37.9 ‰) similar to groundwater (~-45 ‰) or river water (~-44 ‰) while trees higher on the river bank (*E. bella*, *Cathormion umbellatum*, *Pongamia* spp., *Poinciana* spp.) had signatures (-71 to -53.4 ‰) that were markedly different. *Barringtonia acutangula* growing on in-channel benches also had signatures (-46 to -39.5 ‰) similar to river and groundwater. However, *Acacia auriculiformis* (-62.9 to -37.9 ‰) and *C. cunninghamiana* (-66.9 to -52.3 ‰) were opportunistic in their water use and accessed different water sources depending on where they were located on the river bank. Dry season pre-dawn leaf water potentials of trees confirmed the results of the isotopic water sourcing for the trees growing along the river margin, on in-channel benches and on the levee. Pre-dawn leaf water potential is representative of the soil water potential in the zone of water uptake by roots. Similar stable isotope signatures were found for the Daly River and groundwater in the riparian zone.

Stand water use by riparian vegetation on the Daly River was estimated by vegetation surveys at five sites (Dorisvale, Oolloo Crossing, downstream of Oolloo, Black Bull Yards and Douglas/Daly) and by using the heat pulse technique to measure tree water use of each major species on three plots at two sites (two plots at Oolloo and one at Douglas/Daly) between August and December 2001. There was no seasonal pattern in tree water use from the Dry to the Wet season in any tree, except the deciduous *Terminalia microcarpa* at the Douglas/Daly site, which obviously exhibited an increase in water use as the tree flushed. Stand water use was determined by summing mean daily water use for all trees at each site and varied from 1.5 mm d^{-1} to greater than 4.8 mm d^{-1}. Mean water use increased slightly from 2.87 mm d^{-1} in August to 3.3 mm d^{-1} in December. Stand water use was closely related to basal area (r^2 = 0.81). However, stand structure is highly variable with basal area varying from 10 m^2 ha^{-1} to more than 200 m^2 ha^{-1} (mean of 72 m^2 ha^{-1}). It was suggested that total vegetation water use, including understorey and soil evapotranspiration, on the Daly River was close to potential evapotranspiration during the Wet season.

Although it was not possible to determine definitively whether the riparian vegetation on the Daly River is an obligate groundwater dependent system, it is highly likely that there is at least some groundwater dependence. Phreatophytic trees can use soil moisture when in large supply and only revert to groundwater during prolonged droughts. The series of above average wet seasons during the study resulted in high groundwater levels. Groundwater dependence of those species that only used stored soil water throughout the Dry season may only become apparent during times of reduced baseflows and water tables.

Environmental water requirements of *Vallisneria nana* in the Daly River

Rea et al (2002) present the results of Project 23087. This comprehensive project focused on the major riverine plant, *Vallisneria nana* (fig 16), the key habitat for many turtle and fish species, including the pig-nosed turtle.

V. nana is a perennial stoloniferous submerged macrophyte with shoots composed of basal narrow ribbon-like leaves. Dense monospecific stands develop in suitable habitats during the Dry season. The cover of *V. nana* increases by stoloniferous growth and continuous leaf and shoot recruitment throughout the growing season. Flowering takes place in the middle of the Dry season. *V. nana* is comprised of >80% leaf, with roots and stolons accounting for the remainder of biomass during the Dry season. Over the Wet season, small rhizomes develop, allowing a few shoots to survive, supporting new growth in the following growth season.

Figure 16 A *Vallisneria nana* bed with continuous cover ('meadow'). Swathes grazed by pig-nosed turtles appear red (new growth of *V. nana*)(from Rea et al 2002).

Groundwater maintains baseflow at depths of 0.5 to 2 m in pools and less over riffles in the Daly River along the middle reaches. Rainfall from 1997/8 to 2001/02 was above average and resulted in above average minimum streamflows. Between 1974 and 2001, minimum instantaneous streamflow at the study sites near Oolloo Crossing ranged from 11 to 25 m^3s^{-1}. This compared with 7 to 11 m^3s^{-1} during the dry period between 1960 and 1974. Since the early 1900s, there have been cyclical decadal runs of high and low streamflows, as documented elsewhere in Australia (Erskine & Warner 1988, 1999).

There is considerable interannual variation in the timing of groundwater input to the river. During dry periods, groundwater discharge begins early in the year. In 1962 groundwater input at Dorisvale gauge began on 20 March when streamflow was 20 m^3s^{-1}. Streamflow then decreased rapidly over 2–3 weeks, remaining at 7 m^3s^{-1} for the following six months. During the wet period in 2000, groundwater input began on 15 May when streamflow was 80 m^3s^{-1}. Streamflow decreased slowly reaching a minimum of 13 m^3s^{-1} in mid-October.

V. nana is the dominant submerged macrophyte in the Daly/Katherine river from Katherine township to Beeboon Crossing (about 300 km). The major beds of *V. nana* are restricted to the middle Daly River reach; from 32 km downstream of Claravale Crossing to about 20 km upstream of the Douglas River confluence. Fourteen major beds are located in the 30.6 km between Jinduckin Creek and the Douglas River confluence. They occur on the outside of bends, where outcrops of the bedded Oolloo Dolostone (Tickell 2002) form a rock pavement which provides a refuge for *V. nana* shoots to survive high Wet season streamflows. *V. nana* generally occurs in linear beds parallel to the bank edge. Beds are constructed of a mosaic of patches that vary in size and degree of coalescence and vary from hundreds of metres to kilometres long and from metres to tens of metres wide. They are located close to the river bank, occupy 25.6% of the bank edge and 0.02% of the total area of the main study reach.

V. nana beds are a significant habitat for a variety of turtles, macroinvertebrates and fish. Freshwater crocodiles (*Crocodylus johnstoni*) frequent the beds, as well as freshwater whip-rays (*Himantura chaophyra*) and pig-nosed turtle, with the latter two species favouring patches of *V. nana* in fast flowing water. The pig-nosed turtle is closely associated with *V. nana* patches with the majority of their sightings (>90%) located within *V. nana* beds. Ninety-six macroinvertebrate taxa were identified from six habitat types (low current *V. nan*a, fast current *V. nan*a, pebble/gravel, coarse sand in a pool, bare rock, channel edge). The relative abundance of macroinvertebrates differed between habitats, with assemblages in low current *V. nana* being distinct from those in fast current *V. nan*a. Gastropod molluscs were abundant in, but not confined to, *V. nana* beds.

Preference curves for water depth, distance from bank edge and mean and maximum flow velocity were derived from data collected at 27 channel cross sections. During baseflows in August 2001 (minimum flow of 25 m^3s^{-1}), *V. nana* occurred within a depth range of 0–1.3 m, mean flow velocity range of 0-0.6 ms^{-1} and maximum flow velocity range of 0–0.75 ms^{-1}. Major beds occurred in the patch of channel with the highest flow velocity. For *V. nana* beds with 100% cover, the probability of occurrence was greatest at a water depth of 0.6 m and at 5 m from the bank edge. The gracile character of *V. nana* demonstrates it is adapted to moderate flow velocity that keeps leaves narrow (1–4 mm) and relatively short (<80 cm). *V. nana* was generally absent from areas with low flow velocities and present in, or adjacent to, high flow velocities during Dry season baseflows.

V. nana growth increased rapidly from early May until mid-July due to the sudden availability of light and the use of available nutrients. Light is the main cue for growth within physical habitat limits, while the main constraint on growth is the very low supply of nutrients. Low nutrient levels constrain total biomass. This is exacerbated by herbivore grazing (eg turtles), with recycled nutrients most likely captured by the dominant macroalga, *Spirogyra*.

There are naturally high concentrations of heavy metals and trace elements in the water and benthic sediments of the Daly River. As water chemistry changes seasonally, the plant sink for metals and trace elements is a temporary one. During the Wet season, the more acidic water favours metal and trace element accumulation in *V. nana* whereas during the Dry season, groundwater inflow of bicarbonate-dominated water results in the unavailability of metals and so leaching occurs. *V. nana* is able to lose metals and trace elements during the Dry season and hence prevent build up to toxic concentrations.

Net primary production in the river is limited by the availability of light and nutrients. Daily photosynthetically active radiation increases steadily from April to November. At least 40% of the increase is due to increasing day length and sun height after the winter solstice in June. Photosynthesis is proportional to light intensity but plants could further increase their photosynthetic rates if there was even more light.

Early in the growing season when streamflows are receding, a small phytoplankton population dominates primary production due to their ability to grow quickly and sequester the small nutrient pool. Thereafter, the biomass of benthic plants increases and phytoplankton concentrations decline because they are less effective competitors for nutrients. The mass of benthic plants increases rapidly from May to July. Macroalgae mass peaks in August whereas *V. nana* mass remains constant from July onwards. Nutrient concentrations in the water column remain low because of rapid uptake by these plants. The low nitrogen levels mean that phytoplankton primary production can only be sustained for a full day in April and May, and thereafter for only an hour or less. After June, there is only enough nitrogen to support production by *Spirogyra*, *V. nana* and the charophytes for several hours each day. As dissolved reactive phosphorus concentrations are at or below the analytical detection limit they can only sustain primary production for 24 h in April. Thereafter, all primary production is limited by phosphorus availability, phosphorus being more limiting than nitrogen.

Dissolved oxygen is lowest at about 0700 h due to night time respiration and highest at 1700 h due to day time photosynthesis. Daily photosynthetic rates increase from near zero in mid-April to a maximum in early August. Respiration rates similarly increase through the Dry season. Respiration rates significantly exceeded photosynthetic rates, meaning that the Daly River is strongly heterotrophic. Although photosynthetic rates are controlled by biomass and light, the conversion of production into biomass depends on nutrient availability. The extremely nutrient poor conditions in the river mean that only about 15% of photosynthetic production is converted into biomass. The daily nitrogen requirements at the estimated rates of photosynthesis are far in excess of the nitrogen available in the water column. Most carbon produced is excreted as carbohydrate, then lost through respiration by bacteria and microorganisms in the hyporheic zone. The Daly is a net exporter of CO_2 to the atmosphere.

The RMA hydrodynamic model was used to predict the distribution of optimal flow velocity and water depth for *V. nana* under eight streamflows which cover historical minimum instantaneous flows in above- to below-average years (ie 30, 25, 20, 15, 12, 9, 6 and 3 m^3s^{-1}). The RMA model calculates the water surface elevation for each discharge over a 16 km reach. These data were then combined with that from field surveys in the same reach, to determine the percentage exposure of each bed under decreasing flows. As a submerged species with a very small below ground component, *V. nana* is not adapted to subaerial exposure which is considered fatal. Optimal flows are greater than 10-12 m^3s^{-1} and, below 10 m^3s^{-1}, there is a sudden decrease in the habitat availability for *V. nana*. About 12 m^3s^{-1} equates to the long term average minimum discharge around Oolloo Crossing and marks the inflection point on the response curve for percentage exposure and depth preference of *V. nana*. Exposure/inundation does not take into account the effect of flow velocity. Although *V. nana* may survive when flooded by shallow, still water, it needs moderate flow velocities and water depths to maintain its character and hence habitat value.

The amount of exposure of the field-surveyed *V. nana* beds in the hydrodynamic modelled reach since 1960 was calculated from the streamflow record at the Daly River at Mt Nancar gauging station (G8140040). In average to above average conditions (since 1974), the area inundated by the end of the Dry season was always about 95%. In drier years when the minimum flows were 6–11 m^3s^{-1}, the inundated area would have been about 75–90%. However, higher flows are needed for the optimal performance of the plants and for habitat value to be realised.

Changes in water depth have negative effects well before beds are exposed. Depths and flow velocities less than the preferred ranges (40-80 cm, 0.2-0.4 ms^{-1}) are experienced well before bed exposure and these sub-optimal conditions have adverse effects on *V. nana* growth and habitat quality.

Protection of the identified beds is critical because they are the locations where the plant retreats during high Wet season streamflows. These beds are the source of propagules that expand during the Dry season. It cannot be assumed that at low streamflows, *V. nana* will migrate towards the thalweg (deepest water) and create the same habitat in the sandy middle of the channel. Those plants are annually uprooted by Wet season streamflows.

Periphyton and phytoplankton response to reduced Dry season flows in the Daly River

Townsend et al (2002) present the results of Project 22963. This innovative project evaluates whether phytoplankton, benthic diatoms and macroalgae are either directly or indirectly responsive to Dry season streamflows, and provides information for environmental water allocations. These algae are responsive to changes in streamflow and water quality, over a time scale of weeks because of their rapid replication rate of a couple of days.

In the upper reaches of the Daly River catchment, Dry season streamflows originate predominantly from aquifers within Cretaceous sediments (Jolly 2001, 2002). With groundwater inflow from the Cambro-Ordovician Daly Basin carbonate sediments, the conductivity of the Daly River increases 20–30 fold, pH and the carbonate buffering capacity increase at least an order of magnitude, whilst soluble phosphorus and nitrate concentrations more then double. In the Douglas River, inflow from the Tindall Limestone results in an almost 100 fold increase in nitrate concentrations but has not resulted in high phytoplankton concentrations, probably due to phosphorus limitation. Such a marked increase in nitrate concentrations was not measured elsewhere in the catchment, and may be due to modified land-use and management practices. Water extraction from the Daly Basin for consumptive use would be expected to alter water quality in addition to streamflow, depending on the change in the mix of water sources to the river.

Diatoms (microscopic algae) are an abundant component of periphyton (algae that grow on surfaces) in rivers, and are an important primary producer. They provide a simple and time-efficient means of biomonitoring. Diatoms grow on a wide range of substrates, including the epilithon (rocks), epidendron (submerged wood), epipelon (fine sediment ie mud), epipsammon (sand), epiphyton (submerged aquatic plants including macroalgae) and epizoon (aquatic animals). The diatom assemblage on river substrates was investigated to determine the best sampling strategy for diatom sample collection. The diatom assemblage on different river substrates was not always similar, demonstrating the requirement for a monitoring program to use a single substrate, or a number of substrates shown to be equivalent. Epilthic and epidendronic substrates occurred commonly in the river, featured similar diatom flora, and were recommended for sample collection in the Daly River and its tributaries.

A total of 252 diatom species were identified, comprising both cosmopolitan and tropical taxa. Epilithic diatom assemblages in the Daly River are responsive to the ionic composition of river water, as well as nitrate, soluble phosphorus, dissolved oxygen, temperature and turbidity. This sensitivity is independent of streamflow. The diatom flora will respond indirectly to reduced Dry season streamflows caused by water extraction, through its impact on water quality. Diatoms are a potential biomonitoring tool for determining human impacts on aquatic ecosystems.

The water chemistry and diatom data show that the Daly and Douglas rivers exhibit clear biological trends from turbid, dilute, acid to circumneutral waters to those which are clear, concentrated (higher electrical conductivity) and alkaline. Critical hinge-points exist above Oolloo Road Crossing on the Douglas and below Knotts Crossing on the Katherine-Daly rivers where there is an abrupt shift from water dominated by sandstone aquifers to one dominated by Daly Basin limestone/dolostone aquifers. These shifts are clearly differentiated by the diatom flora and represent an efficient means of determining any longitudinal changes associated with catchment development for agriculture.

Phytoplankton species and biomass in the Katherine and Daly rivers and two tributaries (Flora and Douglas rivers) were collected on six occasions from June to November 2000. The phytoplankton population is highly diverse, with most species representing a small percentage (<1%) of the biovolume. A total of 206 species was identified, from all taxonomic groups including the blue-greens (Cyanobacteria). Of these, 36 had not been reported previously from the Northern Territory, and five had not been reported previously from Australia. The

Bacillariophyceae (63 taxa), the Desmidiaceae (47) and the Chlorophyta (34) were dominant with respect to the number of taxa present. Although several samples had up to 640 000 cells/L (due to *Urosolenia eriensis* and *Fragilaria zasuminensis*), all but six samples contained <150 000 cells/L which are densities well below those commonly recorded in the larger rivers of the world, but are similar to those in moderately sized rivers in southeastern Australia. To maintain a population in a river, recruitment rates of phytoplankton need to exceed the mean travel time of streamflow, otherwise populations will decline. Streamflow also has a direct influence on turbulence, and hence the light climate, phytoplankton are exposed to, whilst stratification can indirectly affect river nutrient dynamics. The biotic control of river phytoplankton, for example by zooplankton grazing, can only take place when the physical constraints of streamflow are reduced. These influences combine to make phytoplankton a potentially sensitive component of an aquatic ecosystem to streamflow. The concentration of phytoplankton, measured either as chlorophyll a (a photosynthetic pigment) or biovolume, was limited by streamflow, rather than by light, nutrients or zooplankton grazing. Under lower streamflows, due to either climatic or human influences, phytoplankton concentrations may no longer become limited by streamflow, and instead become nutrient-limited. Under such a scenario, where soluble nitrogen and phosphorus enter the river from Daly Basin groundwater, phytoplankton concentrations could be expected to increase.

Streamflow, as well as ionic chemistry, influences the assemblage (species composition and their relative abundances) of phytoplankton in the river. A possible mechanism for the influence of streamflow is through the volume and proportion of waters with a retention time longer than the average, as for example in backflow or dead zones where there is minimal exchange with the main river. If this mechanism occurs, then the assemblage of phytoplankton would be expected to differ with lower streamflows. Correlation analyses identified streamflow as a factor that explained the phytoplankton assemblage of the Daly River and its tributaries. Streamflow will affect river phytoplankton indirectly through flow velocity, and hence the rate of removal of phytoplankton and also the occurrence of zones where water is retained for periods longer than the average travel time. These occur in the deep pools in Katherine Gorge (Baker & Pickup 1987). The Claravale-Beeboon reach may also have zones of long retention time. The growth of phytoplankton is different in these long retention zones, that are separated from the main streamflow by a boundary across which water is exchanged slowly with the river.

The relationship between the benthic macroalga, *Spirogyra* (fig 17), and streamflow along a 17 km reach of the Daly River was investigated. *Spirogyra* is a widespread species that grows on the river bottom and banks attached to rock, gravel, snags and living plants (fig 17). Being a plant, it is important both as a food source for animals (graziers) and as habitat for smaller organisms. Although the contribution of *Spirogyra* to the ecology of the river is unknown, its significance may be deduced by its status as a primary producer and its abundance. *Spirogyra* is absent early in the Dry season (May-June) but undergoes rapid growth to reach a maximum biomass in July-August that is likely to represent a significant portion of the river's plant biomass and primary productivity. Algal biomass then declines, finally being removed by storm flow early in the Wet season (200 m^3s^{-1} in November 2000). *Spirogyra* was not observed growing on sand (too mobile for attachment). This highlights the importance of gravel/rock substrates as a stable substrate allowing the development of extensive *Spirogyra* strands on the river bottom. Stable substrates along the edges of the river such as exposed roots, plants and rock allow the development of trailing stands of *Spirogyra*. Although both the riverbed and edge provide suitable substrate for the growth of *Spirogyra*, the river bed supports over 95% of the total biomass in the study reach and hence this study focused on the river bed to establish a flow-biomass relationship. In slow flowing areas high biomass was never observed. *Spirogyra* appears to require a minimum flow/shear velocity to enable dense stands to become established. In very high flow velocity environments dense stands are also not observed, presumably due to the drag acting on filaments being sufficiently high to cause tearing or dislodgment.

Figure 17 Dense coverage of *Spirogyra* over a gravel bed on the Daly River (from Townsend et al 2002)

In addition to a substrate preference, *Spirogyra* also has an optimal range of shear velocity. The optimal range for the growth of *Spirogyra* corresponds to shear velocities of 0.025–0.055 ms^{-1}, or a flow velocity at 0.1 m above the bed of 0.17–0.44 ms^{-1}. At the upper range of shear velocity, the algae is physically removed, whereas below this range the alga is unable to grow as well, possibly by not receiving adequate nutrients. The biomass of *Spirogyr*a, over a wide range of streamflows that included ones below the historic range, was modelled.

The relationship between streamflow and biomass was applied to the dry season historical low discharge record in the study reach to determine the annual biomass frequency distribution for the 42 years for which streamflow records are available. The relation between streamflow (Q) and biomass (B) is:

$$B = (0.9969 \ln(Q) + 1.6243)^2 \qquad (2)$$

$r^2 = 0.99$ for the range 0.5–30 m^3s^{-1}.

This provides a comparative assessment of how water extraction may change the distribution of biomass levels from the expected natural state. Above 12 m^3s^{-1}, algal biomass depended primarily on the shear velocity (and therefore streamflow) above river gravel and rock substrates. However, below this value, the loss of habitat (rock and gravel substrate) through drying and stagnation became important. Moreover, the rate of biomass loss with reduced streamflows below the 12 m^3s^{-1} threshold was three times greater, than rates of loss above the threshold. Simulations of water extraction using the streamflow record shows that a proportional extraction regime better maintained the natural interannual variability than a fixed regime. These simulations suggest that a proportional extraction rate >8% would adversely affect the natural variability of *Spirogyra* biomass if historical minimum streamflows were not maintained. If minimum river levels are to be preserved, then simulations show that if no extraction is to occur when discharge is <10 m^3s^{-1}, then a proportional extraction rate >9% will affect the natural variability of *Spirogyra* biomass.

Inventory and risk assessment of water dependent ecosystems in the Daly Basin

Begg et al (2001) present the results of Project 23088. This detailed study focused on the use of a Geographical Information System (GIS) to:

1. Identify the extent, distribution and location of wetlands in the Daly Basin;
2. Establish threats to these ecosystems from existing and forecast water use and land management practices; and
3. Identify which ecosystems are most at risk and, where possible, provide an assessment of the extent of this risk.

The major difference between wetland inventory (point 1) and wetland risk assessment (points 2 and 3) is that wetland inventory is used to collect information to describe the ecological character of wetlands, whereas wetland risk assessment considers the pressures (point 2) and associated risk of adverse change in ecological character (point 3).

A GIS for the Daly Basin was developed to store and manipulate all data and to provide common formats for mapping of wetlands. Detailed and uniformly consistent metadata were not available for all datasets but inconsistencies were most common for the drainage datasets.

For wetland mapping, 1:50 000 topographic maps and the NT Department of Infrastructure Planning and Environment's land unit maps of the Daly Basin were used. The spatial extent of the different wetland types within each subcatchment was determined based on the waterlogging characteristics of each land unit. The combined data were then reclassified into one of ten wetland types (river, creek, channel billabong, backflow billabong, floodplain billabong, floodplain, dampland, sumpland, waterhole (fig 18) or doline) using landform (channel, flat or basin) and water regime (permanently or seasonally inundated or seasonally saturated) criteria. The most common wetland types in the Daly Basin are rivers and creeks (channels – see fig 1, 15, 17 & 19) with a total linear extent of about 25 560 km. The greatest extent of channels occurs on the Daly, Katherine, King and Dry rivers. Approximately 3534 km^2 of the Daly Basin (17.4%) consists of wetlands that are associated with flat land (floodplain and dampland). Floodplains cover 2010 km^2 (57%) and damplands 1524 km^2 in the Daly Basin. The greatest extent of floodplain occurs along the Daly, Katherine, King and Dry rivers whereas the greatest extent of dampland occurs in the Daly, Douglas, King and Dry rivers and Green Ant Creek.

A provisional Land Use Concept Plan (LUCP) up to the year 2025 for the Daly Basin was used to determine the likely extent of the major threats from agriculture and associated land uses. Almost 80% of the region is suitable for some form of agriculture, particularly pastoral activities, but dryland cropping, irrigated cropping and horticultural activities are also considered. Approximately 1750 km^2 within the Douglas, Jindare and Claravale Stations is suitable for arable farming or improved pasture. Other relevant land uses include water impoundment (small farm dams and proposed large dams), roadway and bridge construction, mining, conservation, tourism and urban development. Development of groundwater and dam sites in and around the Daly Basin can potentially impact on the downstream hydrology and the structure and function of wetlands, as documented by a large body of research elsewhere in Australia and overseas (Petts 1980, 1984, Erskine 1985, 1996b, Erskine et al 1999). Four major dam sites, 11 smaller dam sites and 21 natural billabongs have been identified previously as potential water storages. The LUCP also makes provision for approximately 10% of the Daly Basin to be reserved for conservation purposes, while urban development will be centred around two major areas, one existing (Katherine) and the other proposed.

Assessment of land and water use effects on the Daly Basin wetlands was based on the results of numerous studies undertaken elsewhere. Threats most likely to affect the streamflow regimes in the Daly Basin were water abstraction for irrigation, stock and domestic use, water impoundment and land clearing for various forms of agricultural development. Impacts of surface or groundwater abstraction include lowering of groundwater levels, reduction in the temporal and spatial extent of groundwater-dependent, seasonal wetlands, reduced Dry season baseflows in rivers and associated effects on wetland fauna and flora. Threats associated with water impoundment vary with the size of the storage but are substantial (Erskine 1985, 1996b, Sherrard & Erskine 1991, Benn & Erskine 1994, Erskine et al 1999). Farm dams constructed from natural, off-stream wetlands have localised implications, while large dams will affect the streamflow regime of the whole downstream catchment (Erskine 1985, 1996b, Sherrard & Erskine 1991, Benn & Erskine 1994, Erskine et al 1999).

Land use activities posing most risk to wetlands were surface and groundwater extraction, water impoundment, and land clearance and development. Agricultural practices and urban development (for Katherine this also includes intensive horticulture) posed by far the greatest risks to the water regime of the wetlands in the Daly Basin. Areas identified as being of high agricultural potential (ie land suitable for dryland and irrigated cropping, horticulture, and improved pasture activities) were the greatest risk, but comprise <10% of the Daly Basin. Urban development is of some concern but comprises only 2% of the area. However, the Katherine River contributes approximately 40% of the total discharge of the Daly River and hence may impact negatively on the water regime of the Daly River if there is substantial water extraction for urban and agricultural water supply. Low potential agricultural land comprises almost 50% of the Daly Basin and over 25% has been identified as being suitable for pastoral activities only. Impacts from uncontrolled grazing and watering of stock represent a risk in localised areas.

The type and extent of wetlands within each land use was estimated and the risks to the major wetland types were then ranked according to their spatial extent in the major land uses, and the potential of the land uses to alter water regimes. A broad scale assessment of potential risks to the major wetland types showed that approximately 75% of the floodplains could be affected by agricultural activities, although only 10% lie within the areas identified as high agricultural potential and urban development. The latter proportion is likely to be at risk from both destruction, due to land clearance, and altered water regimes due to water extraction. Only 17% of floodplain is likely to be contained in conservation areas.

Approximately 75% of the damplands in the basin could be affected by agricultural activities, with 15% lying within areas identified as high agricultural potential and urban development. Only 15% of the dampland habitats are likely to be contained within conservation areas.

Although 55% of river channels may be contained within conservation zones, streamflow characteristics can still be greatly altered by upstream activities. Approximately 5% of the river channel habitats are located within the greater risk areas of high agricultural potential and urban development.

Almost 40% of the creeks in the Daly Basin are located in areas of low agricultural potential, where impacts, due to land clearance and water extraction, might only occur on localised scales. A further 37% are located on pastoral land and unlikely to be at risk, while 14% are to be contained within conservation reserves. Approximately 10% of the creeks lie within the areas of high agricultural potential and urban development, and are likely be at risk of land clearance and water extraction.

Figure 18 Waterhole in the Douglas component of the Daly Basin on 15/10/2000 (photograph: George Begg)

Figure 19 Tufa Dam on the Flora River on the 20/1/2000 (photograph: Danuta Karp)

September 2002 workshop

Under the terms of the Environment Australia contract, the teams conducting the five projects had to convene at the conclusion of their studies to make recommendations about environmental water requirements for the Daly River. To help achieve this end, a workshop was held in Darwin on 27 September 2002 at which all project teams presented their results. Additional presentations on closely related studies were also invited (for example, see Faulks 1998a&b, Jolly et al 2000, Jolly 2001, 2002) to provide the best available information base for the determination of environmental water requirements. The workshop program is outlined in table 1.

Table 1 Program for Workshop on National River Health Environmental Flow Initiative Projects on the Daly River held at Environment Australia, Darwin on 27 September 2002

Time	Presenter/Facilitator	Topic
MORNING	**SESSION**	
0800-0810	Peter Jolly	Introduction
0810-0830	Peter Jolly	Hydrology of the Daly River Catchment
0830-0840	Peter Cook	Spring Inflows to the Daly River
0840-0900	George Begg	Inventory and Risk Assessment of Wetlands in the Daly Basin
0900-0920	Judy Faulks	Stream Condition in the Daly River Catchment
0920-0940	Derek Eamus	Riparian Vegetation, Water Use and Groundwater Interactions on the Daly River
0940-0950	Derek Eamus for Lindsay Hutley	Evapotranspiration
0950-1020	Wayne Erskine	Discussion of the Implications of the above work for an Environmental Flow Allocation for the Daly River
PRE-LUNCH	**SESSION**	**Topic**
1040-1100	Simon Townsend	Periphyton and Phytoplankton in the Daly River
1100-1120	Armando Padovan	*Spirogyra*-Flow Relationships in the Daly River
1120-1140	Peter Dostine	*Vallisneria nana* Distribution in the Daly River
1140-1200	Naomi Rea	*Vallisneria nana* Growth in the Daly River
1200-1220	Ian Webster	River Metabolism in the Daly River
1220-1230	Helen Larson	Sharks, Rays and Sawfish (Elasmobranchs) in the Daly River
POST-LUNCH	**SESSION**	**Topic**
1320-1340	Enzo Guarino	Effects of Water Extraction on Dry Season Streamflows, Water Temperature and the Pig-Nosed Turtle
1340-1530	Wayne Erskine	Discussion of Principles of Environmental Flow Allocation, Environmental Flow Requirements of the Daly River for the Claravale to Beeboon crossing reach and for the rest of the catchment, and Identification of Gaps in Knowledge
AFTERNOON	**SESSION**	**Topic**
1600-1700	Wayne Erskine	Further Discussion, Summary of the Findings and a Preliminary Recommended Environmental Water Allocations for the Daly River
		Finalisation of the Recommendations in a Report

The attendees and their institutions/agencies were:

- NT Department of Infrastructure Planning and Environment (DIPE) – Peter Jolly, Simon Townsend, Naomi Rea, Peter Dostine, Armando Padovan and Judy Faulks;
- Environment Australia – Gayle Stewart, George Begg, John Lowry, Wayne Erskine, Max Finlayson and Peter Bayliss;
- CSIRO – Peter Cook and Ian Webster;
- Museum and Art Gallery of the Northern Territory – Helen Larson;
- University of Technology, Sydney – Derek Eamus;
- University of Canberra – Enzo Guarino.

Apologies were received from Arthur Georges (University of Canberra) and Lindsay Hutley (Northern Territory University). Wayne Erskine facilitated the workshop and compiled the recommendations in table 2 from the results of the presentations and discussions of workshop participants.

Northern Territory process for allocating water

The *Water Act (1992)* of the Northern Territory provides for the 'investigation, use, control, protection, management and administration of water resources' for surface water, groundwater and water quality. This entails, among other things, the determination of beneficial uses of water, which include agriculture, aquaculture, public water supply, environment, cultural, manufacturing industry and riparian uses. The Act provides for the protection of 'water dependent aquatic ecosystems' but does not stipulate the process. Consequently, once the beneficial uses of a waterway or aquifer have been determined and declared, there is a legal requirement in terms of the Act to ensure their ecological values are sustained with a 'low level of risk'.

Water may be taken without a licence for:

1. domestic purposes or for watering travelling stock (S10);
2. domestic purposes, drinking water for grazing stock or irrigation of a garden not exceeding 0.5 ha which is used solely in connection with a dwelling by the owner or occupier of land next to a waterway (S11).

To date, the following declarations have been made in the Daly River catchment:

- beneficial uses for the middle Edith River surface water;
- beneficial uses and objectives of surface water for the Katherine River; and
- beneficial uses and quality standards for groundwater for the Katherine area.

They include:

- Aquatic ecosystem protection for the middle Edith River and tributaries between where the Edith River intersects lines 191080 m E AMG Zone 53 and 821400 m E AMG Zone 52;
- Aquatic ecosystem protection and recreational water quality and aesthetics for the Katherine River upstream of Donkey Camp pool and Maud Creek;
- Aquatic ecosystem protection for Seventeen Mile Creek and other tributaries of the upper Katherine River;

- Aquatic ecosystem protection and raw water for drinking water supply for the Katherine River at Donkey Camp pool (water supply intake for Katherine);
- Aquatic ecosystem protection, recreational water quality and aesthetics, and agricultural water use for the Katherine River downstream of Donkey Camp pool and for the Dry and King rivers;
- Aquatic ecosystem protection for McAddens Creek;
- Raw water for drinking water, raw water for agriculture and raw water for industrial purposes for groundwaters of the Katherine area which includes most of the Daly catchment upstream of the estuary. The protection of groundwater dependent ecosystems is not included in the declaration.

The Land Resource and Environment Sub-committee at a meeting on 16 May 2001 decided that an interim approach be taken for water allocation planning by DIPE in the Top End of the Northern Territory, namely:

- For rivers, at least 80% of streamflow at any time in any part of a river is allocated to the environment and no more than 20% of streamflow may be diverted at any time in any part of a river; and
- For aquifers, at least 80% of annual recharge is allocated for environmental use and the requirements of all groundwater dependent ecosystems will be maintained and annual extraction will be equivalent to no more than 20% of annual recharge.

This interim approach should be followed by the development of a rigorous, flexible and adaptive process for determining environmental water requirements in the Northern Territory. Petts (1996) and Arthington et al (1998) have proposed methods that could be trialled in the Top End.

Clearing for irrigation is limited to the annual crop area able to be supplied within the allocated limits on extraction from groundwater recharge/storage and/or streamflow, plus a crop rotation/fallow area assumed to be twice the annual irrigated area. Clearing areas required for irrigation are calculated for irrigation at 10 $MLha^{-1}y^{-1}$. Significant irrigation from rivers will require diversion of flood flows to offstream dams. Based on an evaporative loss of 1 my^{-1} and a 3 m storage depth, the required storage area is equivalent to 40% of the area annually irrigated at 10 $MLha^{-1}y^{-1}$. However, this estimate of evaporation is very conservative (Wang et al 2001) and should be revised upwards for a more accurate assessment.

Workshop outcomes

In framing the preliminary environmental water allocations in table 2, it was recognised that the Daly River between Claravale and Beeboon crossings is an important perennial, groundwater-fed river draining karst aquifers that is physically/hydrologically connected to the estuary. Such rivers are rare in the Northern Territory. The most important component of the annual streamflow hydrograph is Dry season baseflow. Hydraulic barriers due to low streamflows interrupt longitudinal connectivity during the Dry season (Georges et al 2002) and physical barriers occur at poorly constructed road crossings under low streamflows (figures 20, 21 & 22). All road crossings should conform to the following principles for fish passage, which also address free movement by pig-nosed turtles:

- Free air/water surface maintained through road crossings for all but high-flows;
- No vertical discontinuity in bed profile through the crossing;

- No vertical headlosses at upstream or downstream openings;
- Low or no gradient through culverts, pipes, etc;
- Maintain natural up- and downstream flow depths through whole crossing;
- Maximise amount of natural light, minimise pipe/culvert length, maximise diameter/size, and use open to air systems, wherever possible;
- Continue natural stream substrate through bed of crossing, pipes and culverts;
- Maintain road crossings so that they remain clear of woody debris and rubbish; and
- The principal of minimum specific head (critical flow depth through the structure to produce the smallest size for the design discharge) should be abandoned as an engineering design approach for **all** road crossings through which aquatic fauna must pass (Erskine & Harris 2003).

However, significant natural barriers to aquatic faunal movement also occur at bedrock falls, tufa dams (fig 19) and cascades as well as through dry sections of river.

Table 2 Preliminary environmental water allocations for the Daly River between Claravale and Beeboon crossings (fig 3) recommended by the September 2002 workshop participants

Environmental Issue identified by Workshop Participants	Recommended Water Allocation and/or Restriction on water extraction
Interdependence of streamflow, groundwater discharge and groundwater and surface water quality	Conjoint regulation ensuring that: • Natural minimum streamflows are not reduced by groundwater and/or surface water extraction • Groundwater and surface water quality, especially nutrient levels, are not altered from current conditions (except Douglas River which has probably experienced elevated nitrogen levels from existing agricultural development)
Maintenance of a healthy river and other wetlands	Flexible and variable agricultural water allocation which is implemented incrementally and prohibits water extraction during critical times of the seasonal hydrograph (see below for further details)
Maintenance of Dry season baseflows	• No groundwater extraction from areas that impact directly on streamflows • No groundwater extraction close to the Daly River; minimum 3 km setback from the Daly River for all wells • Adequacy of 3 km setback to be evaluated by monitoring as part of adaptive ecosystem management approach
Maintenance of minimum streamflows for protection of target species and their minimum habitat requirements throughout the Dry season	No water extraction allowed from the Daly River when streamflows reach the following thresholds at the stated locations: 1. Claravale Crossing – 5 m^3s^{-1} 2. Cattle Creek – 7–10 m^3s^{-1} 3. Oolloo Crossing – 10–15 m^3s^{-1} 4. Mt Nancar – 10–15 m^3s^{-1}
Maintenance of existing water quality	Irrigation return flows to be stored on farm and treated to improve water quality
Maintenance of groundwater levels for periodic/episodic use by riparian vegetation	No extraction of groundwater near the Daly River **and** Dry season baseflow during droughts
Maintenance of Wet season flood peak discharges for reworking and cleaning sand used by pig-nosed turtles for nesting and for connecting the floodplain to the channel	No extraction of the rising stage and peak of Wet season floods
Maintain existing structure and function of all wetlands	No dams to be built on any river
Assessment of the adequacy of imposed licence conditions and discharge thresholds	Adopt an adaptive ecosystem management approach supported by appropriate licencing, auditing, stream gauging, groundwater level measurements, water quality monitoring, biomonitoring and benchmarking programs

Figure 20 Daly River at Claravale Crossing which is a physical barrier to the passage of some aquatic fauna at low streamflows (photograph: Steven Tickell)

Figure 21 Daly River at Beeboon Crossing which is a hydraulic barrier to passage of aquatic fauna under low streamflows (photograph: Steven Tickell)

Figure 22 Daly River at Oolloo Crossing which is a physical barrier to the passage of some aquatic fauna at low streamflows (photograph: Steven Tickell)

Figure 23 Daly River Gauging Station G8140040 at Mount Nancar which is important for water licencing purposes as it measures freshwater inflows to the Daly estuary (photograph: Steven Tickell)

Appropriate target aquatic species for setting environmental water allocations were identified as the following threatened species: Pig-nosed turtle (*C. insculpta*); Freshwater sawfish (*Pristis microdon*); Freshwater whipray (*Himantura chaophyra*); and Strawman (*Craterocephalus stramineus*). Furthermore, *Vallisneria nana* and *Spirogyra* are also recommended as target species because of their significance as pig-nosed turtle and elasmobranch habitat and for primary productivity respectively. However, there is meaningful information for only the pig-nosed turtle, *V. nana* and *Spirogyra* at this time although research is currently being conducted on the elasmobranchs (H Larson, pers com, 2003).

A flexible and incremental water allocation process is necessary so that water extraction does not change natural Dry season streamflow (Georges et al 2002). While the Land Resource and Environment Subcommittee's approach to water allocation is currently conservative, it should not be implemented so that 20% of streamflow or annual aquifer recharge can be extracted at any time. Furthermore, water should not be drawn directly from groundwater close to the river or from the river during the Dry season (Georges et al 2002). Further work leading to the development of a new environmental water allocation process for the Top End is also needed.

Workshop participants recognised that the potential environmental impacts of water resource development and agricultural development on adjacent lands in the Daly catchment include:

- Reduced connectivity in a currently year-round flowing river;
- Reduced streamflows with consequential impact on aquatic habitat availability and flow-dependent species, such as ribbon weed;
- Altered timing of streamflow patterns which may cause species to mis-cue reproductive and other behaviours or trap migrating species at barriers to movement;
- Increased turbidity in a currently clear-water river during the Dry season;
- Changed role and function of the hyporheic zone;
- Altered water quality by altering the mix of water sources with different nutrient levels;
- Altered water temperatures with consequential impacts on primary productivity and metabolism of poikilothermic animals (invertebrates, fish, turtles) higher up the food chain.

The recommended water allocations in table 2 are based on the following assumptions:

- There is simultaneous integrated natural resource management adopted by the Northern Territory Government so that all natural resources in the Daly River catchment are actively managed interdependently on a sustainable basis (Begg et al 2001, Rea et al 2002). Recent approaches to determining environmental water requirements take an ecosystem, catchment-wide and multi-disciplinary perspective (Arthington et al 1998, Quinn & Thoms 2002). Such approaches ensure that the essential features of a riverine ecosystem are protected to achieve geomorphological, water quality and ecological objectives and to maintain the structure and functional integrity of rivers (Rea et al 2002, Quinn & Thoms 2002).
- The current oligotrophic (very low) nutrient status of the Daly River is not changed. Water quality is as important as streamflow (Rea et al 2002) and must be explicitly addressed;
- Vertical (groundwater and hyporheic zone), lateral (floodplain and riparian zone) and longitudinal (aquatic habitats with no artificial barriers to free faunal movement) connectivity are maintained. Connectivity is used to cover not only aquatic and riparian habitats but also streamflows and water quality;

- Natural estuarine biophysical processes and aquatic habitats are maintained; and
- Groundwater-dependent ecosystems are identified and protected.
- A formal, robust and consultative process for the allocation of water will be developed for the Northern Territory.

The workshop participants also recognised that the implementation of an effective environmental water allocation for the Daly River was contingent upon the following:

- The collection of high quality streamflow data for all river gauging stations was emphasised but particular emphasis was placed on establishing reliable and accurate low streamflow rating curves. The stability of natural gauge controls must be investigated and the hydraulic effects of tufa dam formation (fig 19) quantified, where relevant;
- An adaptive ecosystem management approach must be implemented along with the environmental water allocations. Monitoring is essential for adaptive management and a well designed monitoring program must be implemented to test the efficacy of licence conditions;
- Improved understanding of the spatio-temporal distribution of *Carettochelys insculpta*, *Vallisneria nana*, *Spirogyra* and elasmobranchs, and of *Vallisneria*-aquatic fauna interactions must be obtained; and
- Greater understanding of the surface water-groundwater connection for the Daly River is obtained to better specify licence conditions for water extraction that are ecologically sustainable.

The workshop participants also concluded that there were knowledge gaps on the following:

- The environmental condition and biophysical processes of the Daly River estuary. However, Vertessy (1990), Chappell and Bardsley (1985) and Faulks (1998a; 1998b) were noted as important sources of information on the estuary.
- The spatial distribution, abundance, life history and conservation status of a series of threatened elasmobranchs (*Pristis microdon*, *Himantura chaophyra*) and a teleost (*Craterocephalus stramineus*) in the Daly River catchment.
- Water quality dynamics of groundwater and surface water.
- Groundwater dynamics, flows and associated stygofauna.
- The role and function of the hyporheic zone.
- Spatial distribution of all wetland types throughout the Daly River catchment.
- Recharge areas for, and hydrological processes operating in, all wetland types.
- Local, regional, Territory and national significance of the Daly River between Claravale and Beeboon crossings and the associated flora and fauna.
- Conservation significance of riparian corridors in the seasonally wet tropics.

Principles for determining environmental flow requirements

Petts (1996) proposed an approach for determining ‘ecologically acceptable’ flow regimes and volumes based on a set of fundamental scientific principles concerning longitudinal connectivity, vertical exchanges, floodplain flows, channel maintenance flows, minimum flows and optimum flows. The derivation of an ecologically acceptable flow regime involves the following four steps:

- *Ecological assessments*. These entail the classification of a river or catchment into homogeneous river reaches, the review of all available information for the river and catchment, the setting of ecological targets for appropriate indicator species for each reach and the specification of acceptable conditions for the range of indicator species for each reach.
- *Benchmark flows*. These are the streamflows required to meet the ecological targets. The setting of such flows involves extensive work on river hydrology, habitat assessment and simulation models, and analysis of historical data.
- *Ecologically acceptable hydrographs*. Such hydrographs set acceptable streamflow magnitudes, frequencies and durations for wet, median and dry years.
- *Ecologically acceptable flow duration curve.* This is constructed by combining the hydrographs derived at step 3 into a flow duration curve which achieves the ecological targets.

The work reported in the five National River Health Environmental Flow Initiative projects (Georges et al 2002, O'Grady et al 2002, Rea et al 2002, Townsend et al 2002, Begg et al 2002) addresses many of these issues and, with further development, could be used to derive ecologically acceptable flow regimes and volumes for the Daly River between Claravale and Beeboon crossings. This has not been attempted here.

Dunbar et al (1998) reviewed the approaches for determining environmental water allocations and streamflows. They concluded that results/methods/indices are rarely transferable between countries and that justification of individual values is not generally possible under close scrutiny. Nevertheless, biological response modelling, such as conducted by Georges et al (2002), Rea et al (2002) and Townsend et al (2002), was considered the most resource-intensive and defensible. Therefore, the present projects conform to international best practice.

Environmental water requirements for the Daly River

The preliminary environmental water allocations in table 2 were circulated to the project teams and workshop participants for further refinement. Furthermore, the methods and principles for determining environmental water allocations outlined above had not been developed to this degree at the September workshop. Therefore, project teams were supplied with draft material for this section as well as the workshop recommendations and asked to further develop the environmental water allocations. The revised, final recommendations are outlined in table 3.

The recommended environmental streamflows in table 3 should be accompanied by the following actions:

- Northern Territory Government introduces integrated natural resource management for the Daly River catchment;
- Natural estuarine biophysical processes and aquatic habitats are maintained;
- Groundwater-dependent ecosystems are identified and protected;

Table 3 Final environmental water allocations for the Daly River

	Environmental Issue	Recommended Water Allocation and/or Restriction on water extraction
1	Interdependence of streamflow, groundwater discharge and groundwater and surface water quality	Groundwater and streamflow quantity and quality must be managed holistically and supported by an integrated natural resource management approach. Dry season streamflows must continue to be sourced from karst aquifers with bicarbonate dominance and very low nutrient concentrations
2	Protection of critical streamflows that cue various biotic responses	Environmental water allocations can be partly addressed by adopting a flexible and variable approach to agricultural water allocations. Flood peaks and minimum streamflows must be maintained unchanged. Agricultural extraction can be permitted from less ecologically sensitive streamflows, as outlined below
3	Protection of flood peaks for channel maintenance, reworking of sand bars for pig-nosed turtle nesting sites, lateral connection of floodplains, natural disturbance events for riparian vegetation regeneration	• No water extraction on rising stage and peak of flood hydrographs during Wet season • Water extraction of up to 20% of the streamflow allowed when flood stage has dropped at least 1 m below peak during the Wet season
4	Maintenance of groundwater levels and spring inflows to the Daly River	No groundwater extraction allowed within 3 km in a straight line from the Daly River. This condition is to be verified by modelling of aquifers and detailed monitoring of bore levels and revised, as needed. The assessment criterion should be based on a series of bores situated next to the Daly River and at various distances away from the channel up to about 5 km. Control bores next to the river must be outside the cone of depression in groundwater level caused by pumping from bores further from the river.
5	Maintenance of minimum streamflows to protect *Vallisneria nana*, *Spirogyra* and pig-nosed turtle	Agricultural water extraction allowed from the Daly River and aquifers providing spring input must be managed so that the cumulative impact on flows is < 8% when streamflows reach the following thresholds at the stated locations: Claravale Crossing – 6.2 m^3s^{-1} Oolloo Crossing – 12 m^3s^{-1} Mt Nancar – 12 m^3s^{-1} At discharges greater than the above thresholds, no more than 20% of the streamflow greater than the above thresholds (ie 16 m^3s^{-1} when streamflow is 80 m^3s^{-1} but only 3 m^3s^{-1} when streamflow is 15 m^3s^{-1}) can be extracted
6	Maintenance of turtle and fish passage	Same conditions as outlined for point 5 plus: All road crossings should be built according to Erskine & Harris's (2003) principles for unimpeded fish passage Water quality barriers (such as irrigation return flows, drain discharges, etc) to faunal passage should be prohibited
7	Maintenance of groundwater levels for periodic/episodic use by riparian vegetation	No extraction of groundwater within 3 km of the Daly River. All of the riparian vegetation water use can be met by maintaining a streamflow of less than 2 m^3s^{-1} during the Dry season, assuming that there is no loss of streamflow to regional aquifers. Therefore, groundwater levels next to the Daly River must not be lowered below river levels
8	Maintenance of existing water quality	Apply ANZECC & ARMCANZ (2000) water quality guidelines so that trigger values for pH, electrical conductivity, bicarbonate, total nitrogen, total phosphorus, soluble reactive phosphorus and selected metals are derived and applied to the Daly River and groundwater. Exceedances of trigger values must induce a to-be determined response from government and agricultural industry
9	Maintain existing structure and function of all wetlands	No dam or regulatory structure to be built on any river without an EIS.
10	Assessment of the adequacy of imposed licence conditions and discharge thresholds with appropriate revision based on monitoring results	Adopt an adaptive ecosystem management approach supported by appropriate licencing, auditing, stream gauging, groundwater level measurements, water quality monitoring, biomonitoring and benchmarking programs. There must be feedback from the monitoring/auditing results to the licence conditions.

- Significant groundwater-recharge areas are identified and protected;
- High quality data are collected at all river gauging stations for both low and high streamflows;
- A benchmarking and monitoring (including biomonitoring) program is designed and implemented;
- An adaptive ecosystem management approach is implemented along with the environmental water allocations and the benchmarking and monitoring programs;
- The Northern Territory Government develops a robust, formal process for the allocation of water which includes methodologies for determining environmental water allocations.

Potential threats to the health of the Daly River

Existing agricultural development in the Daly catchment includes centre-pivot irrigation supported by groundwater extraction (fig 24), small scale horticulture supported by surface water extraction near Katherine (fig 25) and improved pasture for cattle grazing (fig 26). In addition to water extraction, there are many other significant potential threats to the health of the Daly River from further agricultural development. Such threats, should they occur, will modify the environmental water requirements given in table 3 and will necessitate future revisions, depending on the results of monitoring under the adaptive ecosystem management approach (Stanford et al 1996). The presently identified threats from future agricultural development and land clearing include:

- altered soil and catchment hydrology (Mott et al 1979, Bridge et al 1983a&b, Dilshad & Jonauskas 1992, Dilshad et al 1996);
- accelerated soil erosion and sediment delivery to rivers (Dilshad et al 1996, Elliott et al 2002);
- reduced groundwater recharge and baseflow discharge;
- increased incidence of fish kills.

Each threat is discussed below.

Altered soil and catchment hydrology

Mott et al (1979) documented the development of ‘scalds’ or soil seals on red earths in the Katherine region following light cattle grazing of understorey perennial tall native and introduced grasses in open eucalypt woodland. These surface seals are unvegetated, smooth, crusted, bare areas unrelated to microtopography or vegetation. New seals formed in two years under heavy grazing and persisted thereafter. Runoff from the soil seals was three times that measured from grass-covered areas and twice that recorded from a Townsville stylo/annual grass pasture in the same region. Approximately 90% of the intense early Wet season rainfall infiltrated the soil under grass but only 25–30% infiltrated under seals.

Figure 24 Centre-pivot irrigation supported by groundwater abstraction (from Rea et al 2002)

Figure 25 Small-scale horticulture near Katherine River, supported by surface water extraction (from Rea et al 2002)

Figure 26 Clearing for improved pastures for grazing cattle (photograph: Steven Tickell)

Bridge et al (1983a) determined the effects of burning and overgrazing on soil surface seal development at Katherine. Raindrop impact caused the formation of the surface seal which reduced infiltration. While soil structure decline and reduced sorptivity and hydraulic conductivity occurred in the first Wet season following burning, both soil structure and sorptivity recovered after two Wet seasons. The lack of recovery in hydraulic conductivity indicated that soil structure reformation was only occurring at the surface and not at depth. Following combined overgrazing and burning, there was no recovery in soil structure and infiltration. Dilshad et al (1996) also observed surface seal formation under conventional tillage on loamy red earths at the Douglas Daly Research Farm. Day (1977) found that red earths in the Daly Basin produce high runoff during periods of continuous rainfall and have low moisture holding capacity and available soil moisture. Deep cultivation during the late Dry season and early Wet season was suggested to permit deeper penetration of early Wet season rain (Day 1977).

Bridge et al (1983b) investigated the effects of legumes and improved pasture on soil structure and infiltration for red earth soils at Katherine and Manbulloo. They showed that, provided high macropore space and sorptivity are maintained, heavily grazed improved pastures can be stable in the long term when there is a litter layer on the soil surface. In the absence of this litter layer and/or with high Wet season stocking rates, macropore space, sorptivity and hydraulic conductivity can all decrease greatly, even to values significantly lower than those for degraded native grassland. Land management practices for future grazing areas must address this issue of ground cover to maintain existing infiltration rates and to prevent increased runoff and reduced groundwater accession. For cultivated areas, Day (1977) recommended the return of crop residues to reduce the effect of surface sealing.

The Cropland Erosion Research Project (CERP) on loamy red earths at the Douglas Daly Research Farm was initiated to determine, among other things, land use effects on catchment hydrology (Dilshad & Jonauskas 1992, Dilshad et al 1996). The two conventionally tilled catchments produced 47.4% (mean of 23.7%), the single minimum tilled catchment 11.8% and the two no-till catchments 27.4% (mean of 13.7%) of all runoff events between November 1984 and May 1988 (Dilshad & Jonauskas 1992). The pasture and woodland catchments only produced 9.7 and 4.0% of the runoff events respectively. The two conventionally tilled catchments produced 42.9% (mean of 21.5%), the minimum tilled catchment 17.0% and the two no-till catchments 29.6% (mean of 14.8%) of total runoff over the same time period (Dilshad & Jonauskas 1992). The pasture and woodland catchments only produced 10.2 and 0.3% of total runoff respectively. Clearly, any form of agriculture greatly increased surface runoff over native woodland on the Douglas Daly Research Farm. Dilshad and Jonauskas (1992) and Dilshad et al (1996) explained these differences by large changes in ground cover between treatments and suggested that surface mulches should be used to mitigate these hydrological impacts.

Dilshad et al (1996) presented the results of the CERP for the period 1985–89 and found that the method of tillage but not the crop greatly affected runoff generation and hence soil moisture storage. Unless large numbers of farm dams are constructed to store this increased surface runoff, large scale agricultural development in the Daly catchment will increase Wet season runoff. As discussed below, this has severe implications for the health of the Daly River because it will also significantly decrease groundwater recharge and hence can reduce the reliability of Dry season spring inflows.

Accelerated soil erosion

Elliott et al (2002) used measurements of the activity of the radioactive isotope caesium-137 (^{137}Cs – half-life of 30.2 years) adsorbed to soils following atmospheric fallout due to thermonuclear weapons testing to determine soil erosion rates for the last 40 years by a budget approach at 16 sites throughout the Northern Territory. Atmospheric fallout was measured for stable (ie no erosion or deposition) parts of the landscape. Erosion and deposition on replicated hillslopes or grids were determined by total ^{137}Cs activities for multiple soil profiles that were less or greater than atmospheric fallout, respectively. Soil erosion rates were calculated from plot data of soil erosion rates versus loss of total ^{137}Cs activity for the soil within the plot. Soil losses greater than 0.5 $tha^{-1}y^{-1}$ were considered unsustainable. Three of their sites (Ruby Downs, Bonalbo and Pine Creek) were located in or next to the Daly River catchment. Their results showed that:

1. grazing and up to six years of cropping on hillslopes at Ruby Downs in the Daly Basin resulted in mean net soil losses of between 4.12 and 6.46 $tha^{-1}y^{-1}$ even when treated with contour banks. Soil erosion rates were up to 13 times the rate of soil formation;
2. grazing and cropping on hillslopes treated with contour banks at Bonalbo in the Daly Basin resulted in mean net soil losses of between 2.28 and 5.75 $tha^{-1}y^{-1}$;
3. grazing of native pastures in eucalypt woodlands of the Baker land system near Pine Creek resulted in mean net soil losses of between 6.66 and 6.73 $tha^{-1}y^{-1}$. Soil erosion rates were up to 13 times greater than the sustainable rate;
4. as expected, greatest soil loss rates were found immediately below the hill crest and deposition was often recorded on footslopes.

Dilshad et al (1996) summarised the experimental results of the effects of cropping (conventional tillage and no tillage of maize and soybean) and soil conservation bank spacing (single- and doubled-spaced) on red earths and yellow podzolics on soil erosion in the Daly Basin between 1984 and 1989. Soil losses from the no tillage catchments were always less on a seasonal and on an event basis than from the paired conventional tillage catchments. Mean annual soil loss rates for no tillage catchments ranged from essentially 0 to 2.8 $tha^{-1}y^{-1}$ whereas the same rates for conventionally tilled catchments ranged from 1.9 to 8.1 $tha^{-1}y^{-1}$. Furthermore, agricultural catchments without appropriate soil conservation measures can yield 100 $tha^{-1}y^{-1}$. Dilshad et al (1996) also reported that catchments with double-spaced soil conservation banks lost more soil than those with single-spaced banks and that double-spaced no tillage catchments lost 1.5 to 10 times less soil than single-spaced conventional tillage catchments.

These results clearly indicate that any form of agricultural development (grazing or cropping) will increase soil loss rates that will, in turn, increase sediment yields, as documented elsewhere in Australia (Mahmoudzadeh et al 2002, Erskine et al 2002, 2003). Increased sediment delivery of silt and clay to the channel network will increase turbidity and nutrient concentrations, at least for the particulate fraction. Gullying may also be initiated where grass root mats are destroyed in valley floors and drainage depressions. Gullies are by far the dominant catchment sediment source when they are actively developing although the bulk of the eroded sediment can be deposited immediately downstream in floodouts. Gullies, integrated with the main channel network, can lead to the development of sand slugs in downstream rivers which greatly reduce the amount and diversity of aquatic habitat (Erskine 1994a&b).

Any form of agricultural development in the Daly River catchment must be accompanied by access to innovative advice on farm planning and appropriate soil conservation measures for the seasonally wet tropics. Elliott et al (2002) found that soil erosion rates are high and unsustainable for grazed and cropped areas in the Northern Territory. This situation must be reversed if agriculture is to be sustainable in the Daly River catchment.

Reduced groundwater recharge and baseflow discharge

To protect the geo-ecological character of groundwater dependent ecosystems, groundwater recharge, discharge and quality needs to be maintained. Large-scale vegetation clearing and agriculture pose a significant threat to rivers and wetlands by reduced groundwater recharge and increased groundwater extraction. Reduced infiltration rates (reduced sorptivity and saturated hydraulic conductivity), soil seal and scald development, soil structure decline and accelerated soil erosion induced by agriculture will greatly reduce recharge rates. Conservation farming must be practiced to ensure that agriculture does not reduce the very resource that it is dependent on for its water source. Furthermore, spring inflows to the Daly River during the Dry season are essential for maintaining the critical habitat of the pig-nosed turtle and elasmobranchs. Sustainable groundwater extraction rates need to be determined. The Northern Territory Government will need to provide innovative soil conservation and farm planning support to any agricultural development and will need to monitor groundwater levels at a series of observation wells.

Increased incidence of fish kills

Most fish kills in the Darwin-Katherine-Jabiru area occur during the early Wet season between October and January (Townsend 1994). While the causative factors for the 1987 fish kill at Donkey Camp pool and others in the Darwin-Katherine-Jabiru area are essentially natural (Bishop 1980, Brown et al 1983, Noller 1983, Townsend et al 1992, Townsend 1994, Pidgeon 2001, Pidgeon et al 2002), large scale agricultural development will certainly increase the frequency and magnitude of first flush events of extremely poor water quality in the Daly River catchment. As a result, fish kills are likely to become more common and of greater severity if the water quality of first flush events is not actively managed by pollution abatement and treatment programs. In the seasonally wet tropics, receiving water bodies have a reduced capacity to assimilate runoff with high organic contents and a high oxygen demand because of the high water temperatures. As a result, runoff with high oxygen demand can cause hypoxic and/or anoxic conditions which can produce fish kills despite tropical Australian fish being extremely tolerant of low oxygen concentrations (Townsend et al 1992, Townsend 1994, Pidgeon 2001).

At least 50 fish kills were reported between 1978 and 1990 in the Darwin-Katherine-Jabiru region (Townsend 1994). However, there are a number of potential mechanisms causing fish kills in addition to that discussed above (Pidgeon 2001). Agricultural development can directly and indirectly lead to fish kills by all of the following mechanisms:

- Many rivers are thermally and oxygen stratified during periods of low or no streamflow due to water abstraction and exhibit hypolimnetic anoxia (Turner & Erskine 1997a&b). Any reduction in Dry season baseflows of the Daly River due to groundwater abstraction may increase the incidence of thermal and/or oxygen stratification due to reduced flow turbulence;
- Runoff at the beginning or at the end of the Wet season, can displace oxygen-depleted water with a high biochemical oxygen demand from floodplains into rivers where it also depletes all the dissolved oxygen in the river (Pidgeon 2001). Runoff from agricultural lands of reduced infiltration capacity can either increase the frequency of such events or load floodplain wetlands with organic material, thus depleting them of dissolved oxygen;
- Sedimentary pyrite (acid sulfate soils) and organic-enriched soils oxidise when water tables fall during the Dry season or when wetlands are artificially drained or excavated. All proposed agricultural development must be carefully scrutinised to ensure that there is no oxidation of pyritic and organic-enriched sediments with the consequent liberation of acid slugs and dissolved iron;
- Various diseases can also produce fish kills. Red-spot disease (Epizootic Ulcerative Syndrome – EUS) is present in the region but is often caused by skin damage due to exposure to acid water (Sammut et al 1996).

Innovative, on-farm, water pollution control strategies must be implemented to ensure that agricultural development in the Daly River catchment does not generate first flush events at the start of the Wet season that cause fish kills. These strategies should be combined with those for decreasing surface runoff and increasing groundwater recharge. Multi-purpose, ephemeral, constructed wetlands may address all of these issues.

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