FINAL REPORT

NATIONAL RIVER HEALTH PROGRAM

MODELLING DRY SEASON FLOWS AND PREDICTING THE IMPACT OF WATER EXTRACTION ON A FLAGSHIP SPECIES

[PROJECT ID: 23045]

EXECUTIVE SUMMARY

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Project Details

Project Title: Project reference no: 23045

Modelling dry season flows and predicting the effects of water extraction on a flagship species

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Executive Summary

Introduction

The Daly River drainage is the third largest in the Northern Territory draining an area of 51,800 km^2 and with an annual discharge of 4180 x 106 m^3. Katherine and Pine Creek are the only major urban centres in the catchment and there are no dams on the Daly River or any of its tributaries. Major uses of adjacent rural land are pastoral and to a lesser extent agricultural. There are proposals for major agricultural development adjacent to the Daly, and these will require concurrent development of water resources for agricultural use.

Potential environmental impacts from water resource development and agricultural development on adjacent lands are

- reduced connectivity in what is currently a year-round flowing river;
- reduced flows with consequential impact on flow-dependent species (e.g. ribbon weed);
- altered timing of flow patterns which may cause species to mis-cue reproductive and other behaviours;
- increased turbidity in what is currently a clear-water river in the dry season;
- altered water quality by altering the mix of waters derived from different sources or input of nutrients;
- altered water temperatures, with attendant consequences for primary production and metabolism of poikilothermic animals (invertebrates, fish, turtles) higher up the food chain.

The aim of this project is to contribute to recommendations on environmental flows to ensure that they are consistent with maintaining the biota of the Daly River, given competing demands of agriculture, recreation and tourism, conservation and Aboriginal culture. Our focus is on flow, connectivity and water temperatures.

To achieve this aim, we modelled the impact of potential flow reduction on dry-season river connectivity and water temperatures in the Daly River and explored the impact this would have on the life history and viability of a flagship species, the pig-nosed turtle.

The pig-nosed turtle was chosen as the species for study because it is a high profile flagship species of considerable international concern (the sole remaining member of a once widespread Family), and the best Australian populations of the species reside in the Daly River. It is regarded as particularly sensitive to environmental perturbations, by virtue of its mobility, reliance on food sources that are themselves flow sensitive, and its peculiar mode of sex determination, which depends on temperature. Protecting the interests of the pig-nosed turtle will likely bring attendant benefits for a wide range of other species whose requirements are less stringent. It can therefore be regarded also as an umbrella species. Adverse impact on this species, and those fish and other aquatic life with concordant requirements, such as endangered freshwater shark, would be regarded as major degradation of the riverine environment.

Flow Characterization

Sources of flow to the Daly River include overland runoff, during periods of intense rainfall, and subsurface interflow in the period during and immediately following the wet season; seasonal recharge and discharge to and from local offstream bank storage and offstream aquifers; diffuse recharge to regional aquifers and subsequent discharge; and to a minor extent, inflows from groundwater sources adjacent to the Daly River catchment.

The Daly River is in the wet-dry tropics of the Northern Territory. As such it experiences the extremes of high rainfall during the monsoonal wet seasons and the near absence of rainfall in the intervening dry seasons. This pronounced seasonal pattern is reflected in river flows.

Flow categories are defined in terms of percentiles calculated from daily flows:

1^+ *Record High Flow*: The maximum high flow recorded (8100 cumecs, January 1998)

1. *Extreme High Flow*: Flow > 95th percentile (740 cumecs)

2. *High Flow*: Flow > Q3 (50 cumecs)

3. *Transitional Flow*: Median < Flow < Q3 (10 to 50 cumecs)

4. *Low Flow*: Flow < Median (10 cumecs)

5. *Extreme Low Flow*: Flow < 5th percentile (3 cumecs)

5^+ *Record Low Flow*: The minimum flow recorded (ca 2 cumecs, November 1966)

Several distinct phases in the annual flow cycle are also recognised.

1. *Flood* -- Flows *High* to *Extreme High*; highly variable; frequency of daily rises and falls exceed the frequency of steady state ($\Delta < 1$ cumec) conditions; inputs dominated by overland runoff and subsurface interflow; recharge of offstream storages and aquifers; often occurs in the months of January to March.

2. *High Flow Transitional (Wet-Dry)* –Flows *High* to *Transitional;* frequency of daily rises exceeded by, for the first time in the year, frequency of steady state conditions; inputs are a combination of overland runoff, subsurface interflow and discharge from offstream storages and aquifers; often occurs in April.

3. *Low Flow Transitional (Wet*-Dry) – Flows *Transitional* to *Low*; inputs primarily discharge from offstream storages and aquifers; often occurs in May.

4. *Low Flow Conditions* – Flows Low to Extremely Low; inputs primarily discharge from Oolloo and Tindalll aquifers; typically extends from June through October. Flows are groundwater fed, dominated by input from limestone aquifers. Flows decline in accordance with predictable recession curves.

5. *Low Flow Transitional (Dry-Wet)* -- Flows *Transitional* to *Low*; inputs primarily discharge from offstream storages and aquifers but influenced by early wet season rains; often occurs in November.

6. *High Flow Transitional (Dry-Wet)* -- Flows *High* to *Transitional;* frequency of daily rises exceeds, for the first time in the year, frequency of steady state conditions; inputs are a combination of overland runoff, subsurface interflow and discharge from offstream storages and aquifers; often occurs in December.

The period of *Low Flow Conditions* is the primary focus of this study. The magnitude of flows during *Low Flow Conditions* and the time of onset, duration, and time of termination of Low Flow Conditions vary considerably from year to year. This provides a backdrop of high natural variability that presents a challenge for determining acceptable and unacceptable impact of water resource development on river flow.

Spatial Pattern of Flows

The study site was a 74 km stretch of the Daly River well above the tidal reaches between Claravale Crossing (131^{o} 55'E, 14^{o}37'S) and the inflow of Cattle Creek (131^{o}13'E, 14^{o}03'S) just downstream of Oolloo Crossing. This is adjacent to areas currently flagged for agricultural development. Our study spanned the 2000 and 2001 dry seasons.

There was a nett increase in flow with distance downstream from Claravale Crossing. Much of the flow entered between Station 10 (Hot Spring) and Station 15 (Black Bull Yard), a consequence of a Claystone layer that capped the Oolloo Dolomite aquifer between Bradshaw Creek and Stray Creek. Groundwater input between Stations 10 and 15 was an order of magnitude higher than elsewhere in the study stretch.

Given the source of dry season flow, and the interconnection between the surface flows and the groundwater of adjacent aquifers, any water allocation schedule would need to incorporate both surface and groundwater offtake.

Modelling Flow Reduction

Flow reduction was modelled using a steady state hydrodynamic model of the study stretch using the HecRas River Analysis System. At minimum flow conditions of 2 cumec, the Daly River between Claravale Crossing and Cattle Creek was severely fragmented with 26 small pools (79% of the river length), 7 intermediate pools (21%), and no larger or very large pools. Pools do not differ significantly in attributes apart from length. As we progressively “flood” the river, the number of pools declines in accordance with the relationship shown in Figure 1. When flow exceeds 15.2 cumecs, the river becomes essentially continuous (critical depth 0.5 m – see text of full report).

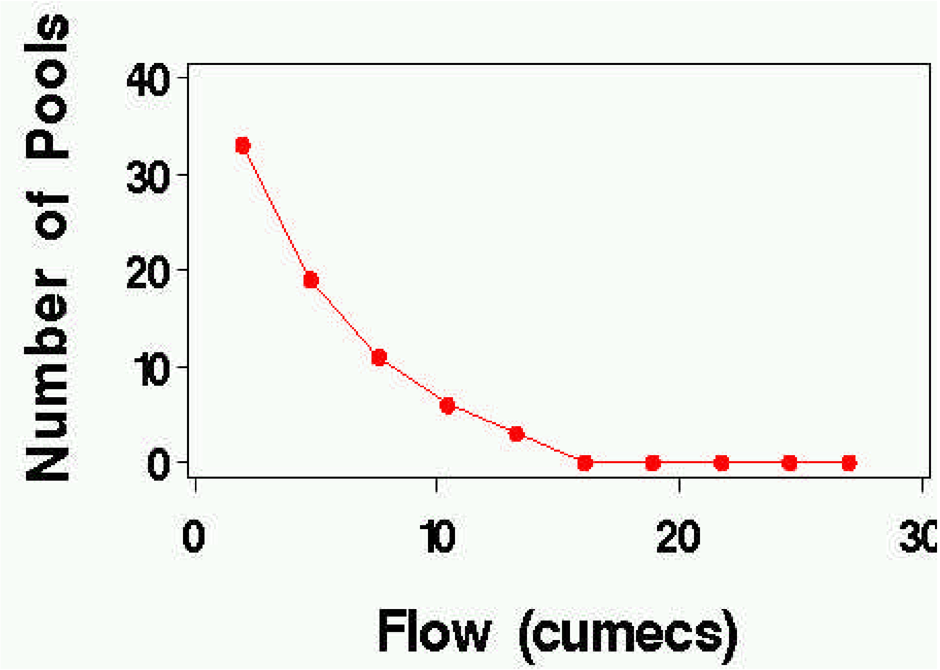


Figure 1. Degree of fragmentation on the Daly River (between Claravale Crossing and Cattle Creek) as a function a function of flow. Flow is as measured at Dorisvale Gauging Station.

Modelling Water Temperatures

Alterations to equilibrium water temperatures arising from flow reductions in the dry season are predicted to be very modest, less than 1.0 ^{0}C, driven primarily by water depth which does not change dramatically during the dry season. We did not model the impact of reduction in water depth below cease-to-flow conditions. The largest impact of flow on water temperature of up to 2.0°C occurred between Claravale Crossing and Station 10 (Hot Spring), but this arose because the water entering the study stretch was in disequilibrium (2.0°C lower than equilibrium), causes unknown. Background temperatures in the river varied over the 58-day study by about 4.0 ^{0}C and these are clearly related to meteorological conditions. Large changes to the temperatures or volumes of the major springs flowing into the Daly River could have a major impact on its temperature.

Synopsis and Recommendations

Table 1 is an integrated analysis of the impact of flow reduction on the life history of the pig-nosed turtle. It shows the outcome for each of several flows, which we have classified as boom or bust.

Table 1. Impact of flow alteration on the life history of the pig-nosed turtle. Flow categories are based on the flow levels used in our modelling. All but zero flow occur naturally. The impact of flow reduction of 3-12 cumecs are shown.

Flow (cumecs)	Outcome		Frequency of Occurrence (%)				
			Natural	- 3 cumecs	-6 cumecs	-9 cumecs	-12 cumecs
>14.7	Boom	River continuous flowing system; home ranges unrestricted; access to nesting banks and feeding beds unrestricted; natural temperature regime. No impact on life history.	6.6	3.7	2.2	1.3	0.9
13.3 (11.9-14.7)	Boom	River fragmented into 3 pools, one large (19.5 km) and two very large (20 and 35.5 km); only 10% of the river would restrict home ranges; access to nesting unrestricted and 40% of the river has no access to feeding grounds; no appreciable thermal impact.	4.3	2.7	1.4	0.8	0.4
10.5 (9.1-11.9)	Boom	River fragmented into 6 pools, two large (7.5 and 9.5 km) and two very large (20 and 31.7 km); 30% of the river would restrict home ranges; access to nesting unrestricted and 46% of the river has no access to feeding grounds; no appreciable thermal impact.	8.6	4.1	2.6	1.3	0.7
7.6 (6.2-9.1)	Bust	River fragmented into 11 pools, 4 large (9.4, 10.2, 16.8, 17.8 km) and none very large; 53% of the river would restrict home ranges; access to nesting unrestricted and 51% of the river has no access to feeding grounds; no appreciable thermal impact.	24.9	8.5	4.2	2.6	1.4
4.8 (3.4-6.2)	Bust	River fragmented into 19 pools, 3 large (9.2, 10.2, 11.1, km) and none very large; 100% of the river would restrict home ranges; substantial probability that a turtle will not be able to nest (up to 35%); and 53% of the river has no access to feeding grounds; no appreciable thermal impact.	40.8	23.5	7.7	3.9	2.5
2.0 (0-3.4)	Bust	River fragmented into 33 pools, none large or very large; 100% of the river would restrict home ranges of all female turtles; substantial probability that a turtle will not be able to nest (up to 55%); and 53% of the river has no access to feeding grounds; no appreciable thermal impact.	14.8	46.3	28.5	10.1	4.8
Zero	Catastrophic	River fragmented into 33 pools, or greater if water levels drop below cease-to-flow levels; none large or very large; 100% of the river would restrict home ranges of all female turtles; substantial probability that a turtle will not be able to nest; feeding grounds threatened as they are flow dependent; potentially substantial thermal impact as water depth drops appreciably below cease-to-flow levels.	0.0	11.3	53.5	79.9	89.3

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 flow alteration is likely to have substantial long-term impact on the population levels sustained locally.

It is clearly evident that all flow categories, regardless of their adverse impact on the turtles, have a finite probability of occurring even under a natural flow regime. For example, flows as low as 2 cumecs (0-3.4 category) can be expected to occur naturally in 14% of years. **The issue for flow allocations becomes not one of what reduction leads to an unsatisfactory outcome in a given year, but rather what reduction leads to an unacceptable increase in the frequency of unsatisfactory years (bust years).** This analysis clearly shows the substantial impact of a fixed flow reduction as small as 3 cumecs. Catastrophic years, where water is extracted in excess of natural flow (mining) will occur in 11.3 % of years. The boom years, important for sustaining turtle populations, will reduce in frequency from 1 in every 5 to 1 in 10 years. This will have a serious impact on the turtle populations.

The lesson here is that a flexible allocation regime is necessary, whereby the cap on flow reduction is defined to be sensitive to the magnitude of the dry season flow in any given year. For example, a 3 cumecs reduction in flow from a 13 cumecs dry season flow will have relatively little impact on turtle life history, whereas the same reduction from a base of 4.8 cumecs, which occurs in 40% of years naturally, will have a major impact. A 3 cumecs reduction in any of the 14% of years with already extremely low flows will be catastrophic, reducing flows and water levels to values not experienced in the years of our historical data set.

Under a flexible allocation regime that meets the needs of environmental flows, assurance of water supply will not be possible. Indeed, one of the major conclusions to come from this analysis is that water should not be drawn directly from the river or from groundwater close to the river if we wish to meet the dual objective of providing adequate environmental flows and assurance of water supply for agriculture. The only satisfactory option is to rely upon the buffering characteristics of groundwater supply taken some distance from the river. The buffering comes from the fact that such water would be derived from the cumulative effects of recharge from successive wet seasons, and so an averaging would occur across boom and bust years. This would buffer the effects of water extraction in any one year, and allow for fixed allocations.

Recommendations

- The dry-season flows represent only a very small proportion of the annual flow. Catastrophic draw-down of dry season environmental flow can occur with no change or only a small change in percentage terms in total annual flow. Consequently, allocations of environmental flow defined in terms of total annual flow or median annual flow are unlikely to be effective in protecting the key elements of dry-season flow.

- Any water allocation policy and limits would need to include both surface water and groundwater, because of the close relationship between the surface flows of the Daly River proper and the groundwater systems upon which it depends.

- A policy of allowing a ***fixed*** annual allocation of water to agriculture from the river and a policy of ensuring adequate environmental flows are irreconcilable.

- Water for agriculture should be drawn from groundwater aquifers representing accumulated recharge over several wet years, in order to assure supply and buffer the river from unacceptable reductions in flow in critical years. This will also remove difficult considerations on the timing of water extraction within years.

- The linkage between groundwater in the areas flagged for agriculture and river flow is not well understood. In the absence of good working models to predict the change in river flow against groundwater extraction from adjacent aquifers, an adaptive approach must be adopted. This would require accurate monitoring of the quantity of water extracted and when it is extracted, accurate monitoring of dry season flows, and accurate estimates of the flows that would be expected in the absence of water resource development. The latter estimates are possible from historical data because of precision in the recession curves once the contribution of surface flow becomes negligible.

- Research needs to be undertaken to determine how far from the river groundwater extraction must be in order to not have an un-buffered, immediate impact on the flows in the river. This distance will set the dimensions of the buffer zone that should be established along the river corridor.

- The quality of data on dry season flows obtained from the Department could be improved. There needs to be a greater commitment to maintaining river gauging stations and to quality control over the data collected. The stations need to be upgraded to more accurately measure dry-season flows. More intensive monitoring of dry season flows at multiple locations is needed if the adaptive approach is to be effective in governing water allocations.

Interpretation of the Brief

The aim of the overall project is to provide recommendations on environmental flows consistent with maintaining the biota of the Daly River, given competing demands of agriculture, recreation and tourism, conservation and Aboriginal culture.

Our contribution to achieving this aim is built upon the following activities:

- model the impact of potential flow reduction, owing to water extraction for agriculture, on dry-season river connectivity in what is currently a year-round, flowing, connected system;

- model the impact of potential reduction in flows on dry-season water temperatures; and,

- provide a concrete link between altered flows and water temperatures on the life history and population dynamics of an umbrella species, the pig-nose turtle.

The major environmental factors likely to influence the persistence of many biota in the Daly River, and potentially influenced by agricultural and water resource development, are

- Connectivity, because the Daly River currently flows in all months of the year.

- Flow Magnitude – related to connectivity, but in addition, many species are likely to depend directly on flow and related physicochemical attributes (e.g. Dissolved Oxygen).

- Flow Timing – timing of flows is likely to be a cue for many species in determining the appropriate timing of reproductive cycles and behaviours.

- Water Clarity -- the Daly River is a clear water river in the dry season.

- Water quality – water in the dry season in the Daly River is of mildly basic pH and high conductivity (half a part per thousand).

- Water Temperature – water temperature is likely to be a cue for many species in determining the appropriate timing of reproductive cycles and behaviours, and a driver of production and metabolism.

The specific objectives of the project are:

(i) To develop flow and temperature models, linked to the population dynamics of an umbrella species, that can be used to predict the likely impact of reduced flow following water extraction for agriculture on ecological values. This will serve as an ongoing management tool, building capacity within the Government Agencies to manage environmental flows.

(ii) Input to recommendations on the initial determinations of the best time and appropriate levels of water extraction in order to maintain critical dry-season environmental flow in the Daly.

(iii) To develop a standard methodology and series of permanent stations for monitoring flows and water levels, with the ability to separate groundwater and surface flow inputs, to facilitate on-going monitoring of the impact of groundwater extraction in the Daly. This methodology will be transferable to other locations within tropical Australia. The data collected together with the permanent reference stations, will provide a baseline reference set, prior to regulations and substantial extraction, against which the impact of future water extractions can be measured.

(iv) To develop information that can be disseminated to increase understanding of the need to maintain environmental flows, and to build constituency support of a rational basis for the determination of water use in the Daly catchment, consistent with sustainability and providing acceptable protection for all commercial and non-commercial values of the region. This will include a well-supported example of the consequential effects of flow alteration on the biology of a key element of the Daly River's fauna.

Variation of the Brief

This project has remained squarely on the three areas of endeavour outlined in the contract (see above) and all milestones were achieved. However, the focus on single "pools" and subsampled stretches outlined in our original proposal gave way to a focus on a broader scale. This decision was made once the data indicated that the river between Claravale Crossing and Cattle Creek (73.7 km) was essentially homogeneous with respect to morphological attributes likely to influence our analysis.

Specific variations to the scope outlined in the brief include:

- The digital terrain modelling described in the project scope was replaced by an analysis using the standard river analysis program HECRAS.

- Maps showing the degree of fragmentation under different flow regimes have been replaced by a single reference map and tabulated data on the location of break points under different flow regimes.

- Water conductivity was to be used to determine the relative contribution of surface flow and spring feed, but it became apparent very early in the study that spring feed made up 100% of the dry season flow after the transitional wet-dry months. Conductivity did not vary appreciably, and so this element of the study was abandoned. We achieved the objective of sourcing spring inputs in other ways.

Background

Alteration of hydrological regime is often claimed as the most serious and continuing threat to the sustainability of healthy riverine ecosystems (Naiman *et al.* 1995; Sparks 1995; Lundqvist 1998; Ward *et al.* 1999; Bunn and Arthington 2002). While the obvious irreversible impacts of large impoundments are now well recognised, there is also growing awareness of the pivotal influence of hydrological regime on the relationship between aquatic dependent organisms and their environment (Bunn and Arthington 2002).

Movement of water across the landscape influences the ecology of rivers at a broad range of spatial and temporal scales (Vannote *et al.* 1980; Sparks 1995). Flow regime directly *influences* the morphology of river macro-channels, the distribution of riffle and pool habitats, and the stability of the bed sediments (Newbury and Gaboury 1993). This complex interaction between flows and physical habitat is a major determinant of the distribution, abundance and diversity of stream and river biota (Poff and Allan 1995; Ward *et al.* 1999). This is evident also at the smallest spatial scales, where variations in flow and velocity along the water column can dictate the distribution and abundance of many species of plants and animals (Wetmore *et al.* 1990). Close associations with physical habitat can be found in many stream organisms ranging from algae and aquatic plants to invertebrates, and large vertebrates such as turtles and fish.

Perhaps more important than the influence of hydrological regime on the physical environment is its influence on animal life history strategies. Many aquatic species have life histories that have evolved in direct response to natural flow regimes (Bunn and Arthington 2002) and draw cues from flow attributes in order to time reproduction, movement and behavioural attributes. In some cases, critical life history events of aquatic vertebrates are tied to flow regime (e.g., phenology of reproduction, spawning or courtship behaviour, larval survival, growth patterns and recruitment) (Welcomme 1985; Junk *et al.* 1989; Sparks 1995; Humphries *et al.* 1999). These life events are synchronised with river temperature and day-length such that any change in the timing and or magnitude of flow can have severe repercussions for aquatic flora and fauna. Modified thermal patterns and day-length cues have been shown not only to disrupt insect emergence patterns but also to reduce population success (Ward and Stanford 1982).

The maintenance of natural patterns of river connectivity is also essential to the viability of many riverine species (Bunn & Arthington 2002). Populations of many species of aquatic organisms depend on their ability to move freely through their lotic environment. The disappearance or decline of migratory fish species often follows river fragmentation (Harris 1984a, b, Joy and Death 2001). In southern Australia, reduced longitudinal connectivity in rivers has contributed to the decline of populations of migratory fish, such as Australian bass, Macquarie perch, and Golden perch (Lake and Marchant 1990, Barmuta *et al.* 1992).

So alteration to flow regime may in turn alter the physical environment, the cues used by the biota to time critical life history events, and connectivity of aquatic environments important for the persistence of aquatic species where migration or movement is an important part of their life histories. Depending upon how attuned a species is to the cues it draws from a natural flow regime, some species may fall into what is called an “ecological trap” (Schlaepfer *et al.* 2002). Such traps occur when organisms make maladaptive behavioural or life-history choices which were formerly based on reliable environmental cues. Organisms often base behavioural and life-history decisions on environmental cues such as when to reproduce, places to eat, what to eat, where to shelter, when to move and so on (Bjorndal 1994; Visser *et al.* 1998; Buse *et al.* 1999). Hence, when such environments are suddenly altered, these formerly reliable cues are no longer associated with beneficial outcomes (Schlaepfer *et al.* 2002). In such cases, organisms can become trapped by their evolutionary responses to the cues and consequently experience reduced survival or reproduction. Although ecological traps are similar to natural cycles of disturbance, energy flow, and fragmentation etc., they differ in frequency because ecological traps are induced by people and occur on a shorter temporal scale than those induced in nature (Schlaepfer *et al.* 2002). If we are to minimise short-term losses to natural populations by virtue of human activities such as water extraction, we need to consider what attributes of a species may cause it to fall into that trap.

An example of this is the boom-bust ecology of many aquatic dependant fauna (Walker *et al.* 1995; Kingsford *et al.* 1999). In energetic terms, a “boom” period occurs when resources are such that the organisms can not only meet their immediate needs for maintenance, growth and reproduction, but can also replenish the resources that were drawn upon unsustainably in preceding "bust" periods. In terms of population dynamics, a “boom” period occurs when resources 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 flow alteration is likely to have substantial long-term impact on the population levels sustained locally, and may even result in local extinction if acting in concert with other factors that depress population numbers.

The Daly River in the top end of Australia undergoes episodic high and low flows annually, the magnitude of which vary considerably from year to year. In this context, we determine how changes in the magnitude of flow effect water temperature and river connectivity in the Daly River and determine the likely consequences of this on a highly aquatic, flagship species, the pig-nosed turtle *Carettochelys insculpta.* Remarkably, there are relatively few examples of studies that directly address the issue of quantity and timing of flows and the life histories of freshwater biota.

The Daly Drainage

The Daly River drainage is the third largest in the Northern Territory draining an area of 51,800 km^2 and with an annual discharge of 4180 x 106 m^3. Katherine and Pine Creek are the only major urban centres in the catchment and there are no dams on the Daly River or any of its tributaries. Major uses of adjacent rural land are pastoral and to a lesser extent agricultural.

The study site was an 80 km stretch of the Daly River well above the tidal reaches between Dorisvale Gauging Station (131^o 55'E, 14^{o}37'S) and the inflow of Cattle Creek (131^{o}13'E, 14^{o}03'S) just downstream of Oolloo Crossing (Plate. 1). The banks are of sand or sandy loam sloping steeply to a height of 20 m and covered in dense complex vegetation visually dominated by *Melaleuca argentea*, *M. leucadendron, Barrintonia acutangula*, *Pandanus aquaticus*, *Cathormion umbellatum, Ficus racemosa*, *F. opposita*, *Nauclea orientalis*, *Casuarina cunninghamii*, *Eucalyptus* spp. (trees), *Diospyros cordifolia*, *Phyllanthus* *reticuloris*, *Tephnosia* sp. (shrubs), *Passiflora foetida*, *Flagellaria indica* (vines), *Sida* sp., *Lindsaea ensifolia*, *Pseudoraphis spinescens* and *Paspalum* sp. (herbs, ferns and grasses).

The riverbed is composed of sand, gravel and silt (sensu McIntyre and Loveday, 1974) interspersed with occasional limestone rock outcrops. Aquatic vegetation (principally *Vallisineria nana*) grows along the edges and in localized mid-stream patches, but for the most part the bed is clear of macrophytes. The river supports 28 species of fish, 3 species of crustacean and 3 species of mollusc (Midgley, 1980; pers. obs). *Carettochelys* may be found together with the northern long-necked turtle *Chelodina rugosa*, the northern snapping turtle *Elseya dentata*, the red-faced turtle *Emydura victoriae* and two yellow-faced species of chelid turtle (formerly *Em. australis* – see Georges and Adams, 1992).

The climate is typical of the wet-dry tropics of northern Australia (Taylor and Tulloch, 1985) with a mean monthly rainfall less than 7 mm from May to September, rising to a peak monthly average of 284 mm in February (Stn 014139/014941, Oolloo, 1962- 1985). Mean relative humidity (at 1500 hrs, Stn 014908, Daly River (Woolianna), 1966-1980) ranges from a low of 32% in august to a high of 73% in February. Mean monthly maximum air temperature ranges from 30.9C in June to a peak of 36.8C in October. Winds blow from the east-southeast during the dry-season. They are more variable in direction during the wet-season, but blow predominantly from the west-northwest.

The Pig-Nosed Turtle

The pig-nosed turtle, *Carettochelys insculpta* (Ramsay 1886) is a high profile species of considerable international concern as the sole remaining member of a once widespread Family. The species conservation status is uncertain, and they are classified by the IUCN as rare and insufficiently known.

Pig-nosed turtles occupy the wet/dry tropics of northern Australia where they occur in four river systems; the most substantial Australian populations of the species reside in the Daly River. Pig-nosed turtles are adapted for a highly aquatic existence, having flippers superficially like a sea turtle making overland movement awkward and extensive overland migration virtually impossible). Their soft skin that overlies the bony shell makes them particularly vulnerable to desiccation.

Pig-nosed turtles are long lived, slow growing and do not reach sexual maturity until about 20 years of age. In the Daly River, they feed principally upon rooted aquatic macrophytes, such as *Vallisneria,* and associated invertebrates (Welsh and Georges, in prep). Their principal food, *Vallisneria,* is flow and turbidity sensitive.

During the dry season, females deposit clutches of 4 to 19 eggs in shallow chambers on sand banks adjacent to water (Georges and Kennett 1992). The eggs are white, hard-shelled and almost perfectly spherical. They incubate rapidly over 50-90 days to maturation depending on date laid and incubation temperature, which rises steadily as the season progresses. Temperatures within the nests are high and fluctuate widely each day (Georges 1992). On reaching maturity, a substantial residual yolk body is internalised; the embryos then enter aestivation within the egg (Webb et al. 1986). The trigger for hatching is inundation by flooding or the first torrential rains of the wet season. Embryos have sufficient resources to carry them through about 60 days at 30^{o}C. This species has temperature-dependent sex determination (Webb et al. 1986; Georges 1992).

Although pig-nose turtles nest in the dry-season, dates vary dramatically in response to weather and ambient temperatures. This in turn determines timing of maturity of the eggs in relation to the early wet season cues for hatching. Too early and the eggs perish in the ground. Too late and they are prematurely washed away by rising waters. Furthermore, the primary determinant of offspring sex is date of laying, so altering water temperatures (but not temperatures of the adjacent ground) will have profound effects on offspring sex ratios, and subsequently population numbers.

Pig-nose turtles undergo extensive movements during the dry-season. This is because of the limited and unpredictable distribution of nesting sandbanks in a system that is dramatically remodelled each wet season. Access to suitable banks requires free movement during the dry, a life history requirement likely to be concordant with a range of other aquatic species.

The complex interaction of this species reproductive biology with water temperature, connectivity, and flood pulses (see below) makes it a sensitive indicator species for assessing the impact of modified environmental flows. As a species particularly sensitive to environmental perturbations, protecting its interests will likely bring attendant benefits for a wide range of other species whose requirements are less stringent. It can therefore be regarded as an umbrella species. Adverse impact on this species, and those fish and other aquatic life with concordant requirements, would be regarded as major degradation.

This project draws substantially on the base of ecological knowledge on the species, arising from recent studies funded by the Australian Research Council, namely

- River banks are extensively remodeled each year, and dry-season movements are a critical element in location of suitable nesting areas;

- Timing of nesting depends upon water temperatures, and this has an over-riding influence on offspring sex ratios – alteration of flows, with concomitant alteration of water but not ground temperatures will have an impact on hatchling sex ratios that can be estimated.

- Nesting is close to the water (0.3-2 m) and premature flooding causes egg mortality. Timing of nesting in relation to early flood pulses is a critical consideration for egg survivorship.

- Home ranges and extent of movement in relation to nesting banks is known.

- Hatching is stimulated by torrential rains and/or flooding. Mismatch in the timing of egg development with respect to early wet season rains and flood pulses leads to high mortality. Again, timing of nesting in relation to early flood pulses is a critical consideration for survivorship.

- Data available on the biology of the species are sufficient for quantitative modeling together with that on the environmental flows.

Analysis of Historical Flow Data

Data Sources and Quality Control

The Northern Territory Department of Lands Planning and Environment provided historical flow data for Dorisvale Gauging Station. The data was an admixture of direct measurements and values estimated from recession curves, which could not be disaggregated. The poor quality of the data required that we apply a series of cross-checks which led to the elimination of data for a number of years: We eliminated data for particular years when there was

- high and unexplained variability in the daily flow data about the recession trend, suggesting equipment failure;
- inexplicable departure from reasonable expectation for recession of flow, post flood;
- inexplicable low variation in daily flows about the recession trend, indicating that the data had been generated rather than measured.

In addition, data for any one month that was based on less than 20 days was eliminated from analysis of data by month.

Despite these deficiencies, we regard the summary of flow conditions for the Daly River to be reasonably accurate. Caution should be exercised in the interpretation of individual values, such as the minimum low flow, though where possible, we have cross-checked these figures with DLPE staff.

Approaches to improving the quality of dry-season flow monitoring for the Daly have been included among our recommendations.

Rainfall data were obtained from the Douglas-Daly Research Farm for the period 1968-97. Rainfall figures for Katherine (DR014902) were obtained from the Bureau of Meteorology for the period 1884-2000.

Rainfall

The Daly River is in the wet-dry tropics of the Northern Territory. As such it experiences the extremes of high rainfall during the monsoonal wet seasons and the near absence of rainfall in the intervening dry seasons (Figure 2).

The wet season extends from December to March inclusive under the influence of the tropical monsoon, whereas virtually no rain is received in the dry season, which extends from June through September. April-May and October-November are the wet-dry and dry-wet transitional months, respectively.

Notwithstanding the general utility of these seasonal definitions, rainfall is highly variable within and across years (Figures 2 and 3) in the quantity that falls and its timing. It can be argued that there is no such thing as a typical year (Taylor and Tulloch, 1985).

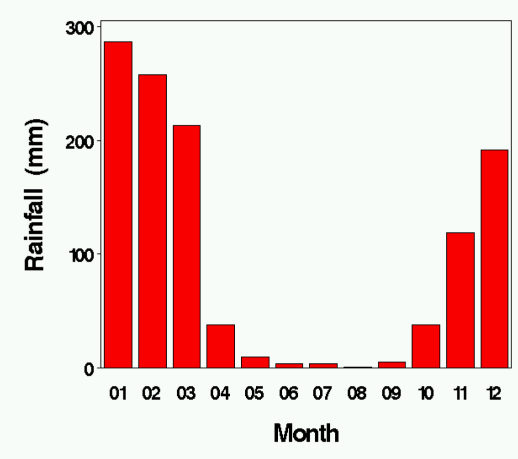


Figure 2. Mean monthly rainfall for the Douglas Daly Research Farm (1968-97).

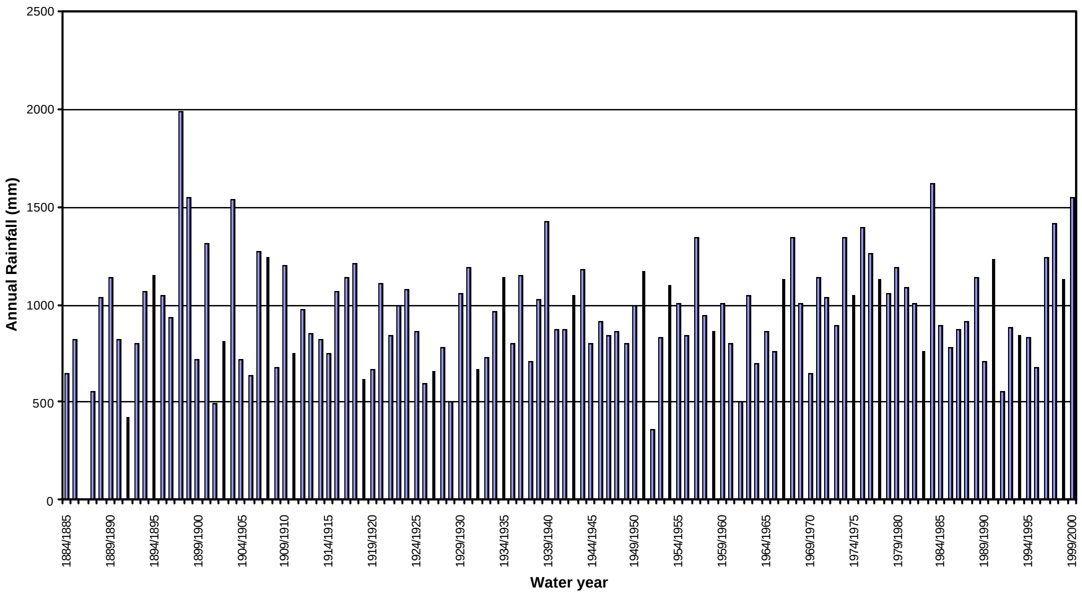


Figure 3. Annual rainfall (October – September) for Katherine GPO (DR014902) from 1884/85 through 1999/2000. Note the high interannual variation.

Definitional Issues for Flow

The rainfall pattern is clearly reflected in river flow, which too is highly variable. Flow may be as low as *ca* 2 cumecs in an extreme dry season (November 1966) or as high as 8,099.5 cumecs in an extreme wet season (January, 1998).

Table 2. Percentiles for flow in all months for the Dorisvale gauging station (G8140067), Daly River, Northern Territory. Flow is in cumecs, stage is in metres from an arbitrary reference (40.309 AHD), and relative stage is stage height relative to the stage height at median flow. Data from months where there were less than 20 gauged days were excluded. N=13225.

Percentile	Flow	Stage	Relative Stage
Max	8100	23.6	22.22
95%	739	8.79	7.41
90%	329	5.39	4.01
Q3	53	2.21	0.83
Median	10.7	1.38	0
Q1	5.4	1.23	-0.15
10%	3.6	1.22	-0.16
5%	2.9	1.19	-0.19
Min	1.5	1.13	-0.25

* Set to 2 cumec on the advice of DPLE

Flow percentiles for available data from 1960 to 2002 (Table 2) provide a basis for defining events and categories of flow.

1$^+$ *Record High Flow*: The maximum high flow recorded, currently 8100 cumecs for January 1998.

6. *Extreme High Flow*: Flow greater than the 95th percentile of 740 cumecs.

7. *High Flow*: Flow greater than the third quartile of 50 cumecs.

8. *Transitional Flow*: Flow greater than the median flow of 10 cumecs, but less than the third quartile (50 cumecs).

9. *Low Flow*: Flow less than the median flow of 10 cumecs.

10. *Extreme Low Flow*: Flow less than the 5th percentile of 3 cumecs

5$^+$ *Record Low Flow*: The minimum flow recorded, currently 2 cumecs for November of 1966.

These flow categories are defined independently of the seasons, which are defined above on rainfall statistics. Hence it is sensible under our terminology to talk, for example, of low flow conditions extending through the first half of the wet season.

Sources of Flow

Overland runoff and subsurface interflow

The primary source of flow in the Daly River is runoff from rain that falls in its catchment. However, owing to the highly permeable nature of the soil profile over most of the catchment, true overland flow rarely occurs, except following very intense rainfall events (Jolly, 2002). Most water moves from where it has fallen to the nearest small creek in some part beneath the ground. Data from the Katherine river indicate that almost all the flow in excess of 10 cumecs is either overland runoff or subsurface interflow (Bore G8140001, Jolly, 2002).

Recharge and discharge to and from offstream storage

A second component of surface water runoff is derived from the seasonal recharge and discharge to and from local offstream bank storage and offstream aquifers. Water from this source recharges the storages and aquifers during the wet-season, the degree of recharge depending upon the magnitude of the wet season flows and the permeability of the river sediments and strata comprising the aquifer. Water then discharges into the river during the dry season.

Both the Tindall Limestone and the Oolloo aquifers recharge and discharge from and to the Daly River system following inundation of the landscape by the previous and earlier wet seasons. The rate of recharge and discharge depends strongly on outcropping. About four times as much water is recharging and discharging from the Oolloo aquifer where it outcrops compared to rates where it is overlain by Cretaceous sandstone (Jolly, 2002). The factor is two times for the Tindall Limestone. Jolly estimates that about 50% of the Oolloo Limestone of the

Daly catchment is overlain by Cretaceous sandstone, but its distribution across the catchment is poorly known.

Diffuse recharge to regional aquifers and subsequent discharge

This is the discharge process identified by Jolly (2002) by which diffuse recharge to the regional aquifer system discharges to adjacent creeks and rivers. This diffuse recharge mechanism also includes recharge via sinkholes and via recharge of the aquifer via the bed of creeks and rivers.

Inflows from adjacent groundwater sources

The Tindall Limestone is a regional aquifer that extends well beyond the boundary of the catchment of the Daly system. Small quantities of groundwater are thought to flow either into or out of the catchment within aquifers that occur adjacent to the catchment boundary, with a nett impact that is not significant. The exception is the aquifer system that provides the source of dry season flow in the Flora River. Approximately 50% of the groundwater fed flow in the Flora River is sourced from recharge that occurs outside of the Daly River catchment, from across the Sturt Plateau to the south east of the Dry River.

Flow Characterization

Average Monthly Flows

The highest median flow occurs in February followed by March. The lowest median flow occurs in October followed closely by August and September. Indeed, a low-flow state typically occurs in all months from June through to November if median flow is the consideration (Figure 4). A similar picture emerges with the mean flows, but the mean is more greatly influenced than the median by the few extreme high flows. The highest monthly mean flow occurred in March.

Full summary statistics for flow are presented in Tables A1 and A2 of Appendix 1.

Monthly flow varies considerably across years while remaining consistent with the overall wet-dry pattern. This inter-annual variability derives from variation in both the magnitude and the timing of the wet season rains and associated discharge.

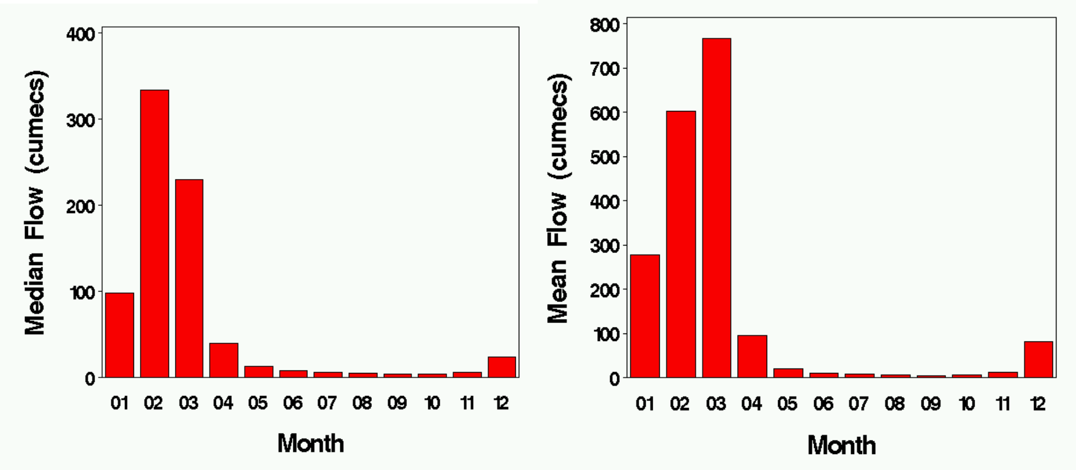


Figure 4. Median and mean flow by month for the Dorisvale gauging station (G8140067), Daly River, Northern Territory. Median flows were calculated from the raw daily heights.

Mean flows were calculated first as a mean for each month, then averaging the monthly mean flows across years. In both cases, data from months where there were less than 20 gauged days were excluded.

Flow Category by Month

The frequency of occurrence of the categories of flow conditions across months is shown in Figure 5. Months can be grouped into four classes. January to March have flows dominated by High to Extremely High flows with very poor representation of years with Low or Extremely Low flows in these months. June to October have flows dominated by Low to Extremely Low flows with no occurrences of High or Extremely High flows in these months for any year.

April and December are similar in the flow categories likely to occur in those months, though of course April is on the transition between high-flow and low-flow conditions, and December is on the transition between low-flow and high-flow conditions. Both months are dominated by Transitional and High Flows with the rare occurrence of an Extremely High flow (Figure 5).

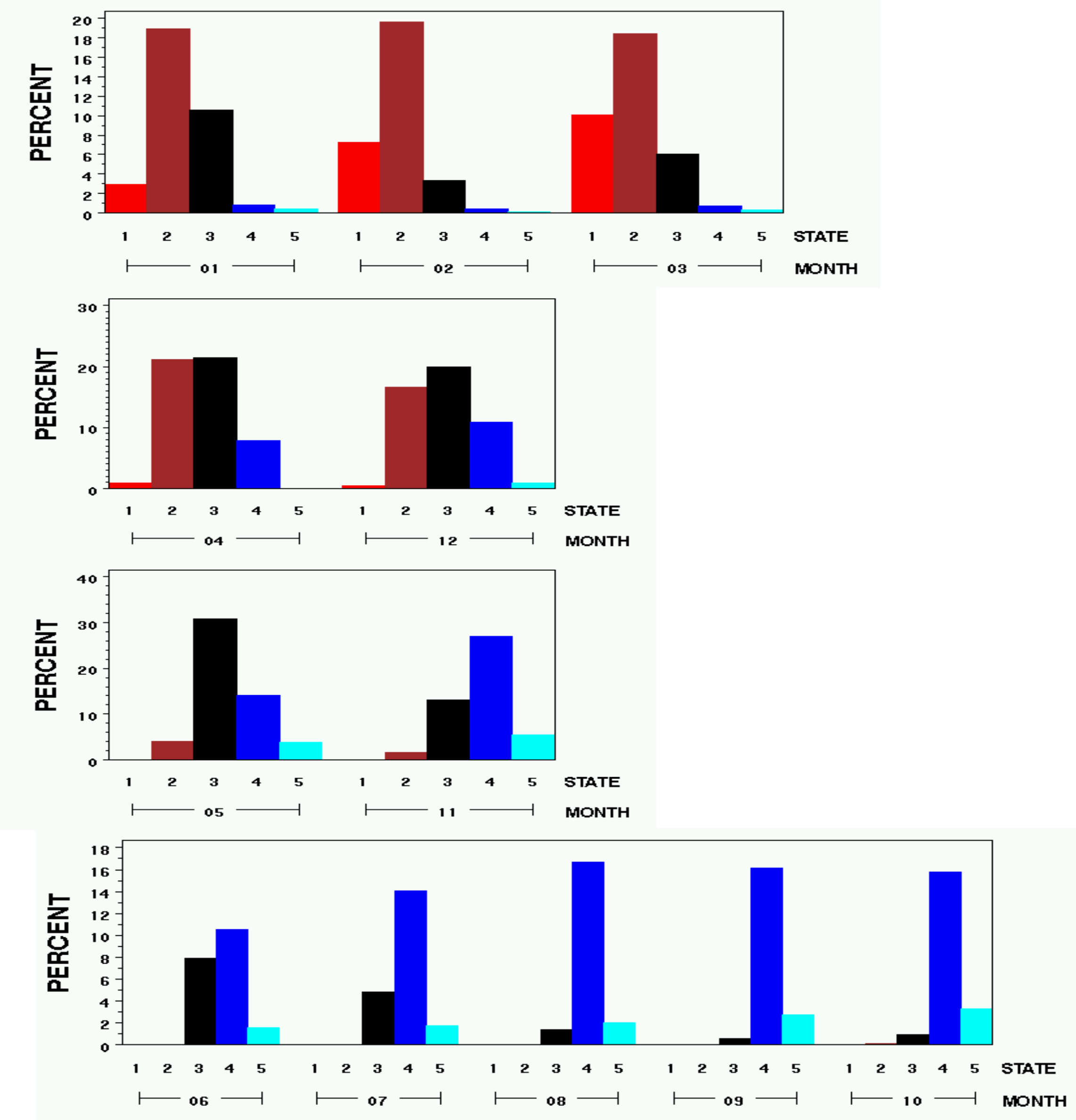


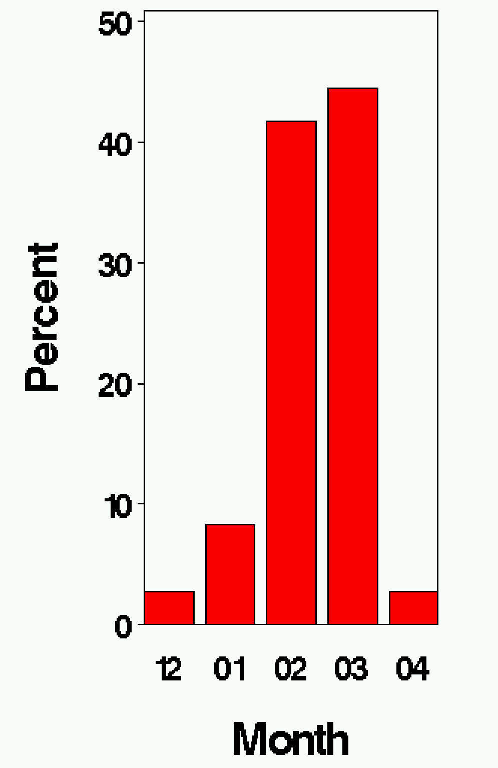
Figure 5. Frequency of occurrence of the five flow categories across months of the year at the Dorisvale gauging station (G8140067), Daly River, Northern Territory. Data are daily flows from

months where there were less than 20 gauged days were excluded. Flow categories are defined in the text.

May and November are also similar in their flow categories. Both are dominated by Transitional and Low flow conditions with the rare occurrence of High flow and Extremely Low flow conditions.

Thus, from the point of view of flows, the season can be defined in terms of high flow conditions which typically occur in January to March, low flow conditions which typically occur from June to October, high-low flow transitional months of April-May, and low-high flow transitional months of November-December.

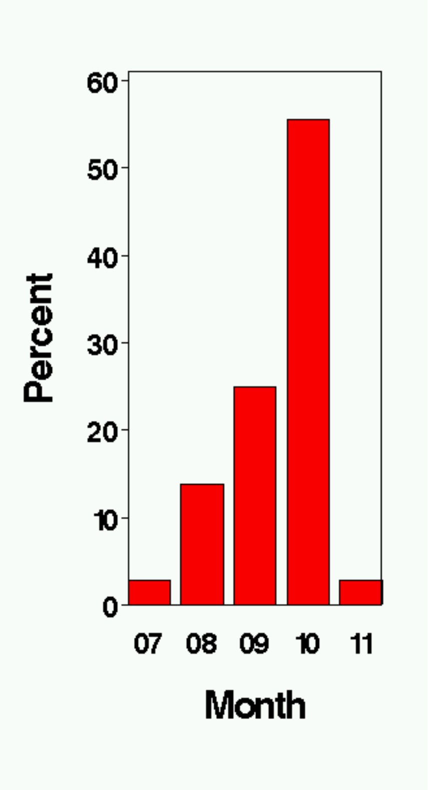
Year	Month	Max
1961	02	147
1962	02	343
1963	02	439
1965	03	275
1966	02	1073
1967	03	898
1969	03	1273
1970	02	156
1971	03	533
1972	03	976
1973	03	899
1974	03	3046
1976	03	3003
1977	03	2444
1978	02	873
1979	03	647
1980	02	2094
1981	02	998
1982	03	613
1983	03	312
1984	03	2033
1985	04	275
1986	01	154
1987	02	1506
1988	12	261
1990	01	80
1991	02	1554
1992	02	361
1993	02	1232
1994	03	1003
1995	02	1193
1996	02	209
1997	02	1719
1998	01	1804
1999	03	1154
2000	03	3710



Timing of Annual Maximum and Minimum Flow

The month in which the peak high flow occurs varies from December through to May (Figure 6) and the month in which flow bottoms varies from June through to November (Figure 7). Thus there is very great variability in the seasonal timing of the high and low flow conditions, respectively.

Year	Month	Min
1961	08	2.2
1962	08	2.6
1965	11	3.4
1966	09	2.0
1967	10	2.2
1968	10	4.3
1969	09	3.6
1970	07	3.2
1971	09	4.0
1972	10	3.6
1973	08	7.0
1974	08	5.6
1975	09	5.3
1976	10	7.3
1977	10	7.6
1978	08	7.1
1979	10	6.2
1980	09	5.9
1981	09	6.3
1982	10	4.9
1983	09	4.8
1984	10	7.6
1985	10	6.6
1986	09	4.7
1987	10	4.8
1988	10	4.1
1989	09	4.9
1990	10	3.3
1991	10	5.1
1992	10	3.2
1993	10	3.9
1994	10	4.4
1995	10	3.9
1996	10	2.8
1997	10	5.6
1998	10	9.2



Coefficient of Variation

The range of flows experienced in a given month is considerable, especially under high flow conditions (Figure 8).

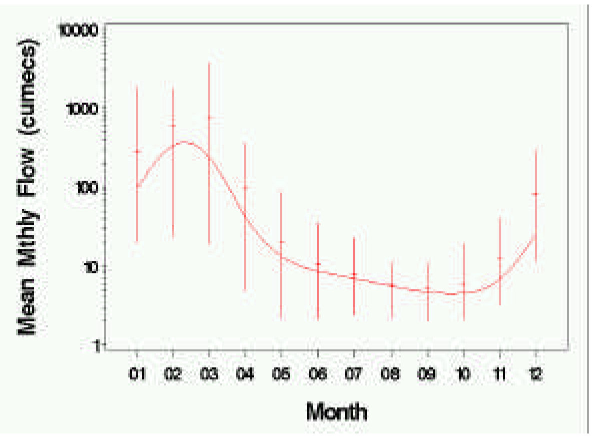


Figure 8. Range in mean monthly flows on a log scale for the Dorisvale gauging station (G8140067), Daly River, Northern Territory. The line shows the median flow; crossbars, the mean. Data from months where there were less than 20 gauged days were excluded.

The coefficient of variation (CV) in the mean monthly flow across years is a measure of predictability of flow conditions. As expected, conditions are highly predictable in the dry season months of May to October, being most predictable in September (Figure 9). The bimodal distribution in the CV (modes in January and March) reflects the greater certainty of high flow conditions in February than in the two months spanning February by virtue of uncertainty in the timing of peak flows (Figure 6).

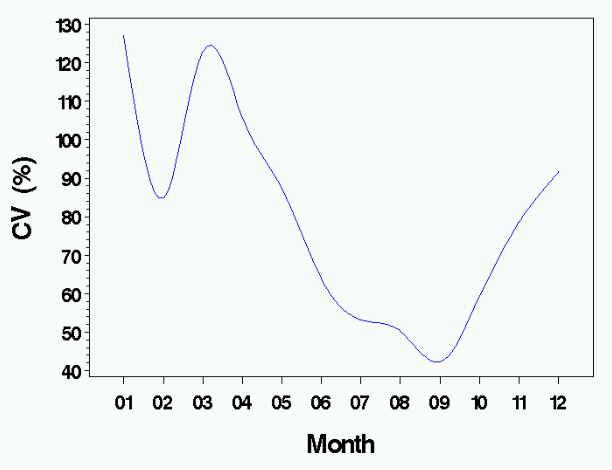


Figure 9. Coefficient of Variation (CV) in mean monthly flow for the Dorisvale gauging station (G8140067), Daly River, Northern Territory. Data from months where there were less than 20 gauged days were excluded.

Variation in flow within months showed a similar pattern, with flows being relatively least variable in the months of May through September, and most variable in the remaining months (Figure 10). For a given month, the CV itself varied considerably, especially in the months of October through to the following April. Again this reflects the unpredictability of high flows compared to that of low flows, within particular months.

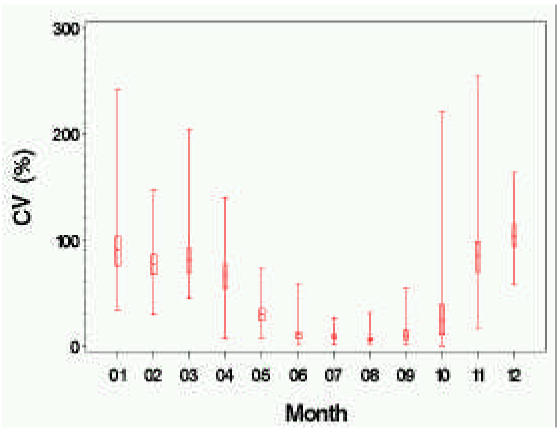


Figure 10. Coefficient of Variation (CV) in flow across months for the Dorisvale gauging station (G8140067), Daly River, Northern Territory. Box diagrams show the means, approximate 95% confidence limits, and the range in CV for each month. Data from months where there were less than 20 gauged days were excluded.

Rises and Falls

The number of days in which a fall in flow was recorded dominated the number of days in which a rise in flow was recorded in all months (Figure 11). This reflects the episodic nature of the rises compared with the more graduate decline in flows after a rise. It is therefore not possible to easily define the transition between high-flow and low-flow seasonal conditions using the ratio of number of rises to falls in a month. A better indication is given by when the number of days experiencing a rise exceeds the number of days of steady state (change in flow < 1 cumec per day). This index measures the relative frequency of episodic rises against the frequency of steady state conditions.

The transitional month between high and low-flow conditions can be defined as the month in which the frequency of rises first becomes dominated by the frequency of steady state conditions. Similarly, the transitional month between low and high-flow conditions can be defined as the month in which the frequency of rises first comes to dominate by the frequency of steady state conditions.

When averaged across years for each month, the transitional months are April and December respectively (Figure 11).

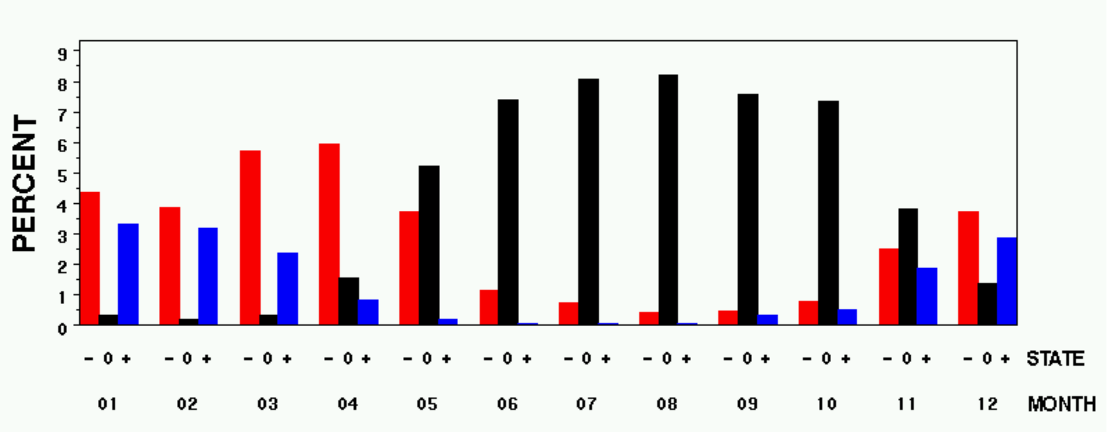
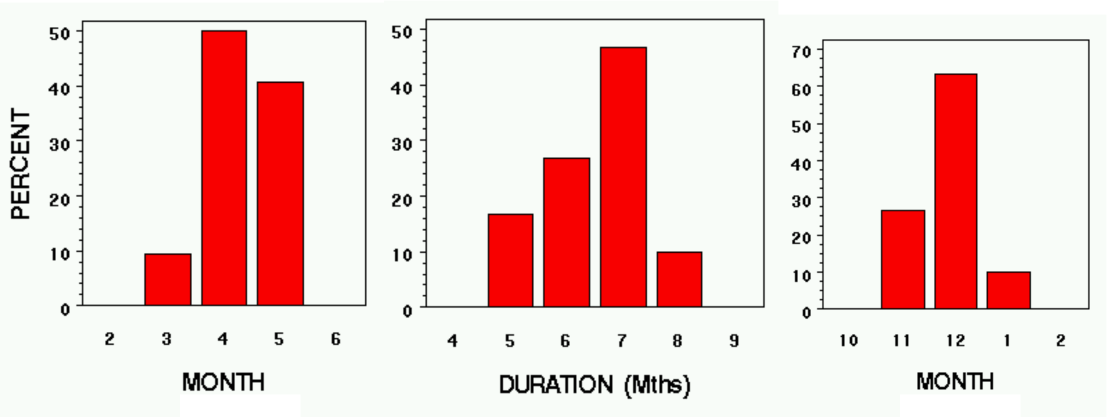


Figure 11. Frequency of occurrence daily falls in flow (-), steady state conditions (0), and rises in flow (+) at the Dorisvale gauging station (G8140067), Daly River, Northern Territory. Steady state flow occurs when the daily change in flow remains less than one cumec. Data from months where there were less than 20 gauged days were excluded.

Transitional months defined in the above terms were calculated for each year with complete data (n=32). Duration of low flow conditions ranged from 5 to 8 months, with the transition from high to low flow ranging from March to May and the transition from low to high flow ranging from November to January (Table 3).

Table 3. Transitional month between high and low flow (H-L), between low and high flow (L-H) and the duration of the intervening period (low flow period). The transition between high and low flow is defined as the month in which the number of days experiencing rises fell for the first time below the number of days of steady state flow (change < 1 cumec). The transition between low and high flow is defined as the month in which the number of days experiencing rises increased for the first time to exceed the number of days of steady state flow. Analysis includes only data from year for which the data were complete.

Year	H-L	L-H	Duration	Year	H-L	L-H	Duration
1961	4	1	8	1981	4	11	6
1962	4	12	7	1982	4	12	7
1965	5	12	6	1983	5	12	6
1966	3	12	8	1984	5	1	7
1967	4	.	.	1985	5	11	5
1969	4	12	7	1986	3	12	8
1970	3	11	7	1987	4	12	7
1971	5	11	5	1988	4	12	7
1972	5	1	7	1991	5	12	6
1973	5	11	5	1992	4	12	7
1974	5	11	5	1993	4	12	7
1976	5	12	6	1994	4	12	7
1977	5	12	6	1995	5	12	6
1978	4	12	7	1996	4	11	6
1979	4	.	.	1997	4	12	7
1980	4	12	7	1998	5	11	5



H-L

L-H

Predicting dry season flows

Once the groundwater contribution comes to dominate flow in the Daly, as it does soon after the rains cease from the previous wet season, flow declines exponentially with time and so follows a predictable recession curve. Log flow is therefore linearly related to time, opening the possibility of predicting dry season flow at any time from a single point gauging.

Rate of decline of flow b depended upon the magnitude of the initial flow (taken for our calculations to be June 1) according to the relationship

$$b = 0.001784 - 0.004706 Log_{10} F_o$$

where F_0 is flow in cumecs at June 1 (Figure 12).

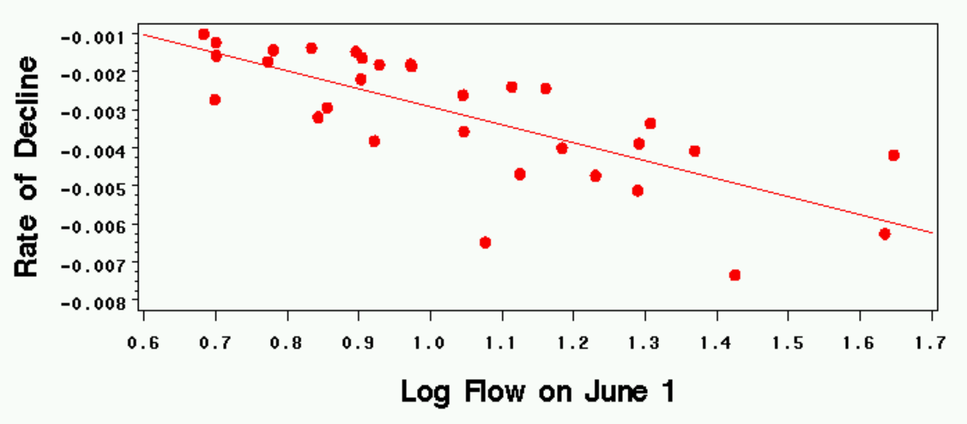


Figure 12. Relationship between rate of decline in flow (cumecs per day) during the dry season and initial flow levels (as at June 1) for Dorisvale gauging station (G8140067) on the Daly River, Northern Territory.

Flow at time t is given by

$$Log_{10} F_t = Log_{10} F_o + bt$$

where b is defined above and t is in days from June 1.

Analysis of Contemporary Flow Data

Data Sources and Quality Control

The Northern Territory Department of Lands Planning and Environment provided flow data for Dorisvale Gauging Station for the two years of our study. Dry-season flows for 2001 provided to us for the Dorisvale Gauging Station were inconsistent with our recession curves (Figure 13) and were not consistent with our gauging data at the same time. It subsequently transpired that the Dorisvale Gauging Station ran out of gas in May of 2001 and was not operational until December. Approaches to improving the quality of dry-season flow monitoring have been included among our recommendations.

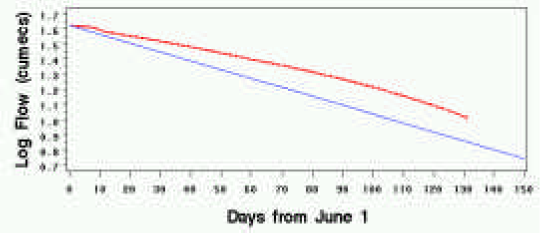


Figure 13. Flow data provided for 2001 versus predicted decline in dry-season flow (cumecs) for 2001 at Dorisvale gauging station (G8140067) on the Daly River, Northern Territory. The observed flow data (red line) do not agree with prediction (blue line), and the recession of the data with time is too smooth.

Our study spanned two years of 2000 and 2001, for which we obtained direct gaugings, identified control points and measured water heights. The focus of effort for 2000 was to undertake the data collection in support of the thermal modelling. In 2001, it was to validate the thermal models and to collect detailed flow data along the 80 km stretch.

Flow Characterisation

In such a highly variable system as the wet-dry tropics, nearly every year is exceptional in some way. It is appropriate to consider in what ways the two years selected for intensive study were exceptional, and whether this is likely to influence the generality of the results. Daily flows for each of the two years are shown in Figure 14.

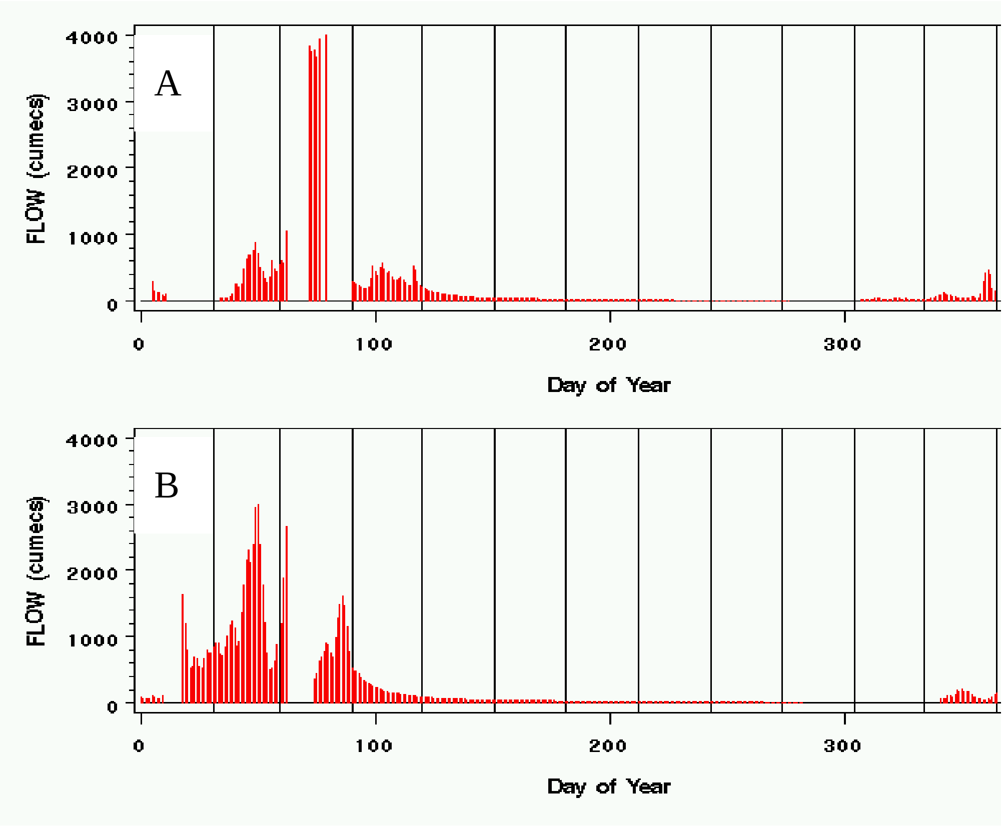


Figure 14. Flows recorded at Dorisvale gauging station (G8140067) for A: 2000 and B: 2001. The Gauging Station failed in May of 2001 and was not operational again until December 2001, so the dry season data are estimated from models applied by DLPE.

Both 2000 and 2001 were exceptionally wet years (Figure 15). In 2000, the transition between high-flow to low flow conditions came late (May-June), which greatly impeded our access to the river. Peak flow at 5092 cumecs was not particularly high, and well below the record of 8100 of January 1998, but well above the 95th percentile for flow in any of the wet season months of January to March. Average monthly flows in the dry-season exceeded the corresponding median monthly average flows in all months, and *Low Flow* (< 10 cumecs) occurred only in September and October. The minimum low flow occurred in October at 8.6 cumecs, which exceeded the 90th percentile for recorded September-October flow (Table A2). The dry-season finished typically, with the low-high flow transition occurring in November.

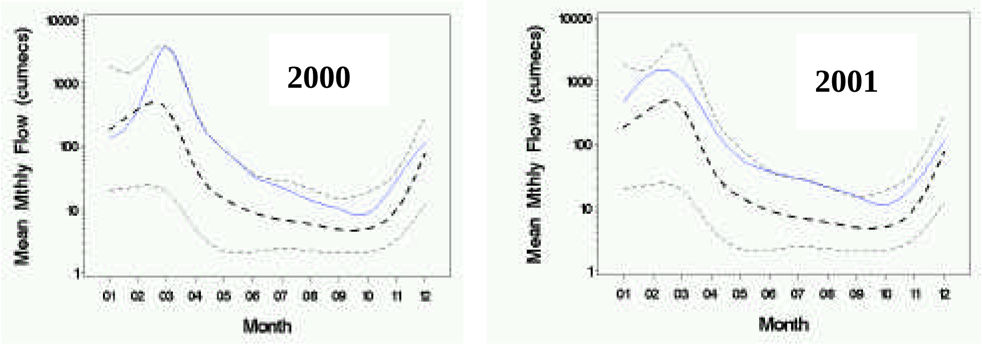


Figure 15. Mean monthly flow at Dorisvale gauging station (G8140067) in the two years of the present study. The mean monthly flow (blue line) is compared to the maximum, median and minimum mean monthly flow calculated across the historical dataset. Data for January, March and October of 2000, and in January, March, October and November of 2001 should be viewed with caution, owing to equipment failure.

In 2001, the transition between high-flow to low flow conditions was more typical, occurring in April. Peak flow at 2995 cumecs was not particularly high, and also well below the record of 8099 of January 1998, but above the 90th percentile for flow in any of the wet season months of January to March. Average monthly flows in the dry-season equalled the maximum monthly average flow in June through September, and *Low Flow* (< 10 cumecs) was not achieved in any month. The minimum low flow occurred in October at 10.36 cumecs, which exceeded the 95th percentile for recorded September-October flow (Table A2). The dry-season finished typically, with the low-high flow transition occurring in November.

The data for 2000 was consistent with the relationship between rate of decline in flow as the dry season progressed and initial flow conditions (as at June 1) (Figure 16), despite the exceptionally high dry season flows. This is an important relationship, as it is one that is likely to change under any regime of dry-season water extraction, whether directly or by groundwater extraction. It may be an important tool for monitoring the impact of water resource development.

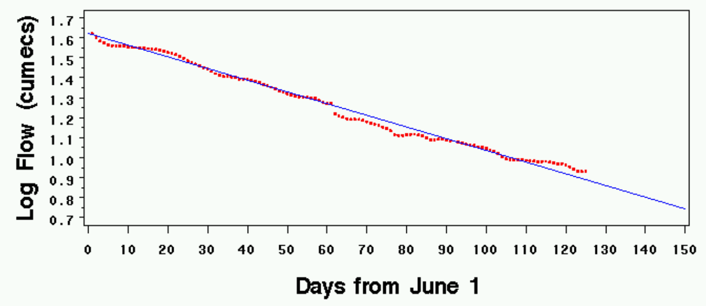


Figure 16. Actual versus predicted decline in dry-season flow (cumecs) for 2000 and 2001 at Dorisvale gauging station (G8140067) on the Daly

River, Northern Territory. Data for 2001 are not available owing to equipment failure.

Spatial Pattern of Low Flows

Flow close to the boundary points of our study site, Dorisvale Gauging Station and Oolloo Crossing, are linked by the relationship (Figure 17)

$$F_{oolloo} = 3.74199 + 1.457\ F_{dorisvale}$$

$$R^2 = 0.92$$

Nett input between Dorisvale and Oolloo depends on the level of flow. When the dry season flow is 10 cumecs, nett input between Dorisvale and Oolloo is 8.2 cumecs.

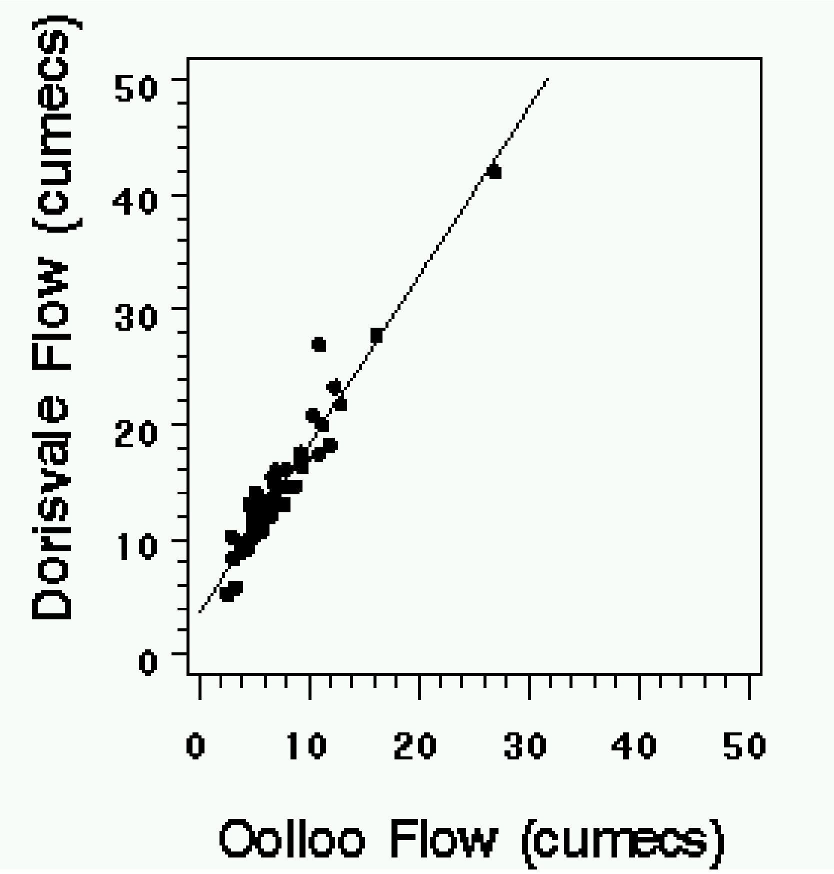
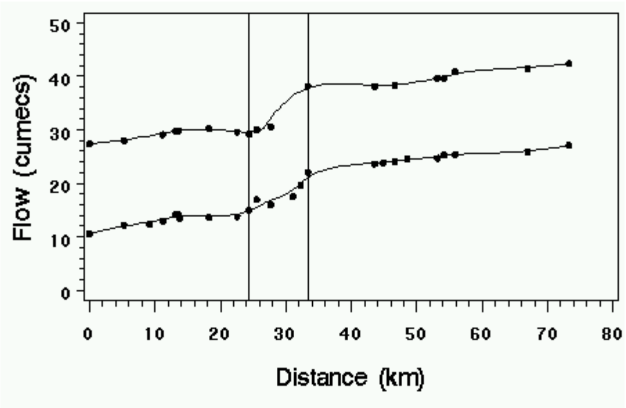


Figure 17. Relationship between discharge at Claravale and Oolloo crossings ($F_{1,52}$=599.95; P<0.0001; r^2=0.92). The relationship expressed as Flow at Oolloo = 3.74199 + 1.457*Flow at Claravale.

Input is not uniform with distance as you move down the Daly from Clarivale Crossing to Oolloo Crossing (Table 4). On June 3, 2001, flow at Clarivale Crossing was 27.39 cumecs and at Oolloo Crossing was 41.53 cumecs. There was a general base increase in flow of 0.12 cumec per km downstream from Claravale Crossing, punctuated by a much more substantial input of 1.0 cumec per km between control point 10 (Hot Spring) and 15 (Black Bull Yard). A total of 63% (8.98 cumecs) of the nett inflow to the Daly River in the 66.9 km between Claravale Crossing and Oolloo Crossing occurred in the 9.0 km between control points 10 and 15. This is adjacent to the Stray Creek development area.

Table 4. Flow measured at control points on the Daly River from Clarivale Crossing (Stn 1) to Cattle Creek (Stn 26). Contribution to flow is greatest in the 9 km between Hot Spring (Stn 10) and Black Bull Yard (Stn 15).

Station	Distance	June 3	September 3
1	0.0	27.4	10.6
2	5.3	28.1	12.3
3	9.2	.	12.4
4	11.2	29.2	13.1
5	13.2	29.8	14.3
6	13.6	29.9	14.3
7	13.8	.	13.6
8	18.3	30.3	13.7
9	22.6	29.6	13.9
10	24.4	29.2	15.1
11	27.7	30.6	16.0
12	25.6	30.1	17.0
13	31.1	.	17.6
14	32.3	.	19.7
15	33.4	38.2	22.1
17	43.6	38.2	23.7
18	44.9	.	23.9
19	46.7	38.4	24.2
20	48.6	.	24.6
21	53.2	39.7	24.8
22	54.2	39.7	25.3
23	55.9	40.9	25.5
25	67.0	41.5	26.0
26	73.3	42.4	27.2



Surface flow inputs included Bradshaw Creek, which discharged 1.06 cumecs into the river, contributing substantially to the nett increase in flow between Clarivale Crossing and control point 10 (Hot Spring) of only 1.8 cumecs. A substantial “hot” spring at control point 10 discharged 0.4 cumecs into the river, and Stray Creek discharged 2.7 cumecs. The remaining nett increase of 5.9 cumecs between control point 10 and control point 15 was from numerous small non-specific point discharges and diffuse discharge.

On September 3, 2001, flow at Clarivale Crossing was 10.6 cumecs and at Oolloo Crossing was 25.9 cumecs. There was a general base increase in flow of 0.14 cumec per km downstream from Clarivale Crossing, punctuated by a much more substantial input of 0.79 cumecs per km between control point 10 (Hot Spring) and 15 (Black Bull Yard). A total of 46% of the nett inflow to the Daly River in the 66.9 km between Clarivale Crossing and Oolloo Crossing occurred in the 9.0 km between control points 10 and 15.

In September, Bradshaw Creek had ceased to flow. The “hot” spring at control point 10 discharged an unknown number of cumecs into the river, and Stray Creek discharged an unknown number of cumecs. The bulk of the nett increase of 7.0 cumecs between control point 10 and control point 15 was from numerous small non-specific point discharges and diffuse discharge.

Geology explains the order of magnitude increase in flows between Hot Spring (Stn 10) and Black Bull Yard (Stn 15) (Tickell 2002). An upper massive unit of the Oolloo Dolostone is the main source of this groundwater (Tickell 2002). Numerous discrete springs and diffuse seepage zones such as upwelling sands are visible

Upstream from station 10, the Oolloo Dolostone aquifer is overlain by first a permeable sandstone layer then a more impermeable claystone layer (Tickell, 2002) between Bradshaw Creek and Stray Creek. Downstream from Station 10, this sandstone layer and Oolloo Dolostone outcrop, providing a conduit for accumulated head of groundwater to enter the Daly system. A large fractured aquifer in the Oolloo Dolostone is the main source of the springs (Tickell 2002). Although numerous springs are evident downstream from Station 10 to Oolloo Crossing, the majority of inflow is through direct seepage into the riverbed (Tickell 2002).

Modelling Flow Reduction

Approach

We constructed a steady state hydrodynamic model of the Daly River between Claravale Crossing and Cattle Creek using the HecRas – River Analysis System. HecRas is a hydraulic model for estimating water levels and flow velocities in rivers and floodplains. It is a one-dimensional, steady flow model, which simulates the water surface profile of waterways under gradually varied flow conditions. The computational procedure is based on the solution of a one-dimensional energy equation. Energy losses are evaluated by friction (Manning’s equation) and contraction / expansion (coefficient multiplied by the change in velocity head). The model incorporates a momentum equation in situations where the water surface profile varies rapidly. We used a boundary condition in the form of a known water level at the downstream end of the model under sub-critical flows.

Our model consisted of 1028 cross-sections and twelve significant flow change locations. We modelled water surface elevation in the Daly River with respect to the plan form geometry of the river under 10 flow regimes increasing in 10% increments from the base flow set at the historical minimum of 2 cumecs.

Data Sources

River Geometry

We measured the cross-sectional geometry of the Daly River using an electronic distance-measuring theodolite (EDM). We placed arbitrary reference marks (RM`s) in the form of galvanised iron nails, in temporary pickets or at the base of solid eucalyptus trees and then blazed the nearest tree with a triangle. Bearings and distances were then taken from the blazed tree to the RM. The position of each RM was also taken using GPS. Each cross section was interpolated to AHD.

We identified and measured the cross-sectional geometry of the 19 major control points in the study reach. Permanent benchmarks were installed at these locations and their height and position surveyed. A further 104 cross-sections were measured authoritatively at points in the river were it changed visually in depth and morphology between Jinduckin and Cattle Creeks.

The longitudinal profile of the Daly River between the Dorisvale GS and the Beeboom GS was also measured (under flood conditions) using a broad band RDI Acoustic Doppler Current Profiler (ADCP). To interpolate the longitudinal profile data into AHD we assumed that the water surface elevation between the Dorisvale and Beeboom gauging stations was linear because their were no river controls during the measurement period. We then subtracted the depths measured by the ADCP from the water surface elevation to obtain a thalweg in AHD.

We then added our measured cross-sections to the longitudinal profile. In areas were there were no cross-sections we filled in using the average cross-section from our data set of 104. The thalweg of the Daly River between Claravale Crossing and Cattle Creek is shown in (Figure 18).

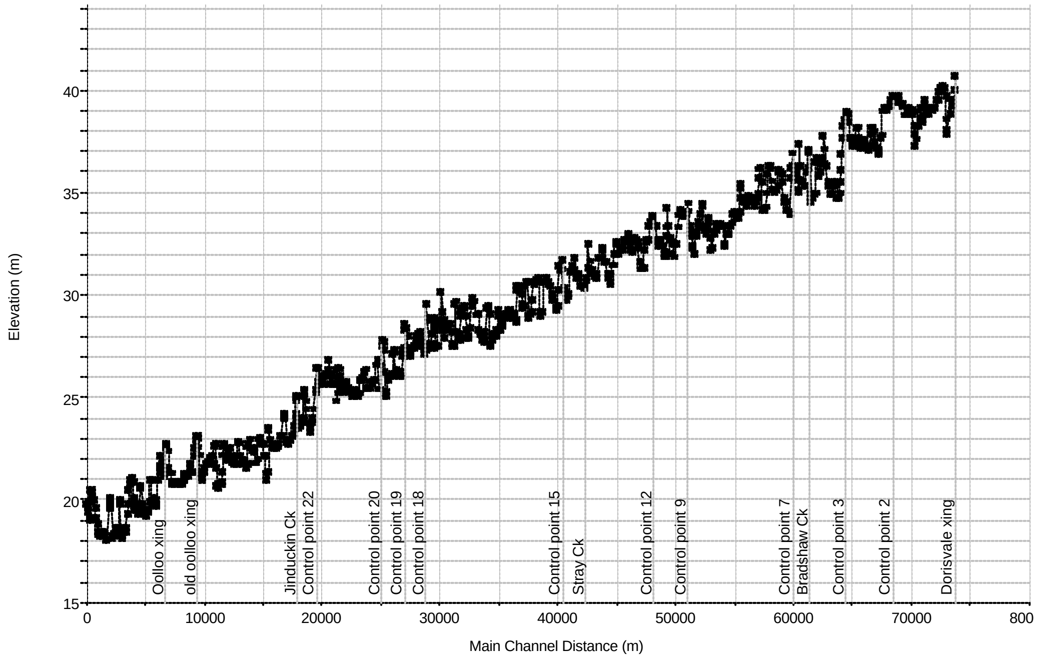


Figure 18. Thalweg and location of control points along the Daly River, between Claravale Crossing and cattle Creek.

Flow data

To determine flow change locations we conducted two series of longitudinal spot gaugings in the study reach during June and September of 2001. A combination of ADCP and electromagnetic technology was used to measure flow. Measured flows and the contributional change in flow during this study are dealt with in the section entitled *Spatial Pattern of Low Flow*. Below we describe a solution to model water heights and pool attributes in the 73.7 km stretch from Claravale Crossing to Cattle Creek under various flow regimes – 10%, 20% …. 90% reduction in flow from June-01.

It is inappropriate to simply remove 10% of the flows from each control point, because the relationship between flow at Clarivale and flow at Oolloo is linear but does not pass through the origin – it is not a simple proportional relationship. Taking 10% off the flow at each control point breaks this relationship, and this becomes apparent at the extremes for extraction when the flows at Claravale and Oolloo are no longer in sync.

F_o Flow at Oolloo in year of study

F_c Flow at Clarivale in year of study

α Intercept for relationship between F_o and F_c

b Slope of relationship between Fo and F_c

r percentage reduction in flow at Oolloo Crossing

δ_r reduction in flow at Oolloo in cumecs for reduction r%

Let $F_c = a + bF_o$

Reduce flow at Oolloo by δ_r cumecs so that

$$F_o^{'} = F_o - d_r$$

$$F_c^{'} = a + bF_o^{'} = F_c - b d_r$$

So a reduction of δ_r cumecs at Oolloo will correspond to a reduction of $\beta\delta_r$ cumecs at Clarivale. The drop in flow from Clarivale to Oolloo after a reduction of r% at Ooloo will be

$$\Delta r = F_o^{'} - F_c^{'} = F_o - d_r - (F_c - b d_r)$$

Take two adjacent control points. Reduction in flow between the two in 2001 was observed to be D_o , then its reduction inflow after r% is given by

$$D_r = \frac{D_o}{\Delta_o}\Delta_r$$

These incremental reductions can be applied from Clarivale to Cattle Creek, in the knowledge that the flow at Oolloo will correspond to a reduction of r%. Results of this analysis are shown in (Table 5).

Table 5. Locations where flow changed in the Daly River between Claravale Crossing and Cattle Creek. Change in flow at June-01 are measured whereas flows between 10% and 90% are estimated based on the calculations above.

Distance (km)	Jun-01	10%	20%	30%	40%	50%	60%	70%	80%	90%
0.00	27.4	24.6	21.8	18.9	16.1	13.3	10.5	7.6	4.8	2.0
5.33	28.1	25.2	22.3	19.4	16.5	13.6	10.8	7.9	5.0	2.1
11.15	29.2	26.2	23.2	20.2	17.2	14.2	11.2	8.2	5.2	2.3
22.63	29.6	26.6	23.6	20.5	17.5	14.5	11.4	8.4	5.4	2.3
24.39	29.2	26.2	23.3	20.2	17.3	14.3	11.3	8.3	5.3	2.3
25.64	30.1	27.0	23.9	20.9	17.8	14.7	11.6	8.6	5.5	2.4
33.38	38.2	34.4	30.5	26.7	22.8	19.0	15.2	11.3	7.5	3.6
46.69	38.4	34.5	30.7	26.8	22.9	19.1	15.2	11.4	7.5	3.7
54.17	39.7	35.7	31.8	27.8	23.8	19.8	15.8	11.8	7.9	3.9

55.91	40.9	36.8	32.7	28.6	24.5	20.4	16.3	12.2	8.1	4.0
66.96	41.5	37.4	33.2	29.1	24.9	20.8	16.6	12.5	8.3	4.2
73.27	42.4	38.2	33.9	29.7	25.5	21.2	17.0	12.8	8.5	4.3

Definitional Issues

We define breakpoints as points in the river, which would restrict movement of pig-nosed turtles along the longitudinal continuum of the Daly River. A break point occurs when maximum water depth for the transverse profile, taken immediately above the control point, drops below 50 cm. Each pair of break points defines an intervening pool. We categorised these pools based on length into

1. Unsubstantial – $L < 300$ m; not substantial enough to contribute to the persistence of turtles in the region. These were few and were eliminated from analysis.
2. Small – $0.3 < L \le 2.5$ km
3. Intermediate -- ($2.5 < L \le 7$km)
4. Large -- ($7 < L < 20$ km)
5. Very Large/Continuous – $L > 20$ km

Flow increments for the modelling are based on 10 percentile reductions from the June flow for 2000 down to the base flow of 2 cumecs (the smallest observed flow in the historical data set). These increments will for convenience be referred to as Base Flow (90% reduction), 80% reduction, 70% reduction etc to 0% reduction (observed June flow).

Flow and Fragmentation

Base Flow (90% reduction) (2.0 cumecs)

Under *Extreme Low* flow conditions (2.0 cumecs of flow entering at Dorisvale Crossing), 34 breaks occur in the Daly River between Claravale Crossing and Cattle Creek (Table 6). This translates into one break point for every 2.16 km of river.

Under base low flow conditions (2.0 cumecs), the 34 break points identified above produce 33 pools in the Daly River, between Claravale Crossing and Cattle Creek, none of which were less than 300 m in length. Notably there were no large or very large pools at base flow conditions. There were 26 small pools (79%) and 7 intermediate pools (21%). Under base flow conditions 79% of the pools formed were small (Figure 19 & 20) and 49.5% (36.6 km) of the study reach would be fragmented into small pools.

Table 6. Location of breakpoints on the Daly River under modelled flow conditions. Upstream flow was 2.0 cumecs at Claravale Crossing and downstream flow was 4.3 cumecs at Cattle Creek. Breakpoints refer to sections of the river that would inhibit movement of pig-nosed turtles (<0.5 m).

Landmark	Distance (km)	Easting	Northing	Pool length (km)
Cp1 “Dorisvale”	0.00	775734	8410582	0.00
Riffle	1.23	775456	8411762	1.23
Cp2	5.16	773627	8413264	3.93
Cp3	9.16	770965	8415100	4.00
Cp4	11.15	769734	8416517	1.99
Cp5	13.20	767888	8416689	2.05
Cp7	13.82	767513	8417064	0.62
Riffle	15.75	765960	8418028	1.93
Riffle	16.47	765700	8418696	0.72
Riffle	18.21	764677	8420100	1.74
Cp9	23.34	762176	8423356	5.13
Cp10 “H springs”	24.39	761242	8423735	1.05
Cp12	25.64	760962	8424597	1.24
Riffle	27.75	761403	8426498	2.12
Riffle	28.81	761505	8427552	1.06
Cp13	31.12	760673	8429515	2.31
Cp15 “B B yard”	33.38	758756	8430438	2.26
Riffle	36.40	755766	8430600	3.02
Riffle	37.20	755268	8431198	0.81
Riffle	39.52	755051	8433240	2.32
Cp17	43.62	751885	8433540	4.10
Cp18	44.87	750816	8432984	1.24
Cp19	46.69	749665	8431792	1.82
Cp20	48.62	749081	8433494	1.93
Cp21	53.16	748556	8437714	4.54
Cp22	54.17	747717	8437410	1.01
Riffle	55.22	747206	8436732	1.05
Cp23 “Jinduckin”	55.91	746875	8437186	0.69
Riffle	57.04	746877	8438200	1.13
Riffle	58.23	746689	8439018	1.20
Old Oolloo Xing	64.34	742564	8441492	6.10
Cp25 Oolloo Xing	66.96	743191	8443228	2.62
Riffle	70.00	740606	8443290	2.42
Cp26 “Cattle ck”	73.27	738867	8445392	3.27

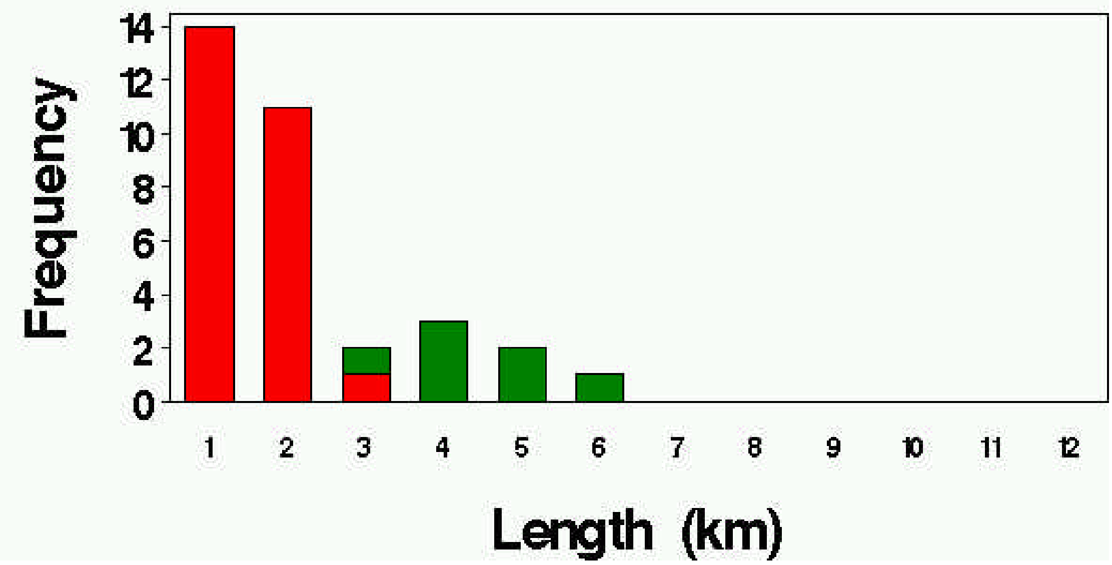


Figure 19. Frequency of occurrence of the three pool length categories under extreme low flow conditions in the Daly River, Northern Territory. Red bars represent small pools (0 – 2.5 km) and green bars represent intermediate pools (2.6 – 7.0 km). There were no large pools (>7.1km) under this flow regime.

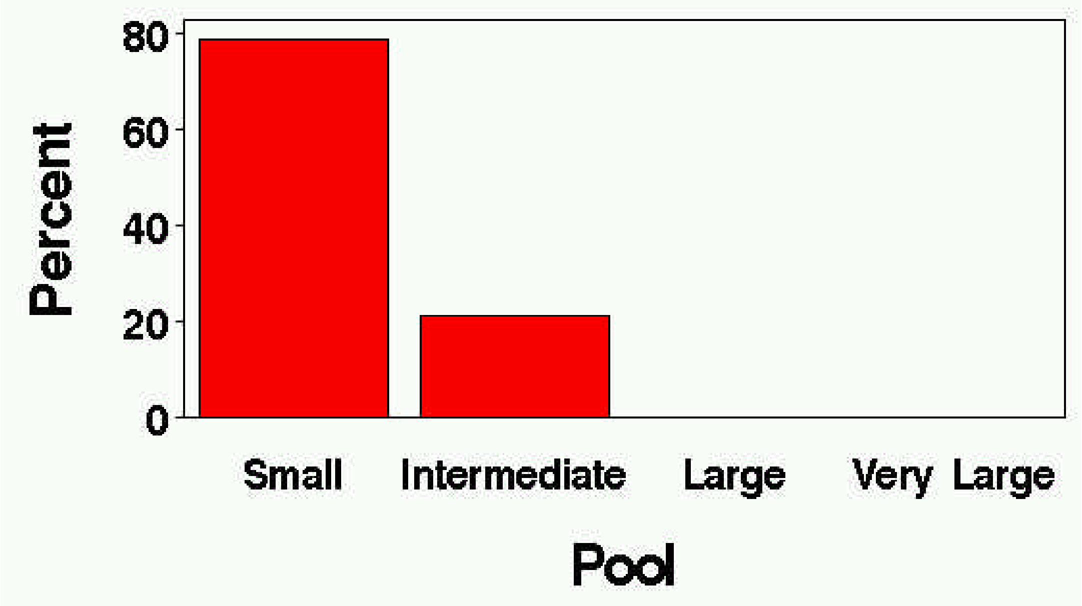


Figure 20. Percent of the Daly River that fragmented into small, intermediate and large pool length categories. Over 75% percent of the Daly River, fragmented into pools, which were less than 2.5km long. The remaining sections of river fragment into pools, which range in length between 2.6km and 7km.

The largest pool under Extreme Low flow conditions (6.1 km) extends from behind Old Oolloo crossing to Neils Rapids (*ca* 1 km below Jinduckin Creek). The next largest pool (5.1 km) extends from behind control point 9. These two pools are separated by 13.8 km of river and are likely to be the main refuges for riverine biota under extreme low flow conditions. The smallest substantial pool (622 m) extends from control point 7 to control point 5.

The overall mean maximum channel depth, flow cross-sectional area, top width and wetted cross-sectional perimeter for the study site was 1.5 m, 64 m^2, 55 m, and 55 m respectively. Corresponding morphology for each of the two-pool size classes are presented in Table 7. Apart from length, their profiles were very similar, a reflection of the relatively common morphology of the Daly River across the study site.

Table 7. Morphological parameters for pools among 2 size classes. Means are given with standard deviations.

Size Class	Length (m)	Flow area (m^2)	Top width (m)	Wetted perimeter (m)	Maximum depth (m)
Small	1507 ± 632 (622-2617) N=26	64.8 ± 21.3 (17.8-106.0) N=26	55.3 ± 4.5 (42.8-62.7) N=26	55.7± 4.6 (42.9-63) N=26	1.5 ± 0.4 (0.7-2.2) N=26
Intermediate	4404±985 (3020-6104) N=7	63.1±19.3 (34.3-86.8) N=7	55.2±3.5 (50.4-59.8) N=7	55.6±3.5 (50.7-60.3) N=7	1.5±0.3 (1.0-1.9) N=7

There were no significant differences (as demonstrated by ANOVA) in flow area, top width, wetted perimeter, and maximum depth between the two size classes. Pool length was the only factor that separated the pools into class. Furthermore, there was no correlation between pool length and any other morphological parameter. Pools shared similar morphological parameters independent of length.

80% Reduction (4.8 cumecs)

When 4.8 cumecs of flow entering at Dorisvale Crossing, 20 breaks occur in the Daly River between Claravale Crossing and Cattle Creek (Table 8). This translates into one break point for every 3.68 km of river.

Table 8. Location of breakpoints on the Daly River under modelled flow conditions. Upstream flow was 4.8 cumecs at Claravale Crossing and downstream flow was 8.5 cumecs at Cattle Creek. Breakpoints refer to sections of the river that would inhibit movement of pig-nosed turtles (<0.5 m).

Landmark	Distance (km)	Easting	Northing	Pool length (km)
Cp1 “Dorisvale”	0.00	775734	8410582	0.00
Cp3	9.16	770965	8415100	9.16
Cp4	11.17	769734	8416517	2.01
Cp5	13.20	767888	8416689	2.03
Riffle	16.54	765700	8418696	3.34
Riffle	18.29	764677	8420100	1.75
Cp10 “H springs”	24.39	761242	8423735	6.11
Cp12	25.96	760962	8424597	1.56
Cp13	31.12	760673	8429515	5.16
Cp14	32.33	759623	8429728	1.21
Cp15 “B B yard”	33.38	758756	8430438	1.05
Cp17	43.62	751885	8433540	10.25
Cp18	44.87	750816	8432984	1.24
Cp19	46.67	749665	8431792	1.80
Cp20	48.62	749081	8433494	1.95
Cp21	53.16	748556	8437714	4.54
Cp22	54.17	747717	8437410	1.01
Cp23 “Jinduckin”	55.91	746875	8437186	1.74
Cp25 Oolloo Xing	66.98	743191	8443228	11.07
Cp26 “Cattle ck”	73.27	738867	8445392	6.29

Under this flow regime (4.8 cumecs), the 20 break points identified above produce 19 pools in the Daly River, between Claravale Crossing and Cattle Creek. Notably there were no very large pools. There were 11 small pools (58%), 5 intermediate pools (26%) and 3 large pools (16%) (Figures 21 & 22). Under these flow conditions, 23.5% (17.3 km) of the study reach would be fragmented into small pools, 34.5% (25.4 km) would be fragmented into intermediate pools and 41.4% (30.5 km) would be fragmented into large pools.

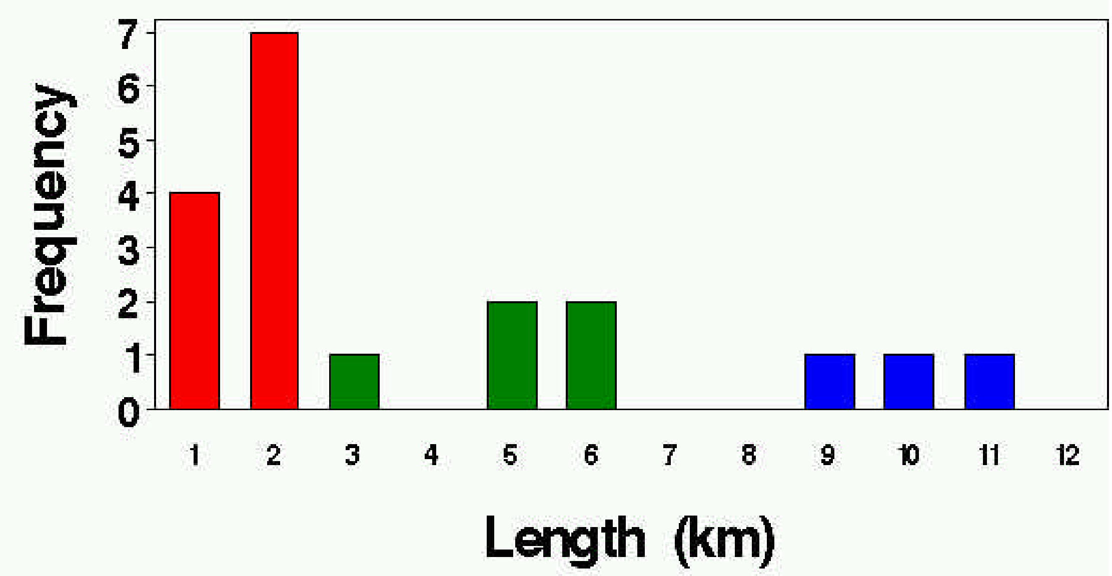


Figure 21. Frequency of occurrence of the five pool length categories under simulated flow conditions in the Daly River, Northern Territory. Red bars represent small pools, green bars represent intermediate pools and blue bars represent large pools.

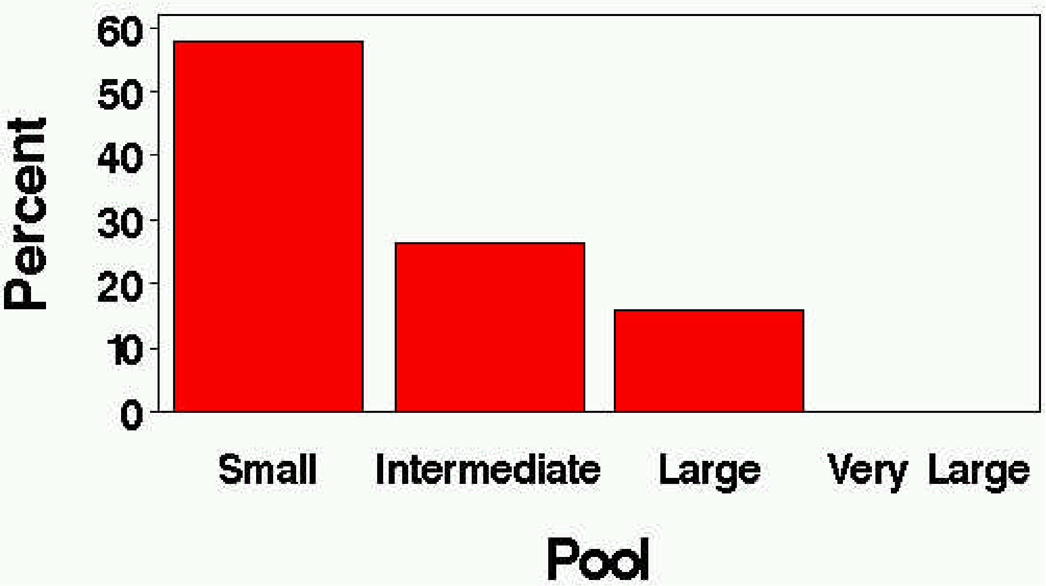


Figure 22. Percent of the Daly River that fragmented into small, intermediate and large pool length categories. Over 57% percent of the Daly River, fragmented into pools, which were less than 2.5km long.

The largest pool (11.1 km) under this Low flow condition extends from behind Oolloo crossing to Jinduckin Creek. The next largest pool (10.2 km) extends from behind control point 17 to control point 15. These two pools are separated by 12.2 km of river. The third largest pool (9.2) is the furthest upstream pool and it extended from behind control point 3 to Claravale Crossing and is 24.2 km upstream from the second largest pool. These three pools are likely to be the main refuges for riverine biota under extreme low flow conditions. The smallest substantial pool (1.0 km) extends from control point 22 to control point 21.

The corresponding morphology for each of the three pool size classes is presented in Table 2. Apart from length, their profiles were very similar, a reflection of the relatively common morphology of the river across the study site.

Table 9. Morphological parameters for pools among 3 pool size classes. Means are given with standard deviations.

Size Class	Length (m)	Flow area (m^2)	Top width (m)	Wetted perimeter (m)	Maximum depth (m)
Small	1.6±0.4 (1.0-2.0) N=11	75.5±20.5 (43.8-113.2) N=11	58.0±3.0 (53.5-62.7) N=11	58.5±3.1 (53.8-63.0) N=11	1.7±0.3 (1.2-2.3) N=11
Intermediate	5.1±1.2 (3.3-6.3) N=5	83.3±17.2 (58.3-100.8) N=5	59.5±2.2 (55.7-61.2) N=5	60.0±2.3 (56.0-61.6) N=5	1.8±0.3 (1.4-2.1) N=5
Large	10.2±1.0 (9.2-11.1) N=3	81.6±11.6 (68.7-91.3) N=3	59.4±1.5 (57.8-60.8) N=3	59.8±1.6 (58.1-61.3) N=3	1.8±0.2 (1.6-2.0) N=3

70% Reduction (7.6 cumecs)

When 7.6 cumecs of flow occurs at Dorisvale Gauging Station, 12 breaks occur in the Daly River between Claravale Crossing and Cattle Creek (Table 10). This translates into one break point for every 6.14 km of river.

Table 10. Location of breakpoints on the Daly River under modelled flow conditions. Upstream flow was 7.6 cumecs at Claravale Crossing and downstream flow was 12.8 cumecs at Cattle Creek. Breakpoints refer to sections of the river that would inhibit movement of pig-nosed turtles (<0.5 m).

Landmark	Distance (km)	Easting	Northing	Pool length (km)
Cp1 “Dorisvale”	0.00	775734	8410582	0.00
Cp3	9.46	770965	8415100	9.46
Cp4	11.17	769734	8416517	1.71
Cp5	13.20	767888	8416689	2.03
Riffle	16.54	765700	8418696	3.34
Cp15 “B B yard”	33.38	758756	8430438	16.84
Cp17	43.62	751885	8433540	10.25
Cp18	44.87	750816	8432984	1.24
Cp19	46.67	749665	8431792	1.80
Cp20	48.62	749081	8433494	1.95
Cp22	54.17	747717	8437410	5.55
Cp23 “Jinduckin”	55.91	746875	8437186	1.74
*Cp26	73.27	738867	8445392	>17.80

*Maximum depth greater than 0.5m

Under these flow conditions (7.6 cumecs), the 12 break points identified above produce 11 pools in the Daly River, between Claravale Crossing and Cattle Creek. Notably there were no very large pools. There were 6 small pools (55%), 2 intermediate pools (18%) and 3 large pools (27%) (Figures 23 & 24). Under these flow conditions 14.2% (10.5 km) of the study reach would be fragmented into small pools, 12.1% (8.9 km) would be fragmented into intermediate pools and 49.5% (36.5 km) would be fragmented into large pools. There were no breakpoints between Jinduckin Creek and Cattle Creek leaving 17.8km of continuous river at the bottom end of our study area.

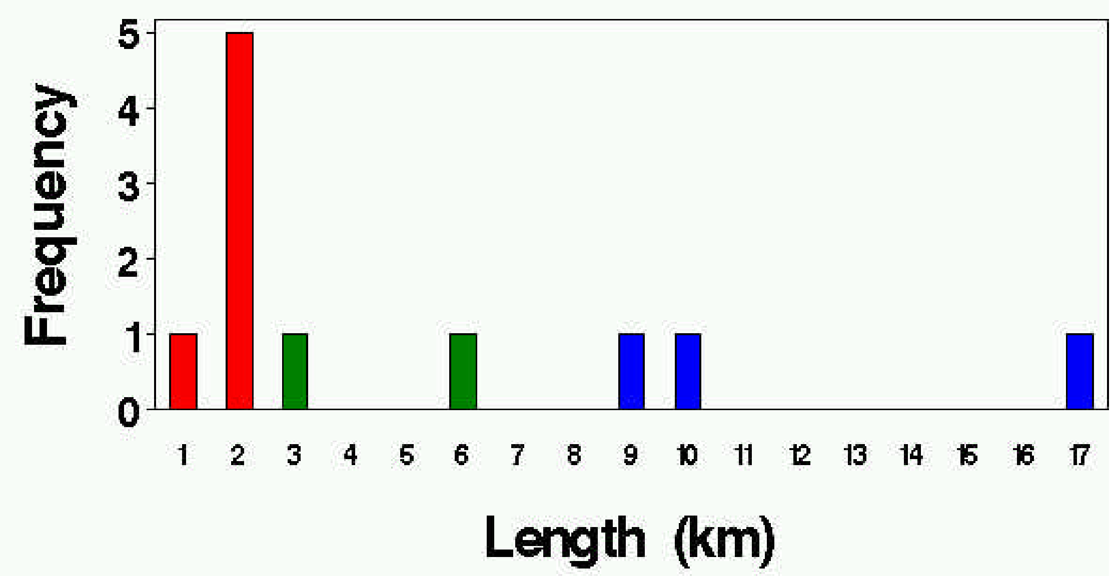


Figure 23. Frequency of occurrence of the five pool length categories under simulated flow conditions in the Daly River, Northern Territory. Red bars represent small pools, green bars represent intermediate pools and blue bars represent large pools.

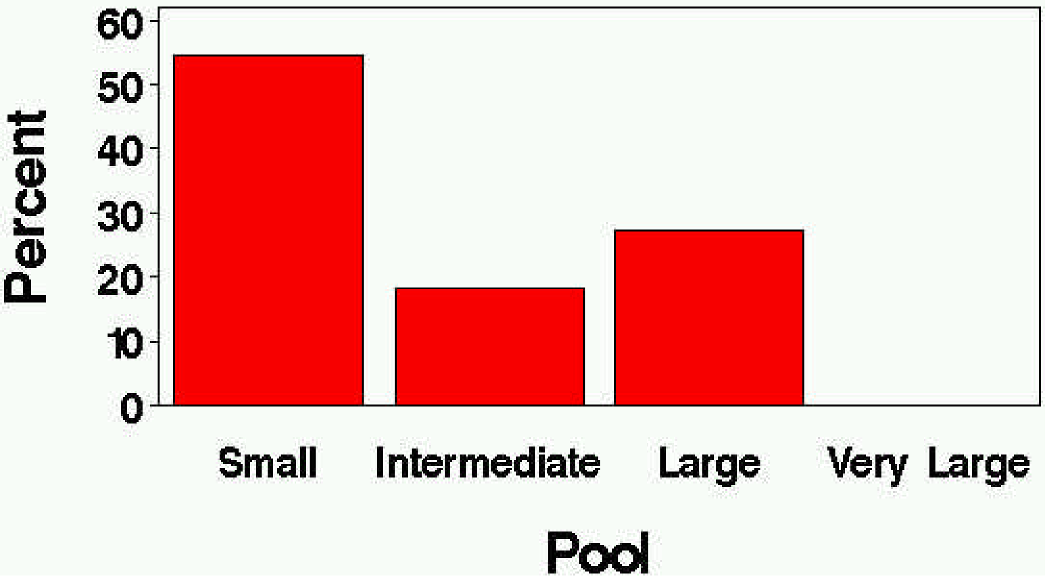


Figure 24. Percent of the Daly River that fragmented into small, intermediate and large pool length categories. Only 14% percent of the Daly River, fragmented into pools, which were less than 2.5km long.

The largest pool under this Low flow condition (16.8 km) extends from behind control point 15. The next largest pool (10.2 km) extends from behind control point 17 to control point 15. These two pools are separated only by the shallow depth at control point 15 km. The third largest pool (9.5) is the furthest upstream pool and it extended from behind control point 3 to Claravale Crossing and is 24.2 km upstream from the second largest pool. These three pools and the continuous section of river below Jinduckin Creek are likely to be the main refuges for riverine biota under extreme low flow conditions. The smallest substantial pool (1.2 km) extends from control point 18 to control point 19.

The corresponding morphology for each of the three pool size classes are presented in Table 11. Apart from length, their profiles were very similar, a reflection of the relatively common morphology of the river across the study site.

Table 11. Morphological parameters for pools among 3 pool size classes. Means are given with standard deviations.

Size Class	Length (m)	Flow area (m^2)	Top width (m)	Wetted perimeter (m)	Maximum depth (m)
Small	1.7±0.3 (1.2-2.0) N=6	98.3±21.5 (76.6-135.5) N=6	60.7±1.3 (59.1-62.4) N=6	61.4±1.4 (59.7-63.0) N=6	2.1±0.3 (1.8-2.7) N=6
Intermediate	4.4±1.6 (3.3-5.6) N=2	84.3±3.1 (82.1-86.5) N=2	61.0±0.4 (60.7-61.3) N=2	61.5±0.3 (61.3-61.7) N=2	1.9±0.1 (1.8-1.9) N=2
Large	12.2±4.1 (9.5-16.8) N=3	83.7±10.4 (73.4-94.1) N=3	59.8±1.1 (58.8-61.0) N=3	60.3±1.2 (59.2-61.5) N=3	1.8±0.2 (1.7-2.0) N=3

60% Reduction (10.5 cumecs)

When 10.5 cumecs occur at Dorisvale Gauging Station, 7 breaks occur in the Daly River between Claravale Crossing and Cattle Creek (Table 12). This translates into one break point for every 10.53 km of river.

Table 12. Location of breakpoints on the Daly River under modelled flow conditions. Upstream flow was 10.5 cumecs at Claravale Crossing and downstream flow was 17.0 cumecs at Cattle Creek. Breakpoints refer to sections of the river that would inhibit movement of pig-nosed turtles (<0.5 m).

Landmark	Distance (km)	Easting	Northing	Pool length (km)
Cp1 “Dorisvale”	0.00	775734	8410582	0.00
Cp3	9.46	770965	8415100	9.46
Cp4	11.17	769734	8416517	1.71
Cp5	13.20	767888	8416689	2.03
Cp18	44.87	750816	8432984	31.67
Cp19	46.67	749665	8431792	1.80
Cp22	54.17	747717	8437410	7.50
*Cp26	73.70	738867	8445392	>19.54

*Maximum depth greater than 0.5m

Under this flow condition (10.5 cumecs), the 7 break points identified above produce 6 pools in the Daly River, between Claravale Crossing and Cattle Creek. There were 3 small pools (50%), no intermediate pools, 2 large pools (33%) and 1 very large pool (17%) (Figures 25 & 26). Under these flow conditions 7.5% (5.5 km) of the study reach would be fragmented into small pools, 23% (17.0 km) would be fragmented into large pools and 69% (51.2 km) would be fragmented into very large/continuous pools.

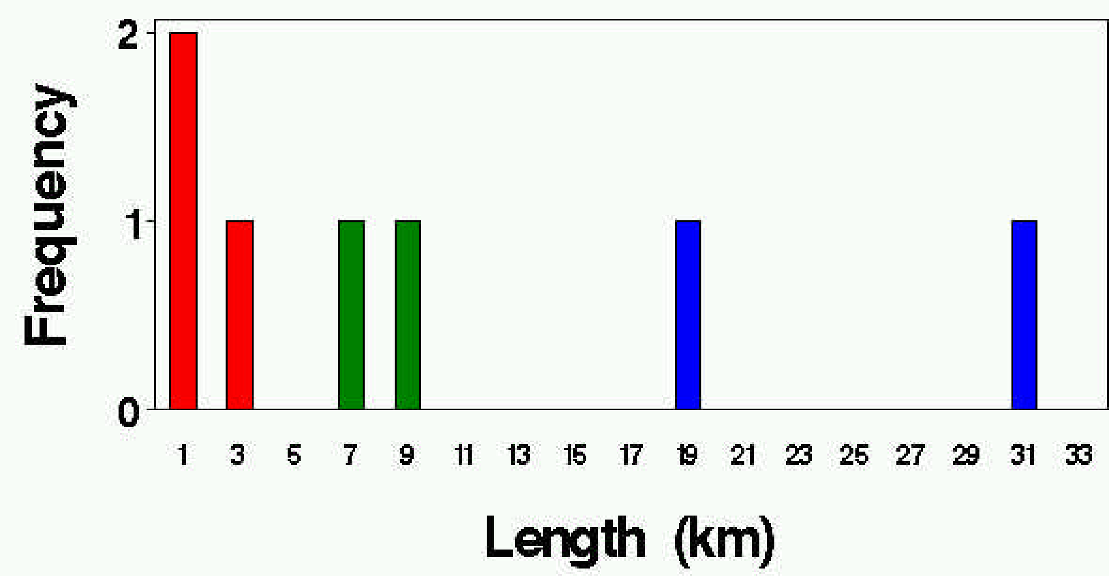


Figure 25. Frequency of occurrence of the five pool length categories under simulated flow conditions in the Daly River, Northern Territory. Red bars represent small pools, green bars represent intermediate pools and blue bars represent large pools.

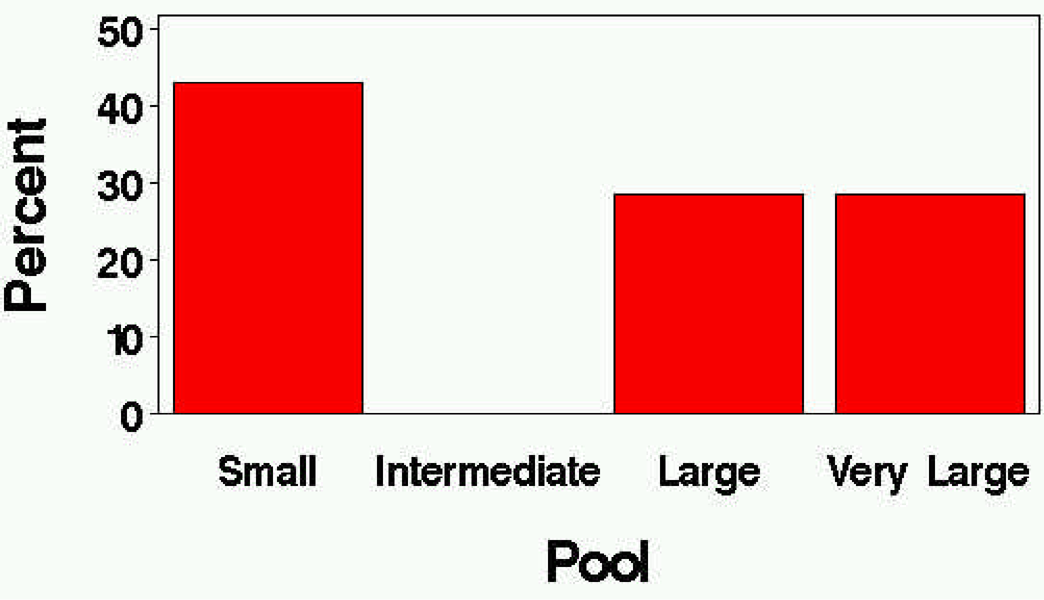


Figure 26. Percent of the Daly River that fragmented into small, intermediate and large pool length categories. Only 7.5% percent of the Daly River fragmented into pools less than 2.5km long.

The largest pool under this Low flow condition (31.7 km) extends from behind control point 18 to control point 5. The next largest pool (20.0 km) extends from behind control point 26 “Cattle Creek” to Control point 22, but this is continuous. The third largest pool (9.5) is the furthest upstream pool and it extended from behind control point 3 to Dorisvale crossing. The smallest substantial pool (1.7 km) extends from control point 3 to control point 4.

The corresponding morphology for each of the three pool size classes are presented in Table 13. Apart from length, their profiles were very similar, a reflection of the relatively common morphology of the river across the study site.

Table 13. Morphological parameters for pools among 3 pool size classes. Means are presented with standard deviations.

Size Class	Length (m)	Flow area (m^2)	Top width (m)	Wetted perimeter (m)	Maximum depth (m)
Small	1.8±0.2 (1.7-2.0) N=3	108.6± 29.8 (83.3-141.5) N=3	61.8±1.4 (60.4-63.2) N=3	62.5±1.5 (60.9-63.8) N=3	2.3±0.5 (1.9-2.8) N=3
Large	8.5±1.4 (7.5-9.5) N=2	87.3±12.0 (78.8-95.7) N=2	61.0±1.6 (59.8-62.1) N=2	61.5±1.7 (60.3-62.7) N=2	1.9±0.1 (1.8-2.0) N=2
Very Large	25.6±8.6 (19.5-31.7) N=2	98.7±7.3 (93.5-103.8) N=2	61.5±0.6 (61.1-61.9) N=2	62.1±0.7 (61.6-62.6) N=2	2.1±0.1 (2.0-2.2) N=2

50% Reduction (13.3 cumecs)

When 13.3 cumecs of flow occurs at Dorisvale Gauging Station, 3 breaks occur in the Daly River between Claravale Crossing and Cattle Creek (Table 14). This translates into one break point for every 24.56 km of river.

Table 14. Location of breakpoints on the Daly River under modelled flow conditions. Upstream flow was 13.3 cumecs at Claravale Crossing and downstream flow was 21.2 cumecs at Cattle Creek. Breakpoints refer to sections of the river that would inhibit movement of pig-nosed turtles (<0.5 m).

Landmark	Distance (km)	Easting	Northing	Pool length (km)
Cp1 "Dorisvale"	0.00	775734	8410582	
Cp3	9.16	770965	8415100	>9.46
Cp4	11.15	769734	8416517	1.80
Cp19	46.69	749665	8431792	35.50
Cp22	54.17	747717	8437410	7.50
Cp26	73.70	738867	8445392	>19.54

Under this flow condition (13.3 cumecs), the 4 break points identified above produce 3 pools in the Daly River, between Claravale Crossing and Cattle Creek. There was one small pool (33.3%), no intermediate pools, 1 large pool (33.3%) and 1 very large pool (33.3%). Under this flow condition only 2.4% (1.8 km) of the study reach would be fragmented into small pools.

Flows at or above 40% Reduction (>16.1 cumecs)

The maximum depth of all our identified breakpoints exceeded 0.5 m at flows, which were above 16.1 cumecs at Claravale Crossing (Table 15). Under these elevated flow conditions pig-nosed turtles would be able to move freely without impediment throughout the study reach (Table 15).

The maximum length of the study reach was 73.7 km. The maximum and average depths of the river channel slightly increased as flow increased (Table 1) and the flow area, top width and wetted perimeter all decreased as flow decreased (Table 1). However, these differences were not significant.

Table 15. Morphological parameters for the Daly River under five different flow conditions.

Flow (km)	Length (m)	Flow area (m^2)	Top width (m)	Wetted perimeter (m)	Max channel depth (m)	Average depth (m)
27.4	73.7	124.8±50.0 (13.1-268.2)	64.6±7.9 (15.7-148.8)	65.4±8.2 (16.1-149.7)	2.5±0.8 (0.6-4.3)	1.9±0.7 (0.3-3.4)
24.6	73.7	120.9±49.5 (12.1-257.8)	64.2±7.9 (15.2-146.5)	65.0±8.1 (15.6-147.4)	2.5±0.8 (0.6-4.2)	1.8±0.7 (0.3-3.4)
21.8	73.7	116.5±49.3 (11.3-245.1)	63.8±7.9 (14.5-144.2)	64.5±8.2 (14.8-145.0)	2.4±0.8 (0.6-4.2)	1.8±0.7 (0.3-3.4)
18.9	73.7	112.1±48.9 (10.1-235.5)	63.3±8.0 (13.7-141.4)	64.0±8.2 (14.1-142.0)	2.3±0.8 (0.6-4.2)	1.7±0.7 (0.2-3.3)
16.1	73.7	107.6±48.4 (9.2-229.5)	62.8±8.0 (12.9-137.4)	63.5±8.3 (13.2-137.9)	2.2±0.8 (0.5-4.1)	1.7±0.7 (0.2-3.2)

Natural Regime and Fragmentation

The magnitude of the flow at any given time is a measure of the availability or suitability of habitat and defines such river habitat attributes as pool length (space available for movement), emergent vegetation rooting zones (feeding grounds) and reproductive zones (nesting bank locations). In this study we have shown that there is a clear correlation between the percent of suitable habitat through river connectivity (i.e. number of pools) and flow (Figure 1). Hence, how often our simulated flow events occurred in a historical context (based on 40 years of gauged data) provides insight into how frequently turtle life history would have been compromised historically (Table 16).

Base flow conditions where Q is less than 2.0 cumecs occurred infrequently (2.5% or 1 year out of 40). In contrast, *extreme low flows* (i.e. less than 3.0 cumecs) occurred on 27.5% of years and *low flows* (i.e. <10cumecs) occurred more frequently (95% of years). Increasing the frequency of occurrence of extreme low flow events would compromise turtle life history through limited access to resources, which are essential for reproduction (e.g. nesting banks) and feeding (e.g. *Vallisineria* meadows).

Table 16. The frequency of occurrence of minimum flows in our 14 flow increments against years at the Dorisvale gauging station (G8140067), Daly River, Northern Territory. N=40years.

Class	Number of Years	Percent of Years	Cumulative frequency	Cumulative percent
$Q < 2.0$	1	2.5	1	2.5
$2.0 < Q \leq 2.5$	4	10	5	12.5
$2.5 < Q \leq 3.0$	6	15	11	27.5
$3.0 < Q \leq 3.5$	4	10	15	37.5
$3.5 < Q \leq 4.0$	6	15	21	52.5
$4.0 < Q \leq 4.8$	7	17.5	28	70
$4.8 < Q \leq 7.6$	9	22.5	37	92.5
$7.6 < Q \leq 10.5$	1	2.5	38	95
$10.5 < Q \leq 13.3$	0	0	38	95
$13.3 < Q \leq 16.1$	0	0	38	95
$16.1 < Q \leq 18.9$	2	5	40	100
$18.9 < Q \leq 21.2$	0	0	40	100
$21.2 < Q \leq 24.6$	0	0	40	100

24.6 < Q ≤ 27.4	0	0	40	100

Water Temperature versus Flow

General Approach

A model has been developed to simulate water temperatures in the Daly River between Claravale and Cattle Creek as they respond to changes in weather, water depth and flow. The purpose of the model is to allow estimation of the potential impact on riverine water temperatures of changes in river flow due to irrigation extraction. The model includes a series of meteorological factors that increase or decrease water temperatures. The water in the river is warmed due to the input of solar radiation and infrared emission from the sky to the water surface. It is cooled by evaporation, by conduction between the air and the water (if the water is warmer than the air) and by thermal infrared emission from the water surface to the sky. The model also includes an input of warm spring water into the river between Claravale and Jinduckin Creek.

A measurement program was instigated to obtain the data necessary to support the model application. Measurements most suitable for model application and calibration were obtained for a 6-day period in July 2000 and for a second 12-day period in September of the same year. In this year, a meteorological station was established in the river to allow estimation of the exchange of heat between the river and the atmosphere. Also, precision water temperature measurements were made at four sites along the river (Claravale, Jinduckin Creek, Oolloo, Cattle Creek) to provide data needed to calibrate and test the model. In 2001, we were able to use measurements obtained during a 58-day measurement period extending from the middle of June to the middle of September. For this period, meteorological measurements were obtained at a station near the river and water temperatures were measured at Claravale, Jinduckin Creek, and Cattle Creek Due to the much longer data record in 2002, most of our analysis was undertaken for this year so the model development and application is described in this context in the following.

Stratification

To test for the possibility that the Daly River may stratify if flows were reduced, we established two depth profiles in Ruby Billabong (Figure 27), a billabong formed in a former channel of the Daly River, with zero flow but water characteristics otherwise similar to that in the river itself. The billabong was full to bank height, and so was of greater depth than water in the river.

The profiles showed that stratification did not occur until a depth of 5.0 m (Figure 28), and even at that depth, a surface influence was evident depending upon wind strength. As the maximum dry season pool depth observed in the river was 4.28 m (flow 27.4 cumecs). It was therefore considered reasonable to eliminate the possibility of stratification from our temperature calculations for even zero flow scenarios.

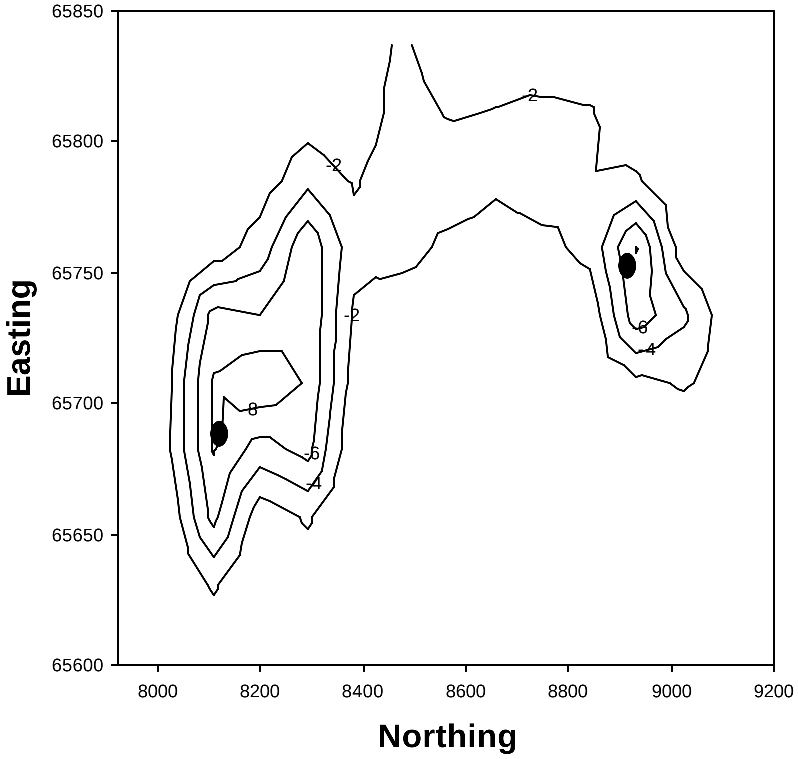


Figure 27. Contour map for Ruby Billabong showing the two locations (•) where the thermal profiles were measured. Temperatures were recorded at 10 cm, 50 cm, 1 m, 2 m, 3 m, 5 m, 7 m.

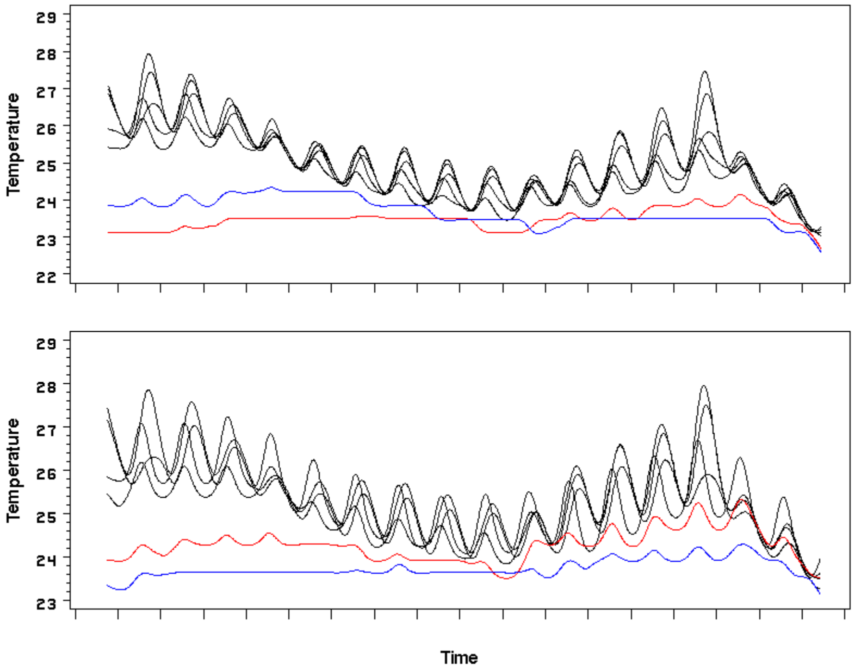


Figure 28. Temperature profiles for two sites in Ruby Billabong, on common land adjacent to the Douglas-Daly Research Farm. The black traces are for depths of 0.1, 0.5, 1.0, 2.0, 3.0 and 4.0 m; red – 5 m; blue – 7 m. July 2000. Stratification occurs at 5 m, but with a surface influence evident on the windier (hotter) days.

The Thermal Model

Model Formulation

The model describes the transport of heat downstream by the river flow. The equation to be solved is:

$$\frac{\partial T}{\partial t} + U\frac{\partial T}{\partial x} = \frac{F}{\rho C_p D} \qquad (1)$$

where T is river water temperature which is a function of distance along the river, x, and of time, t. U is the river flow speed, ρ is water density, C_p, is the specific heat of water, D is water depth, and F is the flux of heat across the water surface due to evaporation, solar radiation etc. The estimation of F is discussed later. The model allows for the injection of spring water at position x_{spring} with a flow volume of Q_{spring} and of temperature T_{spring} (Fig. 29). In fact, there are discharges all the way along the river channel from springs and creeks, (Tickell, 2002), but the largest input accounting for ~65% of the total input between Claravale and Cattle Creek occurs in the 10km section between river distances $x = 24$ to 33km. We assume that all the spring water is input to the river at the average distance x = 29km and that discharges above and below this distance are uniform along the river.

The solution to Eq. 1 was obtained numerically for the river section between Claravale and the spring using an upwind differencing scheme (Roache, 1982). The initial condition required for solution in this river section was the temperature linearly interpolated between Claravale and Jinduckin Creek. Temperatures at the input end of the section (Claravale) were those measured at this site.

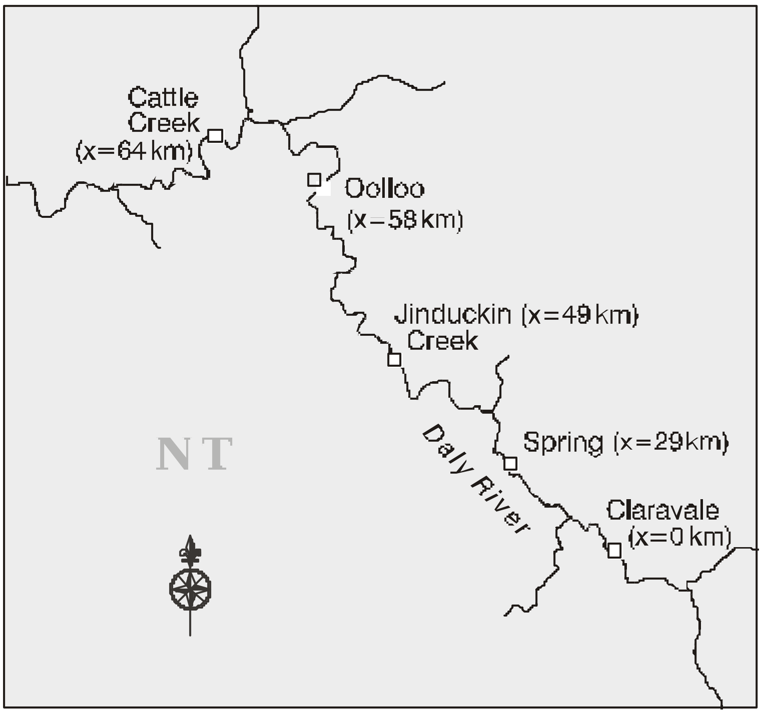


Figure 29. Location map for the river temperature measurement sites and the spring. The Daly River flows approximately towards the northwest.

At the spring, warm water is discharged into the river causing a change in the river water temperature. Suppose $T_{upstream}$ is the modelled temperature in the river upstream from the spring and $T_{downstream}$ is the river temperature immediately downstream from the spring, then:

$$T_{downstream} = \frac{T_{upstream} Q_u + T_{spring} Q_{spring}}{Q_u + Q_{spring}} \qquad (2)$$

where Q_u is the flow in the river upstream from the spring. We calculate the downstream flow speed as:

$$U = \frac{Q_u + Q_{spring}}{WD} \qquad (3)$$

where W is the river width. $T_{upstream}$, as calculated from Eq. 2, was specified as the river temperature just downstream from the spring. The model solution between the spring and Jinduckin Creek and Cattle Creek was integrated with time and distance in the same way as it was for the river section between Claravale and the spring. As in the upstream section, the initial water temperatures specified for the model in the river section downstream from the spring were obtained as linear interpolations of measured temperatures.

The model requires the specification of W and D as a function of river discharge. For model application we divided the river up into three sections each with uniform W and D. These sections were Claravale to the spring, the spring to Jinduckin Creek, and Jinduckin Creek to Cattle Creek. The relationships between discharge, W, and D in each section were determined by applying the hydrology model developed in HECRAS to measured river cross sections and discharges. The river between Claravale and Cattle Creek consists of a series of pools connected by riffle zones and the hydrology model was capable of resolving these. The time spent by a water parcel within a short river section is inversely proportional to the local cross-sectional area of the river channel. Accordingly, the average W and D for each river section were calculated using local cross-sectional area as a weighting function.

Energy Fluxes in the Model

The energy flux F in Eq. 1 has a number of components which are:

R_{SW} - The (downwards) shortwave radiation from the sun.

R_{LWE} - The (upwards) longwave emission from the water surface.

R_{LWS} - The (downwards) longwave emission from the sky.

LE - The latent heat loss from the water surface by evaporation.

H – The rate of sensible heat exchange between the water surface and the air.

These are evaluated as follows:

R_{SW}

The shortwave radiation from the sun was estimated from the PAR measurements made at the meteorological station at Ruby Billabong adjacent to Douglas Daly Research Farm. Strictly speaking, PAR represents the photon flux at the wavelengths of photosynthesis which do not cover the whole of the visible wavelength band, whereas we require a measure of the energy flux from the sun which occurs mostly in the visible wavelength band. We assume that R_{SW} is proportional to measured PAR. The proportionality constant was calculated using the assumption that the surface radiative flux under a pure, clear sky with the sun directly overhead is $1130\,\mathrm{Wm}^{-2}$ (Gaillard, 1981).

In calculating the time series of R_{SW} for input to the model, we account for possible shading of the river by the banks on either side at low sun elevations. The banks are assumed to have a height of 20m, and have an angle of 45^0 to the horizontal. The river channel is assumed to run in a uniform NW-SW direction which is approximately its mean orientation (see Fig. 29). We do not account for the actual meanders in the river through the study section.

A proportion of the shortwave radiation incident at the water surface is reflected. To estimate the shortwave reflectance, we adopt the formula of Anderson (1954) which is:

$$A_{SW} = 0.05230\theta^{-0.77} \qquad (4)$$

where A_{SW} is the shortwave reflectance and θ is the solar altitude in radians.

R_{LWE}

The longwave emission from the water surface is calculated using the Stefan-Boltzmann law:

$$R_{LWE} = \varepsilon_w \sigma (T_w + 273.16)^4 \qquad (5)$$

where ε_w is the emissivity of the water surface assumed to be 0.97 (Henderson-Sellers, 1986), σ is the Stefan-Boltzmann constant, and T_w is the water temperature in degrees Celsius.

R_{LWS}

The longwave emission from the sky adsorbed by the river is estimated using the following formula suggested by HEC (1978) and Zison et al. (1978) which is an extension of the Swinbank formula (Swinbank 1963) including the effects of cloud cover:

$$R_{LWS} = 5.3\times10^{-13}(1-A_{LW})(1+0.17C^2)(T_a + 273.16)^6 \qquad (6)$$

In this equation, the units of R_{LWS} are Wm^{-2}, A_{LW} is the longwave reflectance assumed to be 0.03, C is the fractional cloud cover, and T_a is the air temperature in degrees Celsius.

Penman (1948) suggested the following relationship between the incident shortwave radiation above the atmosphere (Φ_∞), the radiation at ground level (Φ_s), and the ratio of the number of hours of sunshine to the number possible (n/D).

$$\Phi_s = \Phi_\infty(0.18 + 0.55n/D) \qquad (7)$$

Suppose that Φ_s^0 is the radiation at ground level with zero cloud then:

$$\Phi_s^0 = 0.73\Phi_\infty \qquad (8)$$

If n/D is a measure of the duration of the sunshine amount then $1-n/D$ could be taken to be a measure of the amount of cloud so:

$$n/D = 1-C \qquad (9)$$

Solving for C after substitution of Eqs. 8 and 9 into Eq. 7 gives:

$$c = 1.33(1 - \frac{\Phi_s}{\Phi_s^0}) \qquad (10)$$

For the evaluation of Eq. 10, Φ_s is taken to be the measured short-wave radiation and Φ_s^0 is the short-wave radiation that would have been measured on a cloud-free day which is calculated from the height of the sun.

LE

The heat loss due to evaporation is just the product of the latent heat of vaporisation, λ (2.2×10^6 J Kg^{-1}), and the evaporation rate, E (Kg m^{-2}s^{-1}). The evaporation rate is determined using the model of Webster and Sherman (1995) which is applicable to waterbodies of limited wind fetch. It includes evaporation due to forced convection associated with the wind blowing over the water surface as well as free convection which may occur during calm conditions such as at night. The model estimates evaporation rate from prescribed surface water temperature, air temperature, relative humidity, and wind speed.

H

The ratio of the sensible heat flux ,*H*, to the evaporative heat flux, *LE*, is assumed to be provided by Bowen's ratio, *R*, (Bowen, 1926) where:

$$R = 62 \frac{T_w - T_a}{e_w - e_a} \ . \qquad (11)$$

In this equation, e_w is the saturated water vapour pressure at the temperature of the river water and e_a is the vapour pressure in the air which is a function of the air temperature and the relative humidity. Both e_w and e_a are expressed in Pascals. The validity of the use of *R* to represent the ratio of the conductive to evaporative heat exchanges between the water and the air above depends on the assumption that the turbulent transport processes for heat and water vapour above the water surface are the same.

Model Application

Water temperatures were modelled in 2001 for the 58-day period June 18 to September 15. The model was also applied successfully to measurements from 2000, but we do not report the results from this analysis here since the modelled periods are much shorter. Hydrographic surveys conducted in 2001 determined river discharge as a it varied along the channel between Claravale and Cattle Creek. Through the section between x = 24 and 33km, the discharge as measured to increase by 9.0 m^{3}s^{-1} on June 3 and by 7.1m^{3}s^{-1} on September 3. Accordingly, we specify the spring discharge rate volume for the study period to be the average $Q_{spring} = 8$ m^{3}s^{-1}.

For model application, the heat fluxes due to the shortwave solar radiation (R_{SW}) and to the longwave emission from the sky (R_{LWS}) were calculated directly from the meteorological measurements as described above and input to the model. The other three fluxes, namely longwave emission from the water surface (R_{LWE}), the evaporative heat loss (*LE*), and the conductive heat exchange with the air over the river (*H*) all involve the river water temperature. In these cases, we use the predicted water temperature for the present time step to estimate the heat flux for the duration of the next step and so on.

The model was calibrated for two parameters namely for a wind-speed factor (F_{ws}) and for the temperature of spring water discharged into the river (T_{spring}). The wind-speed factor, F_{ws}, is applied as a multiplier to measured winds to account for the likelihood that measured wind speeds at Ruby Billabong in 2000 and Douglas-Daly Research Farm in 2001 on the floodplain may need to be adjusted to obtain an adequate representation of evaporation. The embankments lining the river channel would cause sheltering depending on the orientation of the wind with respect to the local direction of the channel and so actual winds over the river would be less than those measured.

Values for F_{ws} and T_{spring} were obtained by minimising the least squares difference between the time series of predicted temperatures and those measured at Jinduckin Creek and Cattle Creek The optimal values for the fitted parameters were $F_{ws} = 0.52$, and $T_{spring} = 27.6\ ^0\mathrm{C}$. Cook et al. (2002) reports that most springs flowing into the Daly have temperatures of between 25 and 31^{0}C, a range which spans the temperature we estimate here. However, some springs in the region between x = 27 and 30km are reported to have temperatures up to 36^{0}C. For the optimal fitted parameters, the average root-mean-square difference between the model predictions and the measurements at the three downstream sites is 0.35 ^{0}C.

Model Comparisons with Measurements

Figure 30 shows the measured water temperatures over during the 58-dayperiod in 2001. The temperature at all sites undergoes a distinct daily variation of about 1 to 1.5 ^{0}C due to the heating of the sun during the day and cooling at night. A second feature to note is that the temperature records at the three downstream sites are fairly similar to one another in shape, but the upstream site, Claravale, is consistently cooler than Jinduckin Creek by an average of 1.8 ^{0}C; temperatures at Jinduckin Creek are an average of 0.2 ^{0}C cooler than those at Cattle Creek, the site furthest downstream. The temperature increase between Claravale and Jinduckin Creek is attributed mostly to the discharge into the Daly River of the warmer water from the springs.

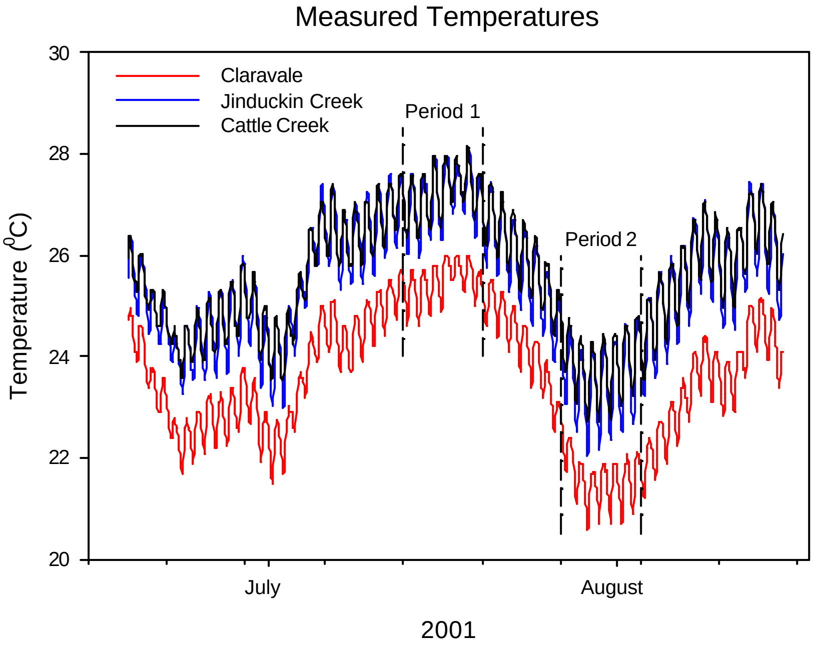


Figure 30. Comparison of measured water temperatures at three sites on the Daly River.

Over the 58-day record the water temperature at the three sites showed longer period cycles of variation which had an amplitude of about 3 ^{0}C. This temperature variability appears to have been due to the weather. The relatively high water temperatures during the third week in July (Period 1 in Fig. 30) had an average wind speed of $1.4\mathrm{ms}^{-1}$ versus $2.1\mathrm{ms}^{-1}$ in the last week of July (Period 2) and the third week had an average relative humidity of 68% in the third week versus only 43% in the last week. The stronger winds and lower relative humidity in the last week would have meant that evaporation would have been more vigorous than in the third week. This higher evaporation would have tended to increase the rate of cooling of the water column. Air temperatures were also an average of 6 ^{0}C cooler in the last week than in the third which would have contributed further to cooling the river during the last week of July. Interestingly, the estimated average downwelling irradiances in the third and last weeks of July were virtually identical being within $1\mathrm{Wm}^{-2}$ of one another, even though the short-wave radiation in the last week was measured to be about $50\mathrm{Wm}^{-2}$ higher than in the third week. The radiation shortfall in the third week appears to have been up with a correspondingly higher downwelling long-wave contribution. Presumably, the variation in the meteorological conditions were due to the presence of a warm, cloudy, humid air mass deriving from the tropical ocean to the north of Australia in week 3 being replaced by a cooler, clear, and dry air mass from continental Australia during the last week in July.

Figure 31 compares the measured and modelled river temperatures at Jinduckin Creek; Figure 32 shows a weeklong expanded section of Figure 31 to better illustrate the diurnal temperature variation. Overall, the model simulates the measurements well both with respect to the longer-term variations and for the diurnal fluctuations. In the expanded section of the record shown in Fig. 32, the amplitude of the diurnal fluctuations is well represented for the whole of the two week piece of record shown although the daily averaged 'background' model temperatures are ~0.5 ^{0}C too high for the first few days and are a little low near the end of this data section. Figure 31 shows that the model underestimated the amplitude of the diurnal fluctuations by ~0.5 ^{0}C and the background temperatures by half this amount from the first week of August onwards. The degree of agreement between measured and modelled temperatures for Cattle Creek was similar to that demonstrated for Jinduckin Creek.

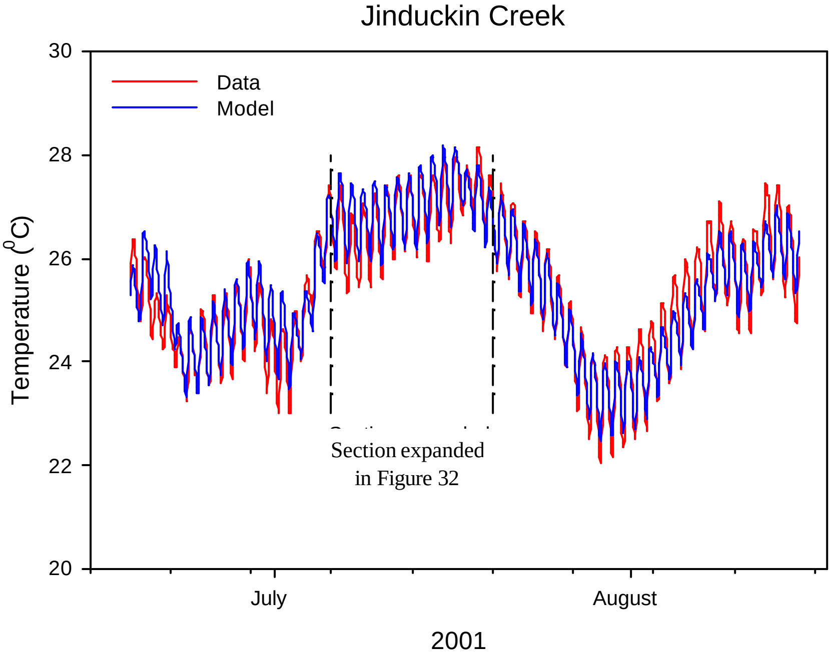


Figure 31. Comparison between measured and modelled water temperatures at Jinduckin Creek for 2001.

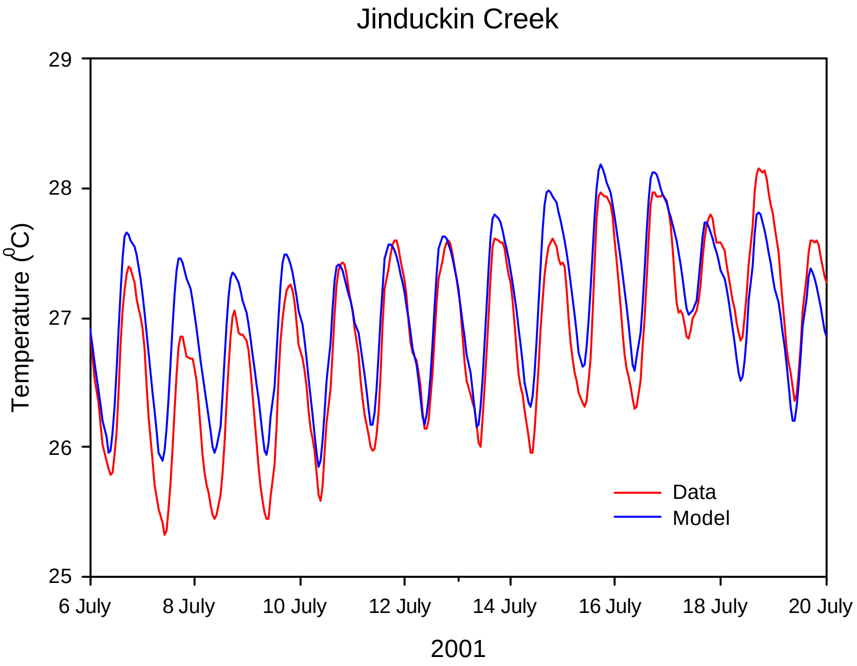


Figure 32. Comparison between measured and modelled water temperatures at Jinduckin Creek for the period between July 6 to 20, 2001.

There are a number of sources of error in the modelling that could lead to the difference between model simulations and measurements. Disagreement between background modelled and measured temperatures could be partly to do with the model's failure to account properly for all the springs that flow into the Daly River between Claravale and Cattle Creek. The model has implicitly included the springs between x = 24 and 33km, but these are estimated to account for 63% of the inflow to the river from the June 3 gauging study. To model the effects of the springs properly we need to know their volumes as well as their temperatures.

Errors in the estimation of the important meteorological parameters including radiation fluxes, wind speed and air temperatures will affect the degree of agreement between both the background and diurnal temperature variations. These errors could arise from the estimation of these parameters at the measurement site itself due to instrument inaccuracy or to the validity of the assumptions used to calculate parameters such as downwelling long-wave radiation for example. Other errors in model forcing could arise from the assumption that meteorological conditions over the river over its 64km length can be represented by measurements made at one site on the floodplain.

Analysis of Water Extraction Scenarios

The major question asked of this project is what is the likely impact of changes in river flow due to water extraction on water temperatures in the Daly River downstream from Claravale? The actual impact will depend on where the water is extracted, on what the background flow conditions are in the Daly at the time, and on the prevailing meteorological conditions. In the following analysis we adopt a scenario approach to analyse this problem. Each scenario is assumed to last for 58 days and utilises the 58-day record of measured meteorological conditions for 2001 that we have employed in the model analysis of the previous section. The flow alteration scenarios are the simplest possible; that is, the flows are specified to be constant in time and uniform in each of the river sections upstream and downstream of the spring at x = 29km. The scenarios are identified by their flow volume downstream from the spring, Q_d. Upstream from the spring, the flow is assumed to be $Q_u = Q_d - 8\ \text{m}^3\text{s}^{-1}$. All scenarios use the time series of measured temperatures at Claravale as their upstream boundary condition.

Figure 33 shows the results of the scenario analysis plotted as the time-averaged modelled temperatures between Claravale and Cattle Creek. The scenario entitled '2001 Flows' uses the measured flows and meteorology for 2001. Thus, unlike all the other scenarios, it allows the flow to change during the 58-day simulation period. The '2001 Flows' scenario illustrates some important features of the temperature response of the Daly River to meteorological forcing. The average temperature of the input water at Claravale for the simulation period is 23.6 ^{0}C. Downstream from Claravale the temperature gradually increases to 24.6 ^{0}C just upstream of the spring. The input of higher temperature water at the spring (x = 29km) causes a jump in river temperature of 0.6 ^{0}C at this point. Further downstream, the river water temperature continues to increase although at a slower rate than it did upstream of the spring. The measured average increase in temperature between Jinduckin Creek and Cattle Creek is 0.17 ^{0}C is consistent with the model-predicted increase of 0.16 ^{0}C, although it should be remembered that part of this agreement may be dictated by model calibration. Another possible cause of temperature increase in the real system is the inflow of warm springs along this section of the Daly River, which has been neglected by the model.

The continuing increase of simulated water temperature between Claravale and Cattle Creek implies that the river did not reach thermal equilibrium with the 'average' meteorological conditions over its length. It would appear that the equilibrium river temperature is about 26.4 ^{0}C. Thus, the average water temperature at Claravale is 2.8 ^{0}C less than the equilibrium temperature. This implies that either the Daly River is being fed by substantial quantities of cool spring water upstream from Claravale or that meteorological conditions above the river in its upstream sections are conducive to a cooler equilibrium river temperature. The similarity between the background variations in temperature at Claravale and at the to downstream stations would suggest that they are subject to similar meteorological systems. Whether cooler temperatures at Claravale are due to the inflow of cool springs or due to differences in the upstream meteorology, the utility of the present model analysis to predict water temperatures at Claravale is limited.

The results of the four alteration scenarios can be largely understood in terms of the preceding analysis. In effect, all four scenarios input cool water into the river at Claravale and river temperatures adjust towards the equilibrium temperature at (spatial) rates that decrease with river discharge. The approach towards equilibrium decreases with increasing discharge for two reasons. First, and most important the flow speed increases with discharge. Thus, water flowing between Claravale and the spring has less time to heat up under elevated flow conditions. Second, the water depth decreases with decreasing discharge. A shallower river will heat up faster in response to a prescribed energy input than a deeper river having a greater discharge. For the lowest discharge scenario shown in Figure 33 ($Q_d = 10\ \mathrm{m^3 s^{-1}}$) the upstream flow is only $Q_u = 2\ \mathrm{m^3 s^{-1}}$. The upstream flow is sufficiently slow and shallow for this scenario that river temperatures approach equilibrium by the time water reaches the spring at x = 29km.

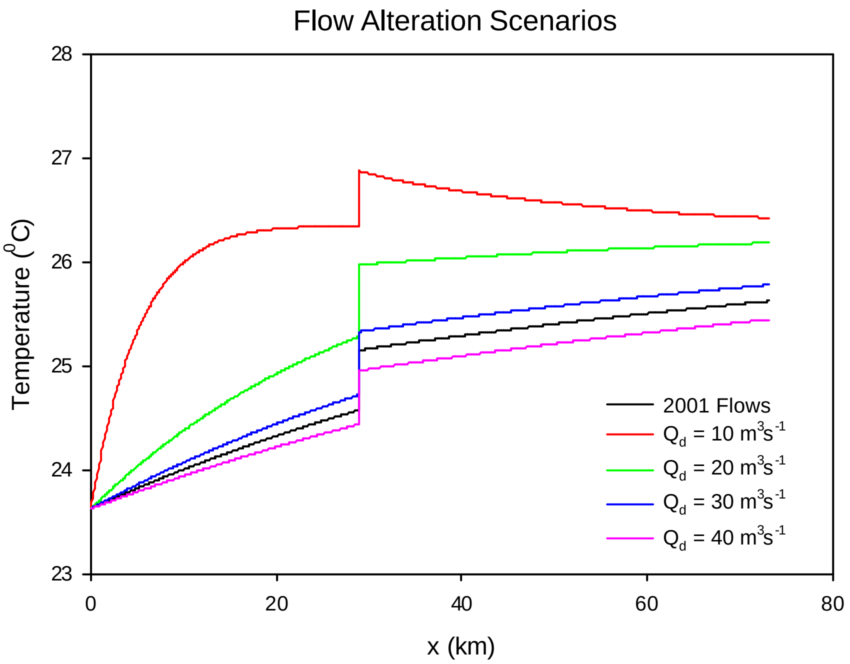


Figure 33. The simulated water temperatures along the Daly River for the present situation (2001 Flows) and for four flow alteration scenarios in which the flow downstream from the spring is specified.

Provided the water temperature just upstream of the spring is less than the spring temperature (which it is for the scenarios shown), spring inflow of spring water at x = 29km increases water temperatures by an amount that depends on the volume of the upstream flow and the difference in temperature between the spring and the upstream river water. These two factors affecting the size of the temperature jump tend to act opposite to one another as discharges change so the jump tends to be fairly constant in size for the scenarios shown. The scenario $Q_d = 20\mathrm{m}^3\mathrm{s}^{-1}$ has a jump of 0.7 ^{0}C and $Q_d = 40\mathrm{m}^3\mathrm{s}^{-1}$ has a jump of 0.5 ^{0}C despite these scenarios having almost a three-fold difference in the flow volumes upstream of the spring.

Downstream from the spring, the river temperatures again tend to approach equilibrium that also tends to depend on flow volume and on the size of the departure of water temperature from equilibrium. For $Q_d = 10\,\mathrm{m}^3\mathrm{s}^{-1}$, the spring caused the river temperature to exceed the equilibrium temperature so the river cooled as it flowed downstream, whereas the downstream river temperatures increased towards equilibrium.

Impact on a Flagship Species

Fragmentation and Home Range

Home range of the pig-nosed turtle at the study site has been determined by radio-telemetry (Doody et al., 2002). Female *Carettochelys insculpta* were more active, moved farther, and occupied home ranges twice the size of that of males (Table 17). Linear home range size (95th percentile) for radio-telemetered females ranged from 2.5 to 13.9 km (8.3 ± 2.88 km, n=13) and for males ranged from 1.5 to 4.5 km (3.2 + 1.32 km, n=5). These differences between the sexes are not likely attributable to food type, as dry season food types do not differ between the sexes (Heaphy, 1990; Welsh, 1999), and are more likely to be associated with the energetic and behavioural demands of reproduction.

We modelled the restriction of home range size against habitat fragmentation caused by flow reduction (Table 18). This table is quite difficult to interpret. For example, under base flow conditions of 2 cumecs, 49.6% of the river is fragmented to a state at which all female turtles would have their observed home ranges restricted and 11 out of 13 turtles would be restricted everywhere. At 16.1 cumecs, there is effectively only one continuous system with no turtles restricted anywhere.

Table 17. Descriptive data for individual *C. insculpta* obtained by radio-telemetry (Doody et al., 2002). Sample sizes are in parentheses when not equal to number of fixes.

Turtle #	Sex	CL (cm)	Reproductive condition	# fixes	Linear home range (m)	Activity (%)
F01	f	44.6	non-gravid	11	-	-
F02	f	42.0	non-gravid	95	7950	76 (62)
F03	f	41.4	non-gravid	51	6540	75 (32)
F04	f	43.6	non-gravid	72	7810	72 (53)
F05	f	42.4	gravid	99	9850	64 (78)
F07	f	46.2	gravid	19	5870	
F08	f	43.0	gravid	91	7405	61 (76)
F12	f	44.6	gravid	61	13890	26 (35)
F16	f	43.6	gravid	29	12630	35 (20)
F40	f	44.4	gravid	52	2450	
F54	f	44.5	non-gravid	11	-	-
F64	f	40.9	gravid	31	9600	53 (17)
F65	f	42.6	non-gravid	102	8460	70 (69)
F67	f	40.2	gravid	100	7280	74 (72)
F69	f	44.5	non-gravid	99	8250	74 (68)
M08	m	37.8	n/a	91	3955	18 (79)
M52	m	37.5	n/a	89	3800	61 (74)
M56	m	40.1	n/a	94	2185	24 (80)
M62	m	40.1	n/a	96	4680	10 (79)
M63	m	39.4	n/a	98	1535	24 (84)

Table 18. Impact of habitat fragmentation on the home range size of pig-nosed turtles. Home range sizes are based on the 95th percentile of the linear extent of movement of 13 female and 5 male radio-tracked turtles (Doody et al., 2002). Data in the table are the percentage of the river under study (73.7 km) where all turtles would have their observed home ranges restricted by fragmentation, and the percentage of the river where none of the turtles would have their home ranges restricted. The p values in brackets are the number of pools that contribute to the stated percentage; the n values are the number of turtles that are restricted everywhere; the m values are the number of turtles that are not restricted anywhere.

FLOW	**FEMALES**		**MALES**	
	All restricted	None restricted	All restricted	None restricted
2.0 cu	49.6 (p=25)	0% (n=11)	18.6 (p=14)	15.2 (p=2)
4.8 cu	23.5 (p=11)	0% (n=2)	6.1 (p=4)	65.2 (p=6)
7.6 cu	14.2 (p=6)	47.0 (p=2)	1.7 (p=1)	81.3 (p=5)
10.5 cu	7.5 (p=3)	69.5 (p=2)	0% (m=1)	92.5 (p=4)
13.3 cu	2.4 (p=1)	93.7 (p=3)	0% (m=1)	97.8 (p=4)
16.1 cu	0% (m=13)	100 (p=1)	0% (m=5)	100 (p=1)

The above analysis is based on a linear home range calculated from the 95th percentile of fixes with respect to the centroid of the turtles distribution. The analysis is conservative for the following reasons:

(a) It does not include occasional sorties outside the primary home range area (i.e. movements in the 95th to 100th percentile) which may serve an essential purpose in their life history. For example, seven gravid females were linked to their nesting locations. Most turtles (87.5 %) nested within 95 % of their linear home range. The exception was turtle F08, who to lay her second nest, made a deliberate movement of ca. 6 km, returning two days later to the area she occupied prior to the sortie. Of 12 nesting events by 10 turtles with sufficient movement data (N > 24), in seven cases females made upstream movements just before nesting, compared to one case of downstream movement, two cases of no movement, and two cases with movements in both directions just prior to nesting. These nesting movements were not included in the home range analysis, but rather were captured in the analysis of nest bank access.

(b) We deliberately chose individuals with established home ranges within the study site, not a random selection of turtles. A number of turtles are transients, presumably seeking a permanent home range or simply behavioural variants. Their needs are not accommodated in this analysis.

Fragmentation and Nest Bank Access

Pig-nosed turtles nest on sand banks adjacent to the river (Doody unpublished data). The sand banks are largely free of vegetation and have a direct connection to the water. Unlike freshwater crocodiles, pig-nosed turtles do not nest on sand banks that are separated from open water by vegetation of any sort, terrestrial or aquatic. Sand banks chosen for nesting are principally those comprised of clean fine sand, though the turtles will occasionally nest in gravel or loam. Sand banks where the sand is falling into the water are preferred.

Suitable sand banks occur where sand is trapped behind woody debris or rocky outcrops, where sand accumulates on bends in the river, and where sand is deposited by small tributaries that flow only as the wet season floods recede. Sand banks used for nesting vary in size from a few square metres to large accumulations up to 300 m in length. The size, number and location of these sand banks varies considerably from year to year, as the river bed and banks are remodeled extensively each wet season. The turtles cannot rely upon the continued existence of a sand bank from year to year, or on the extent and quality of the nesting habitat for those that do persist in some form from year to year. Each year, they must seek out suitable nesting areas, and this no doubt contributes to the extent of their movements up and down the river during the dry season.

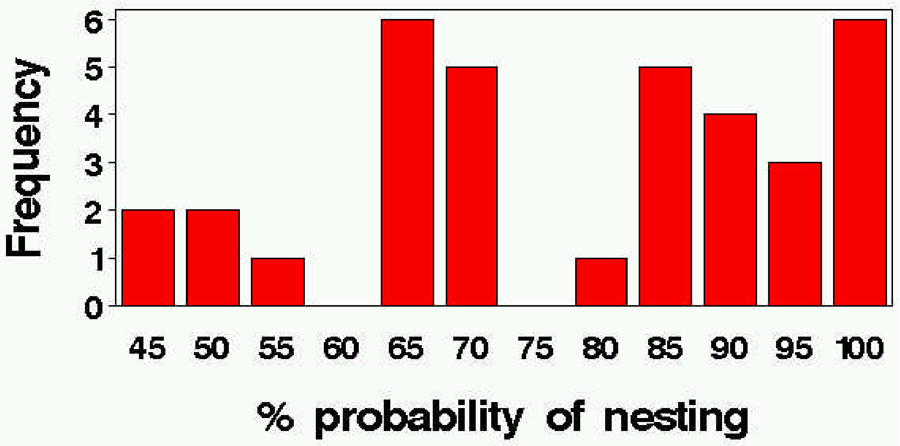
A survey between Claravale Crossing and Jinduckin Creek in 1998 revealed 54 sand banks suitable for nesting, of which 42 were subsequently used (Doody unpublished data). This yields an estimate of the density of nesting beaches as 1.04 beaches per km of river.

Base Flow (90% reduction) (2.0 cumecs)

Under base flow conditions the probability of a pig-nosed turtle being able to nest is determined by whether a nesting bank occurs in each of the 33 fragmented pools. Percentiles for the probability of a nesting bank occurring in a particular pool are shown in (Table 19). Under this regime, 50% of the pools have 83% or less chance of having a nesting bank and 25% of the pools have a 64% or less chance of having a nesting bank. The mean number of pools having a nesting bank under this flow regime was 77.8±17.2%; suggesting on average that 77% of the turtles would be successful in nesting.

Table19. Percentiles for the probability of having the opportunity to nest under base flow conditions in Daly River, Northern Territory. P is the probability of a nesting bank occurring within a particular pool.

Percentile	P
Max	99.75
95%	99.31
90%	98.27
Q3	92.65
Median	83.12
Q1	63.83
10%	49.53
5%	45.53
Min	45.29

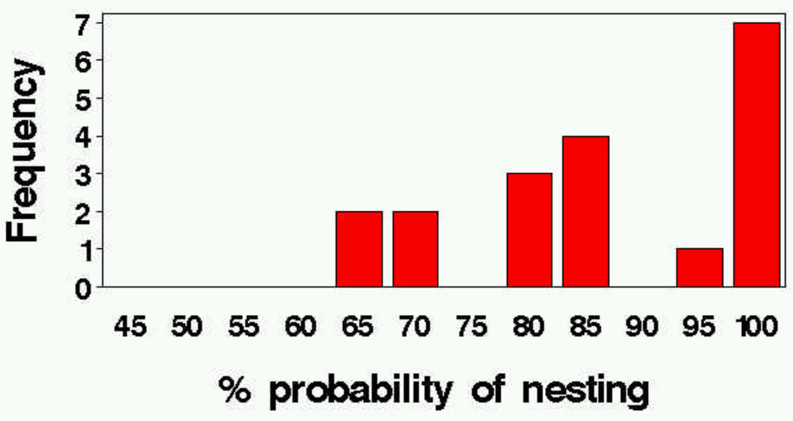


80% Reduction (4.8 cumecs)

As with base flow conditions the probability of a pig-nosed turtle being able to nest is determined by whether a nesting bank occurs in each of the 19 fragmented pools. Percentiles for the probability of a turtle being able nest are shown in (Table 20). Under this regime, 50% of the pools have 85% or less chance of having a nest and 25% of the pools have a 79% or less chance of having a nest. The mean number of pools having a nesting bank under this flow regime was 86.6±12.9%; suggesting on average that 87% of the turtles would be successful in nesting.

Table 20. Percentiles for the probability of having the opportunity to nest under 80% reduction in flow (4.8 cumecs) in Daly River, Northern Territory. P is the probability of a nesting bank occurring within a particular pool.

Percentile	P
Max	100
95%	100
90%	100
Q3	99.78
Median	85.71
Q1	78.82
10%	63.79
5%	63.47
Min	63.47



Flow greater than 7.6 cumecs

All pools produced at flow conditions which have flow corresponding to 70% reduction or more flow have 100% chance of having a nesting bank.

Fragmentation and Access to Vallisineria nana

Pig-nosed turtles are omnivorous, but during the dry-season they feed principally upon rooted aquatic macrophytes, principally *Vallisineria nana*, and associated macroinvertebrates (Heaphy 1990; Welsh 1999). *V. nana* is the visually dominant, annual water plant of the Daly River. It grows during the dry-season and beds are typically 10m wide and 100 to 1000 m long. It typically grows on the outside edge of river bends along rock ledges and areas adjacent to groundwater springs or seepages. *V. nana* grows at depths anywhere from 0 to 1.5 m and is flow and turbidity sensitive.

In 2001, fifty-nine *V. nana* beds were recorded (from a helicopter flight) in the Daly River between Claravale Crossing and Cattle Creek (Dostine *et al*. unpublished data). The density of *V. nana* recorded was one bed per 1.2 km of River. However, the first *V. nana* beds were not recorded until around 32 km downstream of the Claravale Crossing with the beds becoming more frequent with distance downstream from that point.

In this section we have determined the number of pools with or without *V. nana*, the number of patches of *V. nana* per pool and the length of river without *V. nana* under differing flow regimes (Table 21).

Table 21. Impact of habitat fragmentation on the feeding grounds of pig-nosed turtles. Feeding grounds (patches of *V. nana*) were assessed visually from a Helicopter during 2001. Data in the table are the percentage of the river under study (73.7 km) that had *V. nana* beds. Number of pools with or without *V. nana* and the mean number of beds per pool are also included. At below 50% flow reduction there is effectively only one continuous system with no turtles restricted anywhere.

Flow (cumecs)	No. of pools without *Vallisineria* *	No. of pools with *Vallisineria*	Length of reach without *Vallisineria* (km)	No. of beds per pool (mean±sd)
2.0	19 (11)	15	38.8 (53%)	3.9 ± 2.5
4.8	11 (6)	8	38.9 (53%)	7.4 ± 5.9
7.6	8 (4)	4	37.5 (51%)	14.8 ± 6.1
10.5	4 (2)	3	34.2 (46%)	19.7 ± 15.8
13.3	2 (1)	3	32.2 (44%)	19.7 ±1 5.5

**Parentheses* indicate the number of pools (in the first 32km downstream of Claravale Crossing) that did not have major *V. nana* beds.

At base flow conditions, the average number of beds per pool was less than four and more than 53% of these pools had no *V. nana* beds. At the 80% flow increment the average number of beds per pool rose to 7.4, but the proportion of pools without *V. nana* remained similar to that of base flow conditions. This is largely due to the initial 32 km of river having a natural absence of *V. nana* beds and 3 major break points, which we regard as a condition that may be peculiar to our study year yet representative of the system. Consequently, we retained the 32 km data in our modeling.

At flow reductions between 70% and 50% the density of *V. nana* beds per pool are high and appear to level off. Also, the number of pools having *V. nana* begins to outweigh those without, suggesting that little effect would be had on restricting turtle access to feeding grounds under these conditions.

Impact of Thermal Modification

Modelling Turtle Development

We have used the most widely accepted non-linear model of poikilotherm development, that of Sharpe and DeMichele (1977), to model development in response to temperature in the pig-nosed turtle. This model extends the work of Eyring (1935), Johnson and Lewin (1946) and Hultin (1955) in the formulation of a biophysical model that describes the non-linear response of development rate to incubation temperature at both high and low temperatures, as well as a linear response at intermediate temperatures. Six fitted parameters must be estimated using non-linear regression. A computational form of the equation more suitable for this purpose was developed by Schoolfield et al. (1981), namely

$$\frac{ds}{dt} = \frac{RHO_{25}\,\frac{T}{298.15}\exp\left[\frac{H_A}{r}\left(\frac{1}{298.15}-\frac{1}{T}\right)\right]}{1+\exp\left[\frac{H_L}{r}\left(\frac{1}{T_L}-\frac{1}{T}\right)\right]+\exp\left[\frac{H_H}{r}\left(\frac{1}{T_H}-\frac{1}{T}\right)\right]} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{[12]}$$

where $\frac{ds}{dt}$ is development rate at absolute temperature T (K); $r = 1.987$ is the universal gas constant (in calories/degree/mole); RHO_{25} is the development rate at 25°C (298.15 K) ; and T_L, H_L, T_H, H_H and H_A are the remaining fitted parameters.

For the pig-nosed turtle, the coefficients of the curve of best fit were $RHO_{25} = 0.7571$, $H_A = 29605.4896$, $T_L = 297.0371$, $H_L = -80893.0886$, $T_H = 308.7106$, $H_H = 161214.3066$ (Figure 34).

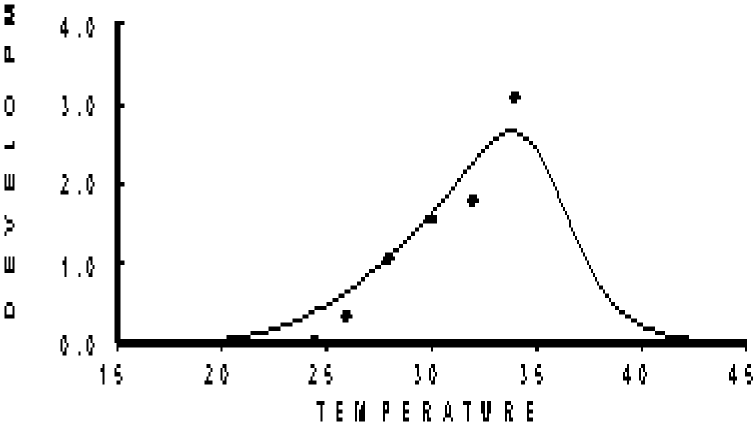


Figure 34. Development rate curves of best fit to known development increments for eggs of *Carettochelys insculpta* incubated under constant and fluctuating temperature regimes in the laboratory, and regimes in natural nests. Development rate is incremental change in head width, expressed as a percentage of final hatchling head width, per day. Note that only data for the constant temperatures can be shown, and as such, the data shown is a small part of that used to derive the model.

A standard station for monitoring sand, water and air temperatures was set up on a small sand bar used for nesting by *Carettochelys insculpta* in May of each year (1996-98), immediately after the preceding wet season. Temperatures were monitored at 15 min intervals at the sand surface and at 10 cm depth intervals to 50 cm. Water and air temperatures were taken in the shade. Temperatures were recorded with four-wire RTD probes fitted to a datalogger (Datataker Model DT500) and calibrated against a mercury thermometer certified as accurate to 0.1°C by the National Association of Testing Agencies (NATA). The apparatus was removed from the riverbank in late November/early December at the first sign of wet-season flooding.

Predictive relationships between nest data for 1997 and 1998 and data from this monitoring station were used to extrapolate “presumptive” nest temperatures for the entire dry season. Development increments occurring within each time interval between temperature measurements were summed (deCandolle 1855; Reibisch 1902). Point temperatures taken at 15 min intervals were again interpolated using cubic splines (PROC EXPAND, SAS_Institute 1988) to yield temperatures that were evenly spaced at equal but arbitrarily small intervals ($Dt = 7 \times 10^{-4}$ days). The amount of development to occur over time increments $t = 1$ to $t = t'$ was then calculated as

$$S = \sum_{t=1}^{t=t'} \frac{ds}{dt} \Delta t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [13]$$

where $\frac{ds}{dt}$ is development rate as a function of temperature, as specified by the Sharpe-DeMichele model. Development *S* is the percentage of total development, and development rate is expressed as a percentage of total development per day. SAS programs for undertaking the above analyses are available on request.

Table 22. Distribution of egg laying events during 1996.

Date	No. of Nests
First Nesting	
17-Aug-96	1
20-Aug-96	3
25-Aug-96	1
27-Aug-96	1
28-Aug-96	4
30-Aug-96	5
31-Aug-96	2
1-Sep-96	1
2-Sep-96	1
4-Sep-96	1
5-Sep-96	1
9-Sep-96	1
10-Sep-96	1
11-Sep-96	1
12-Sep-96	2
Second Nesting	
20-Sep-96	1
23-Sep-96	1
26-Sep-96	1
29-Sep-96	1
30-Sep-96	1
1-Oct-96	2
2-Oct-96	2
3-Oct-96	3
5-Oct-96	4
6-Oct-96	1
7-Oct-96	1
8-Oct-96	3
9-Oct-96	2
10-Oct-96	3
12-Oct-96	1
16-Oct-96	1
17-Oct-96	1
18-Oct-96	1
24-Oct-96	1

Thus we are able to determine from any nesting date, developmental parameters such as duration of incubation and offspring sex ratio. The impact of shift in nesting date will be calculable. Extrapolated nest temperature traces will be coupled with modelling data on water temperatures and timing of nesting to estimate the impact of altered nesting data on timing of hatching and offspring sex ratios, as required under the contract.

Table 23. Statistics for simulations of egg development based on incremental (Δ=10 days) change in the date of first nesting (Lay Date). The thermo-sensitive period (TSP) is the middle third of development when the sex of the embryo is sensitive to temperature.

Lay Date	Day of Year	TSP1	TSP Midpoint	TSP2	TSP Duration	Incubation Period	"Hatch" Date	% Male Nests	% Mixed Nests	% Female Nests	% Males
31-Dec-95	0	16	24-Jan-96	33	17	49	28-Feb-96	34.5	11.2	54.3	34.5
10-Jan-96	10	17	4-Feb-96	34	17	50	10-Mar-96	29.0	11.2	59.8	29.0
20-Jan-96	20	18	14-Feb-96	34	16	51	20-Mar-96	42.3	17.5	40.2	42.3
30-Jan-96	30	17	24-Feb-96	34	17	51	31-Mar-96	49.4	20.4	30.2	49.4
09-Feb-96	40	17	5-Mar-96	34	17	52	10-Apr-96	38.3	14.9	46.8	38.3
19-Feb-96	50	18	16-Mar-96	35	17	54	23-Apr-96	32.1	16.4	51.4	32.1
29-Feb-96	60	19	27-Mar-96	36	18	58	7-May-96	44.9	21.5	33.6	44.9
10-Mar-96	70	19	5-Apr-96	36	19	61	19-May-96	57.0	19.4	23.6	57.0
20-Mar-96	80	20	18-Apr-96	40	22	67	5-Jun-96	53.8	17.4	28.8	53.8
30-Mar-96	90	21	30-Apr-96	45	26	73	20-Jun-96	52.7	17.1	30.1	52.7
09-Apr-96	100	24	15-May-96	50	27	79	6-Jul-96	60.6	19.2	20.2	60.6
19-Apr-96	110	29	30-May-96	56	29	84	22-Jul-96	69.2	17.6	13.2	69.2
29-Apr-96	120	30	10-Jun-96	58	30	86	2-Aug-96	75.2	16.9	7.9	75.2
09-May-96	130	29	19-Jun-96	57	31	84	11-Aug-96	81.3	9.9	8.8	81.3
19-May-96	140	34	4-Jul-96	61	30	87	24-Aug-96	77.9	16.4	5.7	77.9
29-May-96	150	34	14-Jul-96	61	30	85	1-Sep-96	85.7	10.6	3.7	85.7
08-Jun-96	160	36	25-Jul-96	62	29	85	10-Sep-96	88.0	10.7	1.3	88.0
18-Jun-96	170	35	2-Aug-96	59	27	81	16-Sep-96	92.9	6.7	0.5	92.9
28-Jun-96	180	38	13-Aug-96	58	24	78	24-Sep-96	79.2	18.0	2.9	79.2
08-Jul-96	190	37	22-Aug-96	56	23	75	1-Oct-96	81.1	13.2	5.7	81.1
18-Jul-96	200	33	27-Aug-96	51	22	70	5-Oct-96	68.8	21.9	9.3	68.8
28-Jul-96	210	32	4-Sep-96	49	21	66	11-Oct-96	90.6	8.0	1.4	90.6
07-Aug-96	220	29	10-Sep-96	45	21	61	17-Oct-96	65.1	21.2	13.7	65.1
17-Aug-96	230	29	18-Sep-96	42	18	58	23-Oct-96	51.3	21.8	26.9	51.3
27-Aug-96	240	28	26-Sep-96	39	17	55	30-Oct-96	34.0	29.4	36.5	34.0
06-Sep-96	250	26	4-Oct-96	36	16	52	6-Nov-96	56.0	13.8	30.2	56.0
16-Sep-96	260	23	11-Oct-96	33	16	49	14-Nov-96	36.0	21.8	42.3	36.0
26-Sep-96	270	23	20-Oct-96	32	16	48	23-Nov-96	30.4	19.5	50.1	30.4
06-Oct-96	280	22	30-Oct-96	32	16	49	3-Dec-96	20.4	18.9	60.7	20.4
16-Oct-96	290	23	9-Nov-96	32	16	50	14-Dec-96	31.9	28.5	39.6	31.9
26-Oct-96	300	23	20-Nov-96	34	17	50	24-Dec-96	21.5	18.6	59.9	21.5
05-Nov-96	310	24	30-Nov-96	35	17	50	4-Jan-97	32.3	17.1	50.6	32.3
	320							27.5	17.7	54.8	27.5
	330							37.5	22.5	40.0	37.5
	340							26.9	13.9	59.2	26.9
	350							38.6	17.5	43.9	38.6
	360							41.9	20.5	37.6	41.9

Nesting date versus sex ratio

Pig-nosed turtles nest twice every second year, but asynchronously, so there is a dual nesting period each dry season. The distribution of egglaying for 1996 is shown in Table 22.

To analyse the likely effect of temperature change following flow reduction, we ran a series of simulations. For a given date of first nesting, we calculated the development for each of 41 nests from 1996 and used this to estimate the date the thermosensitive period started and ended, and the date at which the embryos matured and were available to hatch given the appropriate trigger. Once the thermosensitive period was determined for each nest, we used the temperature regime within that period to estimate the offspring sex ratio. We undertook this analysis for nest dates ranging in 10 day increments from day zero (31-Dec-95) (Table 23). Offspring sex for each initial nest date was calculated by summing the offspring sex estimated for each of the two nesting bouts.

The sex ratio of the offspring varies dramatically with date of first nesting (Figure 35) reaching almost 100% males for turtles that lay their first nest mid-year. The actual period of first nesting extended from August 17 to September 12 (Figure 35), a period on the range of dates where temperature change would exert its greatest effect on offspring sex ratios. Nevertheless, water temperature change with change in flow was modest, in the order of only 1°C across the range of flow scenarios examined in this study. A 1°C change in temperature could be expected to result in a *ca* 7-day shift in timing of nesting. An increase of 1°C in water temperatures would be expected to shift sex ratios in favor of males from 50% to 58%, however the change is much lower than that caused by natural weather variations and shifts in nesting time in response to other influential factors (35 days).

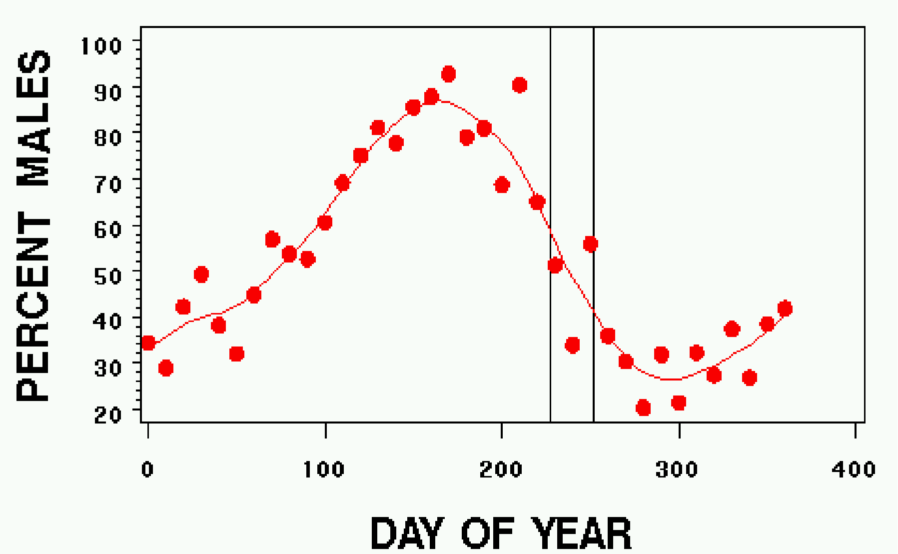


Figure 35. Percent males produced in two nestings per year, 40 days apart, plotted against the time of first nesting. The actual dates of first nesting are given by the period between the two vertical lines. Note that temperatures outside our direct measurement period (May-December) are estimated from regressions against air temperature, and so extend into the wet season, albeit unrealistically.

Synopsis and Recommendations

Table 1 is an integrated analysis of the impact of flow reduction on the life history of the pig-nosed turtle. It shows the outcome for each of several flows, which we have classified as boom or bust.

Table 1. Impact of flow alteration on the life history of the pig-nosed turtle. Flow categories are based on the flow levels used in our modelling. All but zero flow occur naturally. The impact of flow reduction of 3-12 cumecs are shown.

Flow (cumecs)	Outcome		Frequency of Occurrence (%)				
			Natural	- 3 cumecs	-6 cumecs	-9 cumecs	-12 cumecs
>14.7	Boom	River continuous flowing system; home ranges unrestricted; access to nesting banks and feeding beds unrestricted; natural temperature regime. No impact on life history.	6.6	3.7	2.2	1.3	0.9
13.3 (11.9-14.7)	Boom	River fragmented into 3 pools, one large (19.5 km) and two very large (20 and 35.5 km); only 10% of the river would restrict home ranges; access to nesting unrestricted and 40% of the river has no access to feeding grounds; no appreciable thermal impact.	4.3	2.7	1.4	0.8	0.4
10.5 (9.1-11.9)	Boom	River fragmented into 6 pools, two large (7.5 and 9.5 km) and two very large (20 and 31.7 km); 30% of the river would restrict home ranges; access to nesting unrestricted and 46% of the river has no access to feeding grounds; no appreciable thermal impact.	8.6	4.1	2.6	1.3	0.7
7.6 (6.2-9.1)	Bust	River fragmented into 11 pools, 4 large (9.4, 10.2, 16.8, 17.8 km) and none very large; 53% of the river would restrict home ranges; access to nesting unrestricted and 51% of the river has no access to feeding grounds; no appreciable thermal impact.	24.9	8.5	4.2	2.6	1.4
4.8 (3.4-6.2)	Bust	River fragmented into 19 pools, 3 large (9.2, 10.2, 11.1, km) and none very large; 100% of the river would restrict home ranges; substantial probability that a turtle will not be able to nest (up to 35%); and 53% of the river has no access to feeding grounds; no appreciable thermal impact.	40.8	23.5	7.7	3.9	2.5
2.0 (0-3.4)	Bust	River fragmented into 33 pools, none large or very large; 100% of the river would restrict home ranges of all female turtles; substantial probability that a turtle will not be able to nest (up to 55%); and 53% of the river has no access to feeding grounds; no appreciable thermal impact.	14.8	46.3	28.5	10.1	4.8
Zero	Catastrophic	River fragmented into 33 pools, or greater if water levels drop below cease-to-flow levels; none large or very large; 100% of the river would restrict home ranges of all female turtles; substantial probability that a turtle will not be able to nest; feeding grounds threatened as they are flow dependent; potentially substantial thermal impact as water depth drops appreciably below cease-to-flow levels.	0.0	11.3	53.5	79.9	89.3

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 flow alteration is likely to have substantial long-term impact on the population levels sustained locally.

It is clearly evident that all flow categories, regardless of their adverse impact on the turtles, have a finite probability of occurring even under a natural flow regime. For example, flows as low as 2 cumecs (0-3.4 category) can be expected to occur naturally in 14% of years. **The issue for flow allocations becomes not one of what reduction leads to an unsatisfactory outcome in a given year, but rather what reduction leads to an unacceptable increase in the frequency of unsatisfactory years (bust years).** This analysis clearly shows the substantial impact of a fixed flow reduction as small as 3 cumecs. Catastrophic years, where water is extracted in excess of natural flow (mining) will occur in 11.3 % of years. The boom years, important for sustaining turtle populations, will reduce in frequency from 1 in every 5 to 1 in 10 years. This will have a serious impact on the turtle populations.

The lesson here is that a flexible allocation regime is necessary, whereby the cap on flow reduction is defined to be sensitive to the magnitude of the dry season flow in any given year. For example, a 3 cumecs reduction in flow from a 13 cumecs dry season flow will have relatively little impact on turtle life history, whereas the same reduction from a base of 4.8 cumecs, which occurs in 40% of years naturally, will have a major impact. A 3 cumecs reduction in any of the 14% of years with already extremely low flows will be catastrophic, reducing flows and water levels to values not experienced in the years of our historical data set.

Under a flexible allocation regime that meets the needs of environmental flows, assurance of water supply will not be possible. Indeed, one of the major conclusions to come from this analysis is that water should not be drawn directly from the river or from groundwater close to the river if we wish to meet the dual objective of providing adequate environmental flows and assurance of water supply for agriculture. The only satisfactory option is to rely upon the buffering characteristics of groundwater supply taken some distance from the river. The buffering comes from the fact that such water would be derived from the cumulative effects of recharge from successive wet seasons, and so an averaging would occur across boom and bust years. This would buffer the effects of water extraction in any one year, and allow for fixed allocations.

Recommendations

- The dry-season flows represent only a very small proportion of the annual flow. Catastrophic draw-down of dry season environmental flow can occur with no change or only a small change in percentage terms in total annual flow. Consequently, allocations of environmental flow defined in terms of total annual flow or median annual flow are unlikely to be effective in protecting the key elements of dry-season flow.

- Any water allocation policy and limits would need to include both surface water and groundwater, because of the close relationship between the surface flows of the Daly River proper and the groundwater systems upon which it depends.

- A policy of allowing a ***fixed*** annual allocation of water to agriculture from the river and a policy of ensuring adequate environmental flows are irreconcilable.

- Water for agriculture should be drawn from groundwater aquifers representing accumulated recharge over several wet years, in order to assure supply and buffer the river from unacceptable reductions in flow in critical years. This will also remove difficult considerations on the timing of water extraction within years.

- The linkage between groundwater in the areas flagged for agriculture and river flow is not well understood. In the absence of good working models to predict the change in river flow against groundwater extraction from adjacent aquifers, an adaptive approach must be adopted. This would require accurate monitoring of the quantity of water extracted and when it is extracted, accurate monitoring of dry season flows, and accurate estimates of the flows that would be expected in the absence of water resource development. The latter estimates are possible from historical data because of precision in the recession curves once the contribution of surface flow becomes negligible.

- Research needs to be undertaken to determine how far from the river groundwater extraction must be in order to not have an un-buffered, immediate impact on the flows in the river. This distance will set the dimensions of the buffer zone that should be established along the river corridor.

- The quality of data on dry season flows obtained from the Department could be improved. There needs to be a greater commitment to maintaining river gauging stations and to quality control over the data collected. The stations need to be upgraded to more accurately measure dry-season flows. More intensive monitoring of dry season flows at multiple locations is needed if the adaptive approach is to be effective in governing water allocations.

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Appendix 1

Table A1. Flow characteristics by month for Claravale gauging station (G8140067), Daly River, Northern Territory. Daily gaugings were averaged for each month. Data from months where there were less than 20 gauged days were excluded. Statistics were then calculated across years for each month. Abbreviations: Min, Minimum; Max, Maximum; SD, Standard Deviation; SE, Standard Error; CV, Coefficient of Variation; N, sample size (months).

Month	Mean	Min	Max	SD	SE	CV	N
Jan	277.40	19.73	1803.74	382.40	65.58	137.85	34.00
Feb	602.64	23.31	1719.27	505.68	86.72	83.91	34.00
Mar	767.36	19.01	3710.48	943.69	157.28	122.98	36.00
Apr	96.06	4.90	356.31	103.92	17.09	108.19	37.00
May	20.43	2.23	86.36	17.82	2.85	87.22	39.00
Jun	10.52	2.14	34.40	6.71	1.09	63.82	38.00
Jul	7.82	2.42	22.60	4.16	0.67	53.21	38.00
Aug	5.83	2.22	11.38	2.29	0.38	39.29	37.00
Sep	5.29	2.02	10.97	2.23	0.37	42.26	37.00
Oct	5.73	2.11	19.00	3.40	0.56	59.28	37.00
Nov	12.39	3.30	40.19	9.58	1.60	77.30	36.00
Dec	82.05	11.82	293.48	75.62	12.97	92.17	34.00

Table A2. Percentiles for flows by month at Claravale gauging station (G8140067), Daly River, Northern Territory. Data from months where there were less than 20 gauged days were excluded.

Mth	Max	95%	90%	Q3	Median	Q1	10%	5%	Min	N
Jan	8099.54	1010.46	675.93	288.780	98.766	32.699	15.7850	12.6130	2.717	1041
Feb	7282.62	2131.56	1469.94	710.975	334.225	126.777	40.4670	22.8540	5.421	956
Mar	6261.62	3657.27	2279.18	905.136	230.711	71.716	24.2190	15.1370	5.566	1106
Apr	1245.49	388.64	238.97	100.254	40.498	17.949	7.3090	4.9610	3.179	1110
May	186.28	58.76	43.59	24.181	13.115	8.162	4.4270	2.9330	1.673	1193
Jun	41.85	23.23	19.26	13.746	8.535	5.637	3.4425	2.6995	1.687	1140
Jul	27.08	15.63	13.56	9.734	6.856	4.831	3.2950	2.6860	2.127	1178
Aug	12.53	10.48	9.03	7.089	5.594	4.006	3.1630	2.6310	2.098	1138
Sep	22.48	9.49	8.31	6.388	4.681	3.654	2.9250	2.2450	1.924	1109
Oct	167.62	9.99	8.25	6.347	4.522	3.411	2.7340	2.3710	1.892	1147
Nov	257.01	41.40	25.45	12.536	6.702	4.220	2.8930	2.6860	1.538	1068
Dec	1243.52	339.03	228.43	92.088	24.685	10.983	5.6920	4.1840	2.857	1039

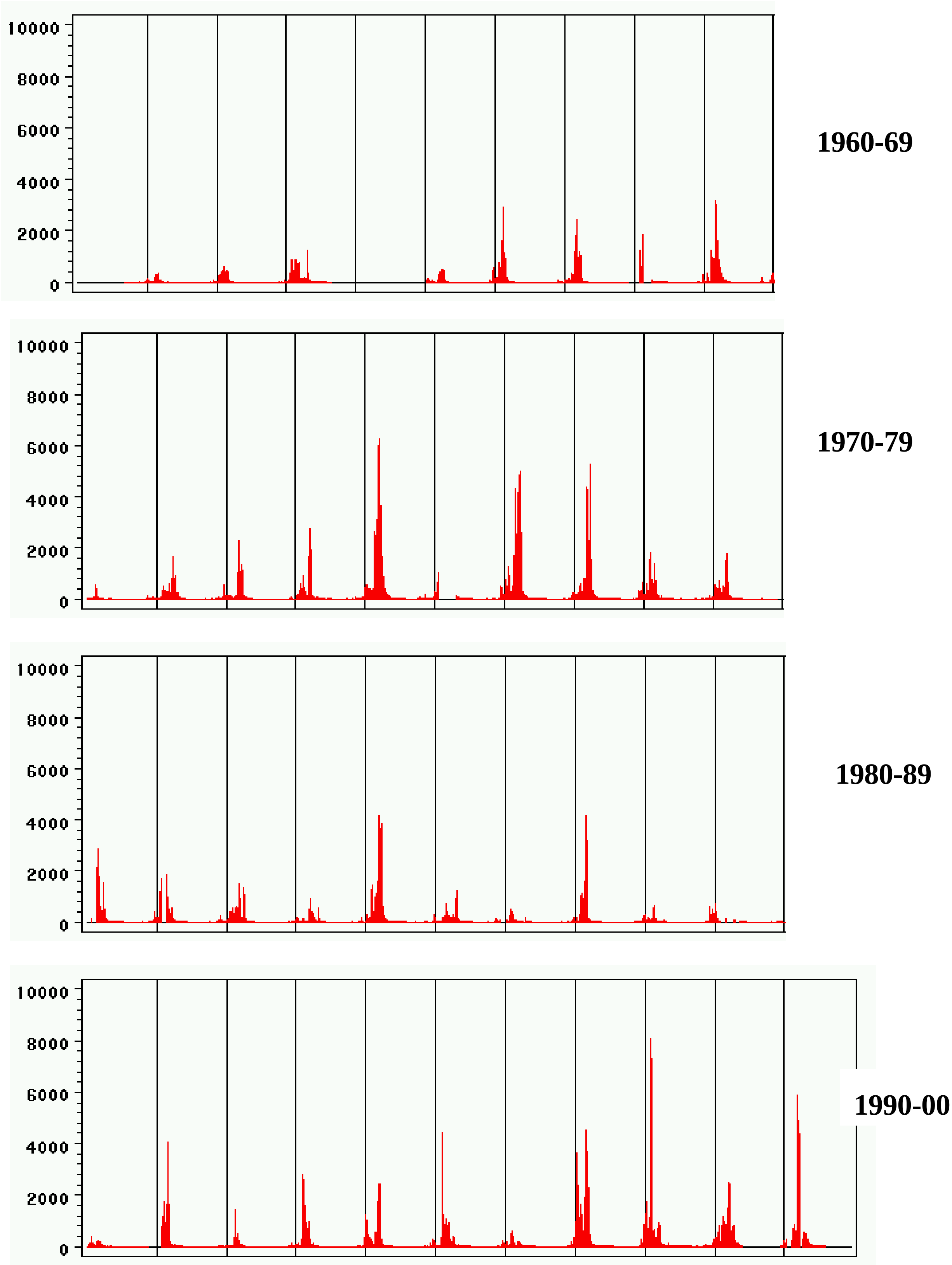

Figure A1. Flows recorded at Claravale gauging station (ref) for the years spanning 1960-2000. Flows are in cumecs.