Environmental Water Requirements of *Vallisneria nana* in the Daly River, Northern Territory[1]

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Introduction

The objective of the Commonwealth's Environmental Flows Initiative (EFI) was to assist state and territory water resource agencies meet the COAG Water Reform requirements for making environmental water allocations. The NT received support due in part to the focus on water resource development shifting to Northern Australia and the concurrent lack of understanding about tropical water resources and their sustainable use. Intensive development of water resources is proceeding in the Daly Basin without an understanding of ecological requirements or environmental constraints.

Between 1985-1997, groundwater use in Australia increased by 88% and the trend is continuing. Irrigation accounts for 76% of that groundwater use. Already, 30% of groundwater management areas are overused compared with their estimated sustainable yield, while a further 30% are fully or over allocated (NLWRA 2001). The COAG Water Reform Framework stipulates that environmental water requirements are to maintain the "health and viability of river systems and groundwater basins".

Shadwick (2002) stated that the intention of the COAG strategic framework to safeguard water resources not only depends on the successful adoption of the water reforms but on simultaneous natural resource management. Governments need to ensure that: "integrated approaches to natural resource management are in place and there is full recognition of the interdependency of the different natural resource components, including water." Recent approaches to determining environmental water requirements take an ecosystem, catchment wide and multi-disciplinary perspective (Arthington *et al.* 1998). Holistic approaches argue that the *essential features* of a riverine ecosystem need to be protected to achieve geomorphological, water quality and ecological objectives and to maintain the rivers' *functional integrity*.

To protect the ecological character of groundwater dependent ecosystems, groundwater supply rate and quality needs to be maintained. While the landscape is vegetated, the majority of water infiltrates throughout the catchment to recharge groundwater aquifers. Run-off is filtered of large sediment loads and associated organic matter, nutrients and pollutants. Land clearing poses a significant threat to rivers and wetlands through reduced recharge and adverse changes to the quality and sediment load of wet season run-off. In the Daly Basin, unregulated land clearing and agricultural expansion within the catchment, along with plans to extract and divert large quantities of surface and groundwater pose a significant risk to the regions' ecology. Alterations to the water regime are forecast from flood harvesting into off-farm storages and the construction of regulatory devices. Alterations to the water regime in the dry season are more likely in the short term because extraction from surface and groundwater systems is greatest at a time when water is most scarce.

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[1] Project No. 23087 – Environmental Water Requirements of *Vallisneria nana* in the Daly River

The Daly is a perennial tropical river, kept flowing in the dry season through groundwater discharge from the Jinduckin, Tindall and Oolloo aquifers (Figure 1). The river is presently unregulated and compared with riverine ecosystems in southern Australia, is relatively unimpacted. The middle reaches of the Daly River are listed on the National Estate as an important wetland area in the Daly Basin biogeographic region, and a major breeding and dry season habitat for a variety of flora and fauna.

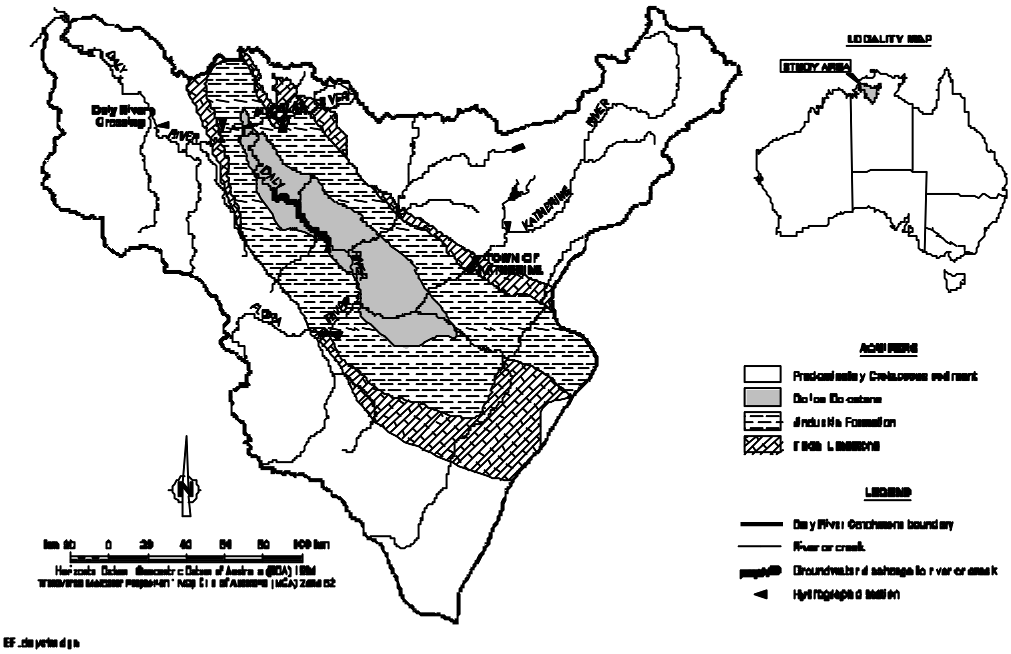


Figure 1 Map of the Daly Basin region in the Northern Territory, showing the middle reaches that overly the Oolloo aquifer

This project focuses on the major riverine plant, *Vallisneria nana* R.Br., the key habitat for many turtle species, including the endangered pig-nosed turtle. The importance of macrophytes in the ecology of running waters is well established (food, breeding, refuge, slow currents, trap organic matter, sediments and nutrients, reduce turbidity, stabilise banks, shade, cool temperatures, cycle and compartmentalise nutrients, metals and carbon). It is speculated that *Vallisneria* species were once considerably abundant in the regulated inland rivers of south-eastern Australia. Their loss is attributed to adverse changes in water quality and flow (Roberts and Sainty 1996, Bailey *et al* 2002). *V. nana* in the Daly River is a keystone habitat. Without it, there would be a cascade of adverse changes across the food web. Faced with the forecast and present development pressures in the Daly River Basin, it was clear that provision of conditions to maintain *V. nana* is critical to ecology of the river and the region in general.

The understanding of the functional role of riverine plants is not matched by knowledge of their growth or ecological requirements. This project addresses this gap. *V. nana* in the Daly River provides an opportunity to examine the ecology and requirements of riverine plants, and to understand why they disappear so easily. The overall objective of the project was to make recommendations about the environmental conditions needed to sustain *V. nana* and its functional role in the Daly River.

Project objectives

Initially, broad scale information was collected in order to design more detailed and applicable surveys. A description of river hydrology and quantitative hydrological data collection was undertaken to underpin the study. Mapping of *V. nana* beds took place at the catchment, reach and site scale and enabled the project to focus on the area of most significance. The habitat value of *V. nana* was confirmed through faunal surveys at the reach level. The habitat preference of *V. nana* for depth, substrate and velocity was determined from 27 cross channel transects. A detailed physico-chemical survey of the river identified other factors important for plant growth and investigated the role of groundwater flow throughout the dry season. This was followed by a 6 month plant ecological survey to measure the relationship between plant growth and environmental conditions. This data was underpinned by an analysis of whole river production that provided baseline information about the functioning of a tropical spring-fed river. The above information provided a fundamental context to the more detailed questions about flow and plant performance. The influence of reduced flows on *V. nana* distribution and performance were modelled. We advise about the potential role of *V.nana* in future monitoring programs and make recommendations about the water quality and flows required to maintain this ecologically significant component of the Daly River. The following 9 objectives are outlined below.

1. Summarise the past hydrological conditions in the middle reaches of the Daly River and generate hypotheses relevant to *V. nana*

2. Map the distribution and dimensions of *V. nana* beds and habitat correlates at the catchment, reach and site scale

3. Assess the habitat value of *V. nana* for macroinvertebrates and other fauna (fish, turtles, crocodiles) at the reach scale

4. Determine the physico-chemical habitat of *V. nana* by describing the seasonal water quality of the Daly River and its associated springs

5. Measure the growth and performance of *V.nana* across the growing season under a range of environmental conditions

6. Measure habitat preference of *V. nana* from multiple transects across channel sections

7. Use modelling to predict changes in *V. nana* performance under different flow regimes

8. Describe whole river ecosystem production from seasonal water chemistry and physical parameters

9. Recommend how *V. nana*, macroinvertebrates and other fauna might be used in monitoring programs that assess the efficacy of environmental water provisions

Hydrology

Wet and dry season flow in the Daly River is highly predictable. Variability in the timing and magnitude of wet season flows relates to the rainfall patterns of the preceding wet season. Variability of dry season flow also relates to antecedent conditions. The magnitude of the preceding wet season(s) determines the amount of recharge to aquifers and the pressure under which water is held and therefore the timing and rate at which groundwater discharges to the river. Essential features relevant to the Daly River include base flow requirements, perenniality, predictability and recharge to aquifers.

During the dry season, the Oolloo aquifer discharges to the Daly River along the middle reaches via numerous springs in the channel bed and banks. This groundwater gives the river its perennial status. Groundwater maintains base-flow at depths ~0.5 to 2 m in the pools and considerably less over the riffles. Small changes in depth threaten the continuity of the river. Biota are adapted to minimum instantaneous flows that the hydrological record indicates ranged from ~6-25 cumecs.

Rainfall from 1997/8 to 2001/02 has been above average and resulted in above average minimum flows. In 2002, peizometric levels in groundwater bores adjacent to the river were well above average and are causing groundwater to discharge into the river while levels are still relatively high. Between 1974-2001, minimum instantaneous flow at the study sites near Oolloo crossing ranged from 11-25 cumecs. This compared with 7-11 cumecs between 1960-1974. Simulated minimum flows (from rainfall and flow data, Jolly 2001) showed that since early this century, there have been distinct runs of high and low flow periods, indicating that the present high flow period will eventually cease.

The recession curves for these extreme periods illustrates the interannual variation in the timing of groundwater input to the river. During below average conditions, groundwater discharge begins early in the year when the river is shallow and at low flow. For example, in 1962 groundwater input at Dorisvale Station, began on 20-Mar when flow was 20 cumecs. Flow then decreased rapidly over 2-3 weeks, remaining at 7 cumecs for the following 6 months. During above average conditions in 2000, groundwater input began on 15-May when flow was 80 cumecs. Flow kept decreasing all year reaching a minimum of 13 cumecs in mid-October.

Considerable groundwater input occurs downstream of Dorisvale Crossing, starting around the confluence with Stray Creek and continuing to just upstream of the Douglas River. In the last 4-5 years, between 15-30 cumecs was added to the river between Dorisvale station and Mt Nancar station, whereas in below average conditions, the input is only 3-5 cumecs.

Minimum flows from Mt Nancar station are more similar to flows at the Oolloo study sites, and together with the now closed Gourley station, those hydrographic records are of greater use than upstream stations (Figure 2). The emphasis of gaugings has been on high flows and flood forecasting rather than on low flows and environmental requirements.

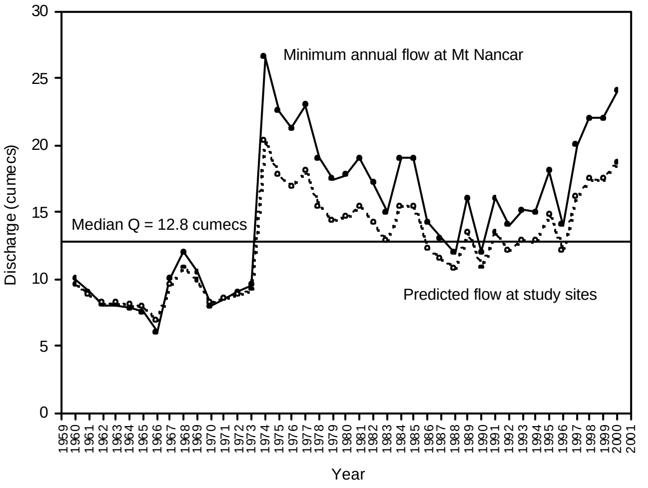


Figure 2 Minimum instantaneous annual flows at Mt Nancar (closed circles incorporating Gourley station record) and mean predicted flow (open circles) at the 4 study sites near Oolloo crossing from 1960-2000

Water physico-chemistry

Water chemistry differs markedly between the seasons. The river is kept flowing in the wet season by rainwater which has a very low conductivity and surface run-off which carries nutrients and organic matter. In the dry season, the river is kept flowing by groundwater which has been housed in limestone aquifers and is dominated by bicarbonate ions. This highly buffered, highly ionic water (order HCO_3> Cl> Ca> Na> Mg) provides a very different aquatic environment during the dry season. High Cl and Na concentrations were typical in springs around Oolloo Crossing but atypical for the wider groundwaters of the Daly Basin.

Groundwater from the Oolloo aquifer and therefore the Daly River in the dry season has very low nutrient levels (nitrate-nitrite 0.001–0.01 mg/L, nitrate 0.004-0.04 mg/L, reactive phosphorus <0.005 mg/L). This fragile condition makes the river extremely susceptible to small increases in nutrients.

Over the transition period between wet and dry season flow, there was a steady increase in conductivity (Figure 3), TDS and light, and concomitant decrease in suspended solids, turbidity, Fe, nitrate-nitrite and total phosphorus. The sharp fall in turbidity from 17 to 5 NLU over the 1st week of May-01, coincided with an increase in light measurements (mean daily PAR, attenuation coefficient, euphotic depth). The fall in turbidity was too rapid to be attributed to the physical process of sediments settling as flow decreased. The chemical process of agglomeration and flocculation was responsible with the input of positively charged ions in the groundwater being attracted to the negatively charged dispersed particles typical of wet season flow. It is the chemistry and flow rate of groundwater entering the river that is responsible for the trade-mark chrystal clear waters of the Daly River. Both need to be maintained to provide light for plant growth. The onset of the growing season can be predicted from recession curves.

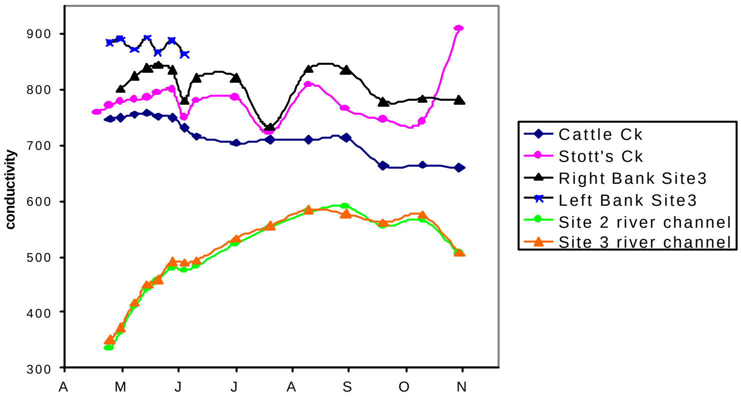


Figure 3 Conductivity from April to November 2001 in the main channel and in 4 springs discharging to the river

Photosynthetically Active Radiation at the bottom of the water column where submerged macrophytes are rooted, increased from 30 to 140 µEm^{-2}s^{-1} from mid-April to mid-May (Figure 4). Given that the modal range for light saturation for phytoplankton photosynthesis is 60-100 µEm^{-2}s^{-1} (Reynolds 1984), this suggests that light became available for the growth of all plants from early May.

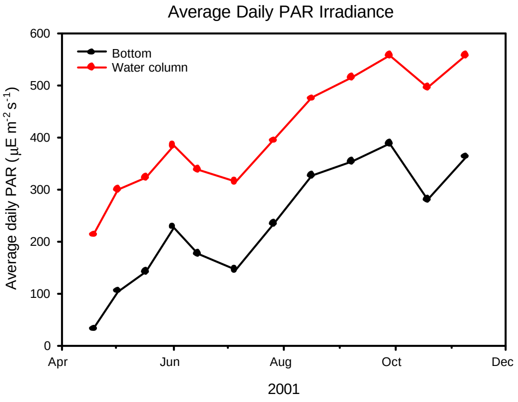
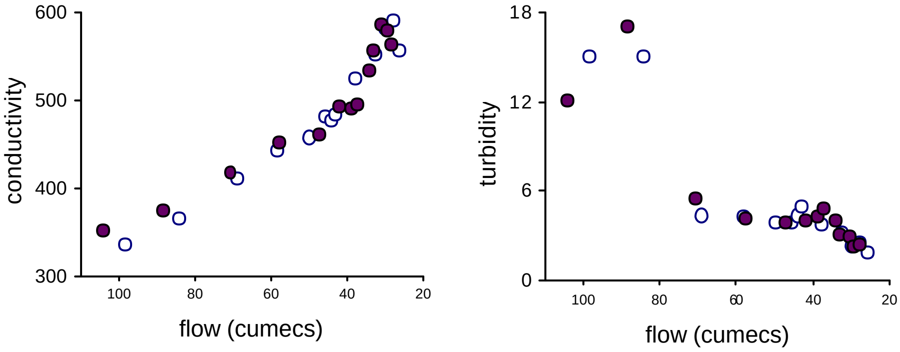


Figure 4 Average daily irradiance through the water column ($\overline{I_W}$) and at the bottom ($\overline{I_B}$)

As flow decreases, conductivity increases gradually whereas turbidity falls sharply at ~70-80 cumecs (Figure 5). This 'threshhold' flow occurs when groundwater exceeds wet season flow and causes the sudden flocculation of dispersed particles. This 'threshhold' flow varies interannually according to the timing and rate of groundwater input



.Figure 5 The relationship between flow, and conductivity and turbidity at Site 2 and 3 (open, closed circles)

Vallisneria nana habitat value

V. nana beds provide significant habitat to a wide variety of turtles, macroinvertebrates and fish. The distribution of 6 vertebrate taxa were mapped. Freshwater crocodiles frequent the beds, as well as freshwater whip-rays and the pig-nosed turtle. These latter two species appear to favour patches of *V. nana* in fast flowing water at the start of beds. The pig-nosed turtle was significantly associated with *V. nana* patches. During a boat survey of both sides of a 16 km stretch of the river, 59 sightings were made of individuals or groups of pig-nosed turtle, with the majority (>90%) located within *V. nana* beds.

Ninety-six macroinvertebrate taxa were identified from 6 habitat types (low current *V. nana*, fast current *V. nana*, pebbles/gravel, coarse sand in a pool, bare rock, channel edge). The relative abundance of macroinvertebrates differed between habitats, with assemblages in low current *V. nana* being distinct from those in fast current *V. nana.* The variables velocity and depth were significantly correlated with the ordination solution (Table 1). Gastropod molluscs were abundant in, but not confined to, *V. nana* beds.

Table 1 Environmental variables with significant correlations with HMDS ordination solution using macroinvertebrate relative abundance and presence-absence data from principal axis correlation procedure in PATN

Data type	**Variable**	***R***	***P* value**
Relative abundance	Water velocity	0.97	**<0.01**
	Water depth	0.59	**<0.01**
	pH	0.40	>0.05
	Dissolved oxygen	0.25	>0.05
	Conductivity	0.15	>0.05
Presence-absence	Water velocity	0.92	**<0.01**
	Water depth	0.54	>0.05
	pH	0.42	>0.05
	Dissolved oxygen	0.28	>0.05
	Conductivity	0.13	>0.05

Vallisneria nana distribution and habitat preference

V. nana is the dominant submerged macrophyte in the surveyed stretch of the Daly River from Katherine township to Beeboom Crossing (~300 km). Patches of *Blyxa aubertii* are rare. Charophyte species typical of low nutrient and unpolluted waters were recorded and noted as forming large beds in the main channel of the middle reaches. Although their ecological role is unknown, their presence and pattern of occurrence should be maintained.

The distribution pattern and broadscale habitat correlates of *V. nana* were determined from an aerial catchment scale survey, a reach scale boat survey and a site scale survey of 27 cross channel transects. The major beds of *V. nana* are restricted to the middle reaches; from 32 km downstream of Dorisvale Crossing (near entrance of Stray Creek) to ~20 km upstream of the Douglas River confluence. 14 major beds were located between Jinduckin Creek and the Douglas River confluence (30.6 kms; Figure 6).

The major beds occur on the outside edge of river meander bends, where outcrops of the bedded Oolloo dolostone occur. Crevices in the pavement like surface of these rock 'platforms' provide a refuge for *V. nana* shoots to survive the adversity of the high wet season flows. *V. nana* generally occurs in linear beds parallel to the bank edge. Beds are constructed of a mosaic of individual patches that vary in size and degree of coalescence. Within this reach, beds varied from 370-2,580 m long, 4.5-14 m wide and at 1-15 m from the bank. The beds occupied 25.6 % of the bank edge and 0.02 % of the total area of the reach.

Preference curves for depth, distance from bank edge and mean and maximum velocity were generated from 27 cross channel transects that recorded % *V. nana* cover in 0.25 x 0.25m quadrats and the associated depth and mean and maximum water column velocity. During August 2001, *V. nana* occurred within a depth range of 0-1.3 m, mean velocity range of 0-0.6 m/s, and maximum velocity range of 0-0.75 m/s. The major beds occurred in the area of channel with the highest velocity (Figure 7 ab).

For *V. nana* with 100% cover, the probability of occurrence was greatest at 0.6 m water depth (0.4-0.8 m) and 5 m from the bank edge (4-6 m; Figure 8). The range of channel characteristics where *V. nana* beds were present were; width 40.0-64.7 m, depth 0.76-1.81 m, and mean velocity 0.30-0.68 m/s.

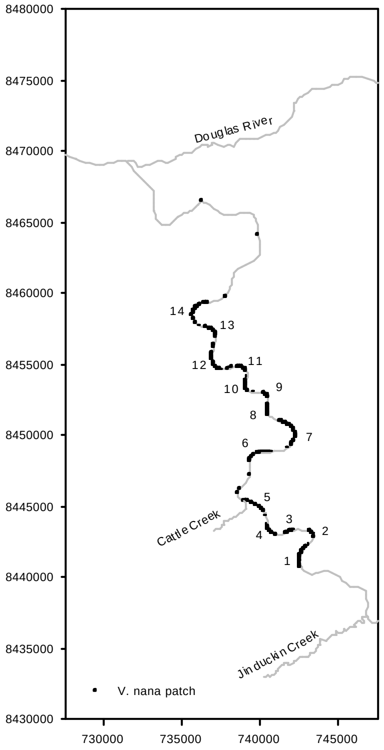


Figure 6 The distribution of *V. nana* beds in the middle reaches of the Daly River

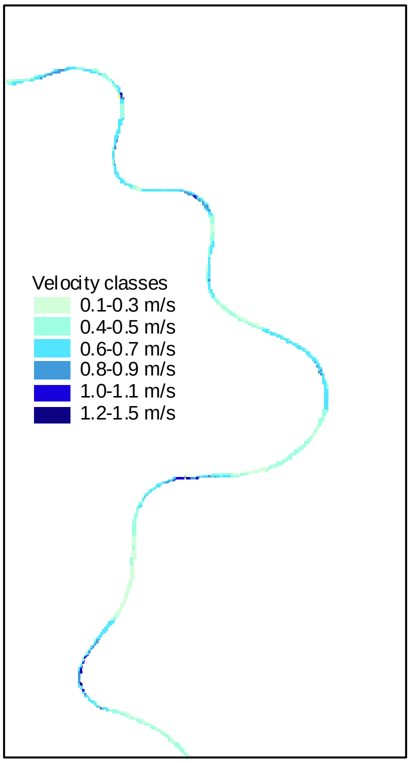


Figure 7a Distribution of velocity classes at a flow of 30 cumecs from the RMA hydrodynamic model

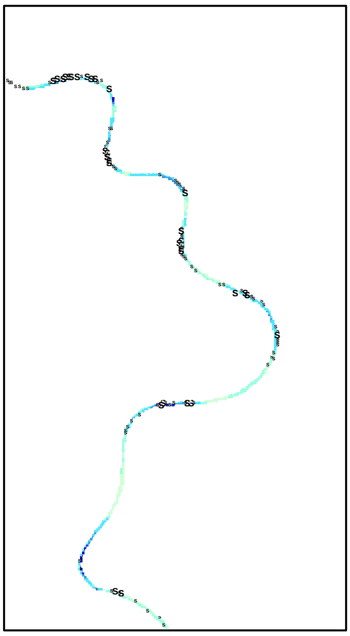


Figure 7b Distribution of velocity classes at a flow of 30 cumecs from the RMA hydrodynamic model with overlay of *V. nana* records

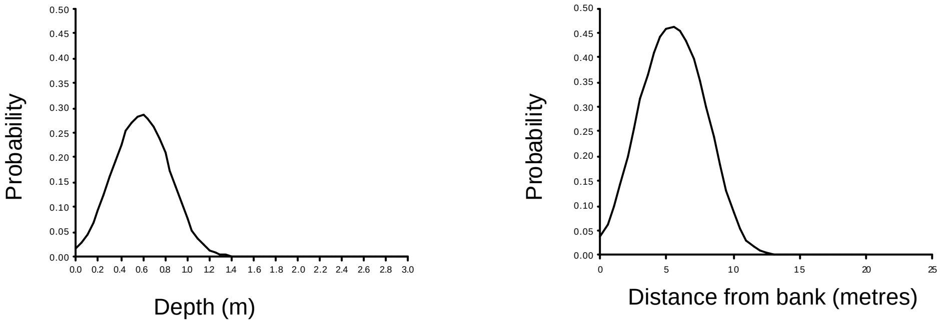


Figure 8 Curves of probability of occurrence of *V. nana* at 100% cover versus depth and distance from bank derived from logistic regression

The gracile character of V. nana identifies it as adapted to moderate current that keeps leaves narrow (1-4 mm) and relatively short (<80 cm). *V. nana* was generally absent from areas with low channel velocities and present in, or adjacent to, high current. This defines a zone on the channel slope in which conditions are most favourable. Growth appears to be limited by substrate stability and current at the channel side of the depth/distance gradient, and by the probability of exposure leading to mortality at the bank edge.

Vallisneria nana ecology

Morphology

V. nana is a perennial stoloniferous submerged macrophyte with shoots composed of basal narrow ribbon-like leaves. Dense monospecific stands develop during the dry season. The cover of *V. nana* increases by stoloniferous growth and continuous leaf and shoot recruitment throughout the growing season with no evidence of cohorts. Clonal patches expand across the rock platform and toward the end of the dry season can occasionally spread downslope onto the sandy substrate of the main channel.

Some flowering took place in August and September but was not prolific. The literature suggests that flowering is limited in this genus by fast velocities. There was some indication that recruitment slowed after flowering. Existing leaves continued to grow by becoming longer and broader. This response may also relate to slower velocities. *V. nana* is comprised of >80 % leaf, with roots and stolons accounting for the remainder of mass during the dry season. Over the wet season, small rhizomes develop, allowing a few shoots to survive the wet season and supporting new growth in the following growth season.

Three measures of *V. nana* growth (morphological measurements, mass and its allocation, tissue nutrient concentrations) were employed to determine demographic characteristics, environmental cues and constraints, and the onset and cessation of growth. The allocation of new leaf and root mass, the % number and length of new leaf (Figure 9), and the Na concentration of new leaves, all increased rapidly from early May till mid-July, indicating that the cue for growth was the sudden availability of light. *V. nana* growth falls within flow, depth and velocity limits. Light is the main cue for growth within these limits, while the main constraint to growth is the very low supply of nutrients.

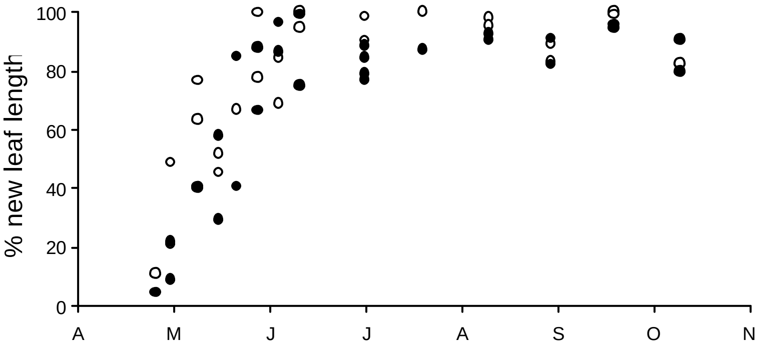


Figure 9 The % of *V. nana* leaf that was new at Site 2 & 3 (open, closed circles) throughout the 2001 dry season

Figure 9 was a typical response for a number of growth parameters, as was their relationship with flow shown for the % of leaf mass that was new (Figure 10). The onset of growth occurred below ~70 cumecs which matches the flow at which light became available.

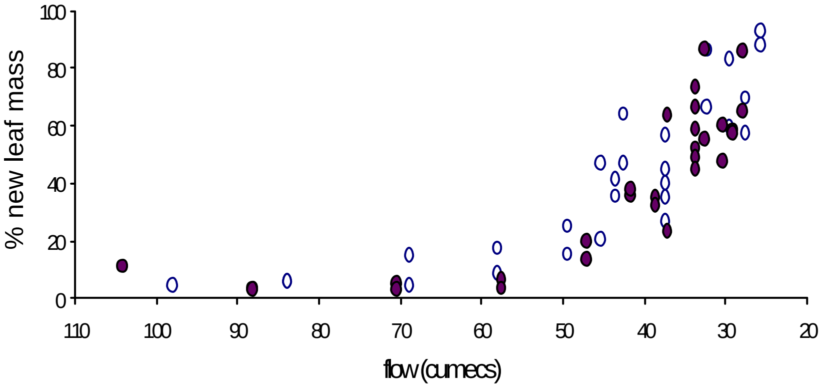


Figure 10 The relationship between flow in 2001 and the % of *V. nana* leaf mass that was new at Site 2 (open circles) and Site 3 (closed circles)

Tissue Chemistry

Tissue nutrient concentrations above and belowground are at healthy levels at the start of the growing season. Concentrations in new leaves fell to critical levels (1.3 mgN/g, 0.13 mgP/g) by the end of the dry season. There were no spare nutrients to take up from the water column. The available nutrient pool was spread throughout the growing clonal plant, thereby diluting concentrations. The decrease in Na and especially P is more rapid at Site 3, indicating higher production of mass or better growing conditions at site 3 (Figure 11). Low nutrient levels appear to constrain *V. nana*'s total biomass accumulation. This is exacerbated by herbivore grazing (eg turtles), with recycled nutrients most likely captured by the dominant macroalga *Spirogyra.*

Concentrations of heavy metals and trace elements indicated their naturally high levels in the water and sediments of the Daly Basin. Ions that accumulated in the old leaves of *V. nana* were Mg, Ca, S, B, Mn, Zn and Fe. In contrast, N, P and K were always greater in new leaves illustrating their essential role in growth processes. Metal uptake by plants is favoured by oxygenated sediments, low in organic matter and with a low cation exchange capacity (ie the Daly River). As trace element levels in sediments are correlated with those in aquatic plants, the medium to high levels of Cu, Zn, Mn and B indicate their natural occurrence in the Daly River sediments. As water chemistry changes seasonally, the plant sink for metals and elements is a temporary one.

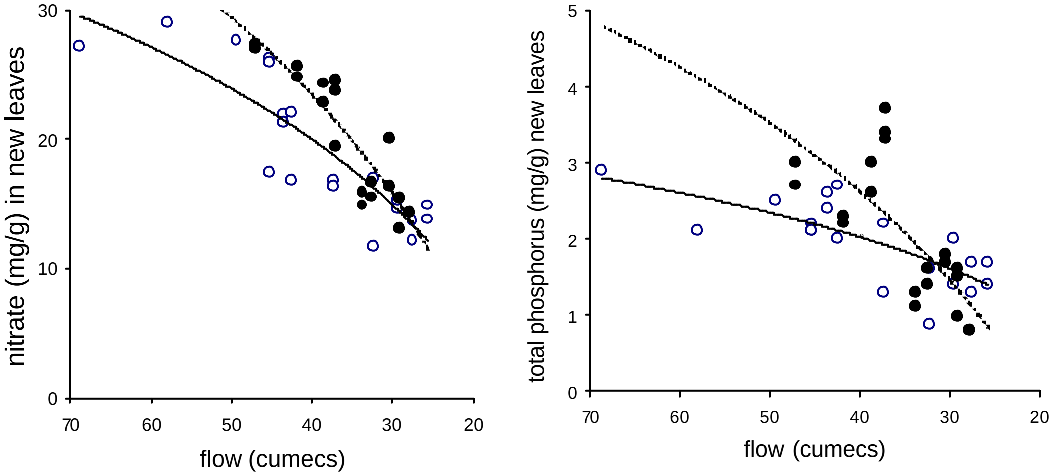


Figure 11 Concentrations of nitrate and total phosphorus in the new leaves of *V. nana* in relation to the decrease in flow throughout the 2001 dry season at site 2 (open circles) and Site 3 (closed circles).

Metal and trace element solubility and uptake increase with water acidity. In the wet season, the more acidic water favours accumulation. During the dry season, groundwater flow keeps the river highly buffered, so that metals are unavailable and leaching can occur. High concentrations of Cu and Zn in the growth season indicate their accumulation over the wet season. Their decrease over the dry season indicates leaching from leaves, mediated by cell-water chemical concentration gradients. *V. nana* is able to lose these elements and prevent the build up of toxic concentrations.

High Mn levels were found throughout *V. nana*, with extremely high levels in old leaves in July (10,000-30,000 ug/g). Those levels relate to the peak in productivity and biomass of epiphytic algae. Very high Mn concentrations in aquatic plants may relate to epiphytic precipitation of Mn mediated by bacteria. For large algal colonies, such as *Spirogyra*, Mn can accumulate in the mucilage that binds cell colonies.

Site 2 vs Site 3

Early in the 2001 dry season, plant growth at Site 2 and Site 3 was similar. However, late in the season, growth appeared to be better at Site 3. Although flow decreased proportionally at these sites and was similar, mean channel velocity remained constant at Site 3 (0.65 m/s) but decreased at Site 2 (0.58 m/s - 0.3 m/s). This difference is due to channel morphology; Site 2 is at the deeper and slower flowing end of a pool and has a greater sectional area than Site 3 which is at the shallower, faster flowing start of a pool.

Leaf recruitment continued for longer at Site 3, whereas at Site 2 existing leaves grew longer and wider. P concentrations in new leaves at Site 3 were nearly double those at Site 2 early in the growth season, however they fell to levels below Site 2 from August onwards. This indicates greater growth and biomass accumulation at Site 3 and the dilution of a limited amount of nutrients. The faster current, higher light and tissue nutrient levels at Site 3 appear to provide better growing conditions for *V. nana*.

Ecosystem modelling

Daily PAR increased steadily from April to November. At least 40% of the increase can be attributed to increasing day length and sun height after the winter solstice in June. Photosynthesis was shown to be proportional to light intensity, meaning that even though the underwater light climate is very favourable, plants could further increase their photosynthetic rates if provided with even more light.

Early in the growing season while flows are subsiding, a small phytoplankton population dominates primary production due to their ability to grow quickly and sequester the small nutrient pool available at this time. Thereafter, the biomass of benthic plants increases and phytoplankton concentrations decline because they are less effective competitors for nutrients. The mass of benthic plants increases rapidly from May to July. Macroalgae mass peaks in August whereas macrophyte mass appears to remain constant from July onwards. Nutrient concentrations in the water column remain low because of rapid uptake by these plants.

The low nitrogen levels meant that phytoplankton primary production could only be sustained for a full day in April and May, and thereafter for only an hour or less. After June, there was only enough N to support production by *Spirogyra*, *V. nana* and the charophytes for several hours each day. As dissolved reactive P concentrations were at or below the analytical detection limit they could only sustain primary production for 24h in April. Thereafter, all primary production was limited by P availability. P was more limiting than N.

Measured and modelled O_2 and total CO_2 concentrations show pronounced diurnal cycles, with DO lowest at ~ 0700 due to night time respiration and highest at 1700 due to day time photosynthesis. Daily photosynthetic rates estimated from the diurnal curve method increased from near zero in mid-April to a maximum of ~0.15 $molm^{-3}d^{-1}$ in early August. Respiration rates similarly increased through the 8 months of the study. Respiration rates significantly exceeded photosynthetic rates (P/R ratios range between 0–0.5) meaning that the Daly River is strongly heterotrophic (Figure 12).

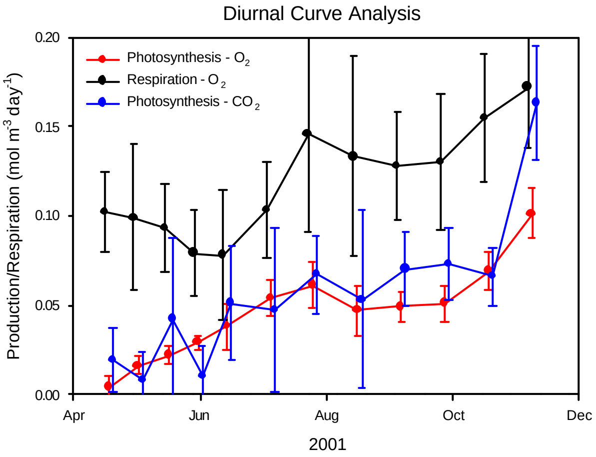


Figure 12 Photosynthesis and respiration rates derived from the oxygen and carbon dioxide diurnal-curve analyses

Although photosynthetic rates are controlled by biomass and light, the conversion of production into biomass depends on nutrient availability. The extremely nutrient poor conditions in the river means that only about 15% of photosynthetic production is converted into biomass. The daily N requirements at the estimated rates of photosynthesis are far in excess of the N available in the water column (Figure 13). Most carbon produced is excreted as carbohydrate, then lost through respiration by bacteria and microorganisms in the hyporheic zone. The Daly River is a net exporter of CO_2 to the atmosphere. Areal net CO_2 production in the dry season is ~6 times larger than estimated rates for rivers in the Amazon Basin (Richey *et al* 2002).

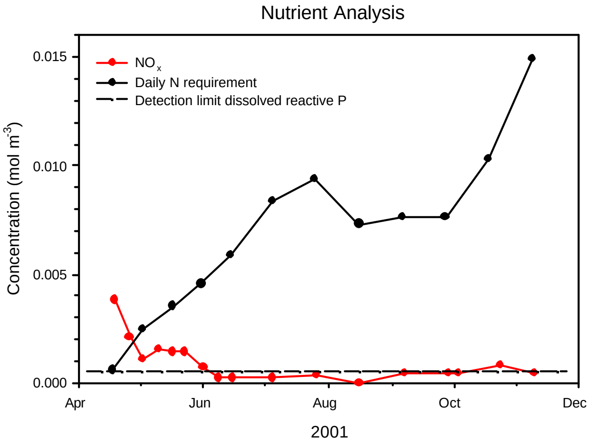


Figure 13 Concentrations of NO_x through the study period. Also shown is the N concentration required to sustain primary production at the estimated rate of photosynthesis for 24h

Predicted effect of reduced dry season flow

Data from multiple channel transects included depth, velocity, and % cover of *V. nana.* The RMA model was used to predict the distribution of the optimal velocity and depth classes under 8 flows which cover minimum instantaneous flows in above- to below-average years (eg 30, 25, 20, 15, 12, 9, 6, 3 cumecs).

The RMA model was used to predict the elevation of the river over a 16 km reach. This data was combined with elevation data from 8 of the 27 transects, to determine the % exposure of each bed under decreasing flows. The response curve showed a threshhold at ~12 cumecs (Figure 14). At slower flows, there was a rapid decrease in the % of *V. nana* inundated. As a submerged species with a very small belowground component, *V. nana* is not adapted to exposure. Exposure can therefore be considered fatal. Further work is needed to determine the full consequences of exposure for different durations.

Depending on channel morphology, the area of *V. nana* beds inundated either decreased steadily <20 cumecs or suddenly between 3-6 cumecs. The average inflection point or threshold where flow reduced wetted area significantly was between 10-15 cumecs (Figure 14). Below 10 cumecs the decline was sharp. At 3 and 6 cumecs respectively, 60% and 28% of beds would be exposed or lost. The response curve for the preferred depth range also showed that 75% and 60% of beds would be lost at 3 and 6 cumecs respectively.

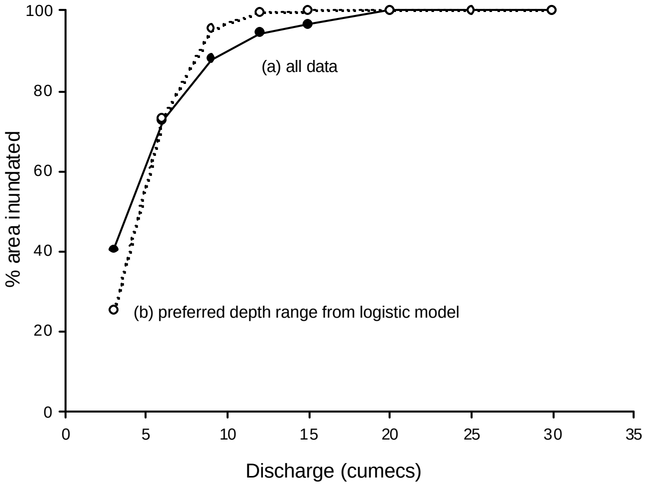


Figure 14 (a) The relationship between flow and the mean percent area of inundated *V. nana* predicted by the hydrodynamic model. (b) The relationship between flow and the mean percent width of inundated *V. nana* when growing at its optimal depth range of 0.4-0.8 m (as predicted by the hydrodynamic model and modelled habitat preference data). Data is the mean from 8 selected channel transects within a 17 km reach.

The degree to which the 8 selected *V. nana* beds would have been exposed since 1960 was calculated from the hydrologic record from Mt Nancar station. Figure 15 illustrates that in average to above average conditions (since 1974), the area inundated by the end of the dry season was always ~95 %. In drier years when the minimum flows were 6-11 cumecs, the inundated area would have been ~75-90 %. A substantially less area would have been inundated under favourable conditions. This percentage also relates to 8 good quality sites. For the full range of beds, the inundated area would be even less.

Figure 3 The estimated percent exposure of *Vallisneria* at minimum annual flow from 1960-2000. Data derived from estimated minimum flow at study sites and predictions of *Vallisneria* exposure.

It is important to note that changes in water surface elevation (depth) have negative effects well before beds are exposed. Depths and velocities less than the preferred ranges (40-80 cm, 0.2-0.4 m/s) would be experienced well before bed exposure and would have adverse effects on *V. nana* growth and habitat quality. Secondly, the protection of the identified beds is critical because they are the locations where the plant retreats to during high flows. These beds are the source of propagules that expand cover during the dry season. It cannot be assumed that at low flows, *V. nana* will migrate downslope and create the same habitat in the sandy middle of the main channel. Those plants are annually uprooted by wet season flows.

Conclusions

V. nana beds are a significant vegetation formation. The environmental and habitat values they provide indicate their protection is of critical importance.

The presence of *V. nana* beds is due to the conjunction of several factors, namely geological formations in the river, and sustained input of groundwater of high quality throughout the dry season. This water bestows high light, moderate velocities and low nutrient levels. This conjunction of factors is rare in Northern Australia or elsewhere.

Net primary production in the river is limited by the availability of light and nutrients. Moderate velocities and the low nutrient status of the Daly River during the dry season control the character of *V. nana*. Increasing nutrient inputs to the river would result in higher net primary production and biomass, which in turn would increase photosynthesis and respiration rates and cause an increase in the magnitude of the diurnal oxygen cycle. This could have a major deleterious effect on riverine biota if oxygen concentrations were to fall sufficiently through the night.

V. nana can withstand a range of dry season flows. Optimal flows were shown to be greater than 10-12 cumecs. Below 10 cumecs, there is a sudden decrease in the habitat availability for *V. nana*. 12 cumecs equates with the long term minimum average around Oolloo crossing and also marks the inflection point on the response curve for % exposure and depth preference of *V. nana.*

Exposure/inundation does not take into account velocity. Although *V. nana* may survive when flooded by shallow water with little to no current, it needs moderate velocities and depths of 0.4-0.8 m to maintain its character and the habitat value it provides.

Information about macrophyte requirements in an unregulated, unimpacted river provides useful insight about macrophyte loss and wider riverine ecological impacts from rivers where the flow regime and water quality has changed.

There is a need for careful management based on the precautionary principle and ongoing monitoring to ensure that management objectives are met. The conservation value of the middle reaches of the Daly River warrants caution concerning any land or water use in the catchment.

Land clearing has the potential to reduce recharge and together with degradation of the riparian zone and poor agricultural practises, increase surface run-off of sediments, nutrients and chemicals. Knowledge of how water moves through the landscape and relates to soil and vegetation cover is needed.

Recommendations

1. *V. nana* beds (as opposed to *V. nana* in general), play a critical role in maintaining the wider ecology of the riverine landscape. The aim should be to maintain the existing *V. nana* beds and their integrity (ie diversity of localised current, depth and substrate environments within).

2. Water quality is as important as water flow. As in other jurisdictions *environmental water requirements* (EWR) should be used in preference to *environmental flows*.

3. Sustained groundwater input of Oolloo aquifer water from early in the dry season is essential to maintain:
   - the conditions that cause light to become available (agglomeration of ions and flocculation)
   - low nutrient levels in the river
   - highly buffered water that keeps metals unavailable and aids in their leaching from plant tissue.

4. Groundwater input that supports dry season flows >12 cumecs in the vicinity of Oolloo Crossing should be maintained to protect the environmental values provided by *V. nana.* This flow equates with the long term minimum average and is a hydrologic statistic that could be considered ‘a line in the sand’, below which water levels should not fall. Although *V. nana* may be able to bounce back from unavoidable drought years with a lower minimum flow, several years of artificially induced low flows should be avoided at all costs. This recommendation is based on the degree of exposure of V. nana beds. Adverse conditions exist well before exposure (which is considered to be fatal).

5. The optimal depth and velocity ranges need to be provided over the rock platforms where the major beds occur and from where *V. nana* expands from and retreats to. During 2001, when the minimum flow was 25 cumecs, the optimal ranges were 0.4-0.6m depth and 0.2-0.4 m/s within the beds. All plants growing on sand are annually uprooted and do not allow *V. nana* to persist from year to year.

6. Annual monitoring of the persistence, dimensions and inundation/exposure of *V. nana* beds is necessary to ensure management objectives are met.

7. The conservation value of the middle reaches of the Daly River warrants application of the precautionary principles concerning land and water use.

8. Natural Resource Management frameworks need to operate in unison with Environmental Water Provisions for either to be effective.

9. Management of catchment use and practises must prevent any change to the present status of the river with regard to nutrients, light and sediments.

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