

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

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Summary

This project evaluates whether phytoplankton, benthic diatoms and macroalgae are directly, or indirectly, responsive to dry season river flow, and provide information for the allocation of water for the environment. Owing to their rapid replication rate of a couple of days, these algae are responsive over a time scale of weeks to changes in the aquatic environment, notably flow and water quality.

Flow in the Daly River and its major tributaries, during the dry season, is maintained by groundwater. The extraction of water directly from these rivers or from the groundwater during the “dry” will reduce flows in the Daly River and its tributaries. There is also potential for the river’s water quality to be directly affected. In the upper reaches of the catchment, dry season flows originate predominantly from aquifers within Cretaceous sediments. With groundwater inflow from the Daly River Basin, the conductivity of the Daly River increases 20-30 fold, pH and the carbonate buffering capacity increases at least an order of magnitude, whilst soluble phosphorus and nitrate concentrations more than double. In the Douglas River, inflow from the Tindal Limestone results in an almost 100 fold increase in nitrate concentrations but has not resulted in high phytoplankton concentrations due probably to phosphorus limitation. Such a marked increase in nitrate concentrations was not measured elsewhere in the catchment, and may be due to modified land-use and management practices. Extraction from the Daly River Basin for consumptive use would be expected to alter, in addition to flow, river water quality, depending of the change in the mix of river sources.

Diatoms (microscopic algae) are an abundant component of periphyton (algae that grow on surfaces) in rivers, and an important primary producer. They provide a simple and time-efficient means of biomonitoring. The diatom assemblage on river substrates was investigated to determine the best sampling strategy for diatom sample collection. The diatom assemblage on different river substrates was not always similar, underpinning the requirement for a monitoring program to use a single substrate, or substrates shown to be equivalent. Epilithic (rock) and epidendronic (woody debris) substrates occurred commonly in the river, featured similar diatom flora, and were recommended for sample collection in the Daly River and its tributaries.

A total of 252 diatom species were identified, comprising both cosmopolitan and tropical taxa. Epilithic diatom assemblages in the Daly River are responsive to the ionic composition of river water, as well as nitrate, soluble phosphorus, dissolved oxygen, temperature and turbidity. This sensitivity is independent of flow. The diatom flora will respond indirectly to reduced dry season flow caused by water extraction, through its impact on water quality.

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Diatoms are a potential biomonitoring tool for determining anthropogenic impacts on the aquatic ecosystem.

Phytoplankton in the river are highly diverse, with most species representing a small percentage (<1%) of the biovolume. A total of 206 species were identified, from all taxonomic groups including the blue-greens (Cyanobacteria). The concentration of phytoplankton, measured either as chlorophyll a (a photosynthetic pigment) or biovolume, was limited by river flow, rather than light, nutrients or zooplankton grazing. Under lower flows, however, due to either climatic or anthropogenic influences, phytoplankton concentrations may no longer become limited by flow, and instead become nutrient limited. Under such a scenario, where soluble nitrogen and phosphorus enter the river from the Daly River Basin, phytoplankton concentrations could be expected to increase.

Flow, as well as ionic chemistry, influences the assemblage (species composition and their relative abundances) of phytoplankton in the river. A possible mechanism for the influence of flow is through the volume and proportion of waters with a retention time longer than the river's average, for example back-flow waters and "dead" zones where there is minimal exchange with the main river. If this mechanism occurs, then the assemblage of phytoplankton would be expected to differ with lower river flows.

The macroalgae *Spirogyra*, is present on gravel and rock substrates, and along the banks, of the Daly River and some tributaries during the dry season. From being absent early in the dry season (May-June), the alga undergoes rapid growth to reach a maximum biomass in July-August that is likely to represent a significant portion of the river's plant biomass and primary productivity. Algal biomass then declines, finally being removed by storm flow early in the wet season. In addition to a substrate preference, *Spirogyra* also has an optimal range of shear velocity. At the upper range of shear velocity, the algae is physically removed, whereas below this range the alga is unable to grow as well, possibly by not receiving adequate nutrients. The biomass of *Spirogyra*, over a wide range of flows that included ones below the historic range, was modelled. Above 12 cumecs, algal biomass depended primarily on the shear velocity (and thereby flow) above river gravel and rock substrates. Below this value, though, the loss of habitat (rock and gravel substrate) through drying and stagnation became important. Moreover, the rate of biomass loss with reduced flows below the 12 cumecs threshold was three times greater, than rates of loss above the threshold. Simulations of water extraction from the flow record shows that a proportional extraction regime better maintained the natural interannual variability than a fixed regime. These simulations suggest that a proportional extraction rate >8% would adversely affect the natural variability of *Spirogyra* biomass if historical minimum river flows were not to be maintained. If minimum river levels are to be preserved, then simulations show that if no extraction is to occur <10 cumecs, then a proportional extraction rate >9% will affect the natural variability of *Spirogyra* biomass.

River phytoplankton

Phytoplankton species and biomass in the Katherine and Daly Rivers and two tributaries (Flora and Douglas Rivers) was collected on six occasions from June - November 2000. The report includes a phytoplankton species list for each site, and graphical displays of algal numbers and biovolume month by month, site by site, and in terms of the 18 principal taxa identified. Its greatest value undoubtedly lies in the raw data generated within this relatively acute study, and these data are provided in electronic form to facilitate their future publication and use, especially within the more predictive aspects of the current project.

There is a relatively constant presence of planktonic algae at all sites, and of substantial diversity. Calculations made of biovolume agree well with independently determined Chlorophyll a concentrations, in both magnitude and consistency.

Despite the work being limited by the frequency of sampling (monthly vs. the more desirable weekly sampling), we believe it has adequately determined the nature of the algal populations present, and the extent of their fluctuations in time and space.

Some 202 algal taxa were observed during the study. Of these, 36 had not been reported previously from the Northern Territory, and 5 had not been reported previously from Australia. The Bacillariophyceae (63 taxa), the Desmidiaceae (47) and the Chlorophyta (34) were dominant with respect to the number of taxa present. Although several samples had up to 640,000 cells/L (due to *Urosolenia eriensis* and *Fragilaria zasuminensis*), all but 6 samples contained <150,000 cells/L which are densities well below those commonly recorded in the larger rivers of the world, but are similar to those in moderately sized rivers in south-eastern Australia. These suggest an oligotrophic to mesotrophic status within the Katherine/Daly system.

Relatively few species contributed significantly to the algal biomass: only four taxa (*Peridinium inconspicuum*, *Cryptomonas* sp., *Synedra ulna* and *Encyonema silesiacum*) usually contributed more than 1% to total biovolume. *Peridinium inconspicuum* was the most substantial consistent contributor, occurring at up to 195,000 cells/L, and usually comprising 2-15% of total biovolume (maximum 74%). Four taxa (*Spirogyra* spp., *Urosolenia eriensis*, *Fragilaria zasuminensis* and *Peridinium umbonatum*) usually comprised less than 1% of the biomass, but occasionally occurred in high numbers, contributing substantially to biovolume. The occurrence of one of these, *Spirogyra* spp. was something of a confounding factor. Presumed to be present within the water column due to detachment from its usual benthic state, it comprised up to 96% of the calculated biovolume on occasions, but appeared to contribute little to biomass in terms of Chlorophyll a concentrations. A potential explanation of this is the relatively large proportion of cells present from which the chloroplast had been lost.

With respect to downstream and lateral distribution within the Katherine and Daly Rivers, there were no marked trends of increasing numbers. Indeed, several of the higher peaks occurred at the sites furthest upstream, particularly due to *Urosolenia eriensis* and *Fragilaria zasuminensis*. Cell numbers within the Flora and Douglas Rivers were generally similar to those recorded in the upper reaches of the Daly River.

An attempt to quantify downstream increases/decreases in algal “loadings” of four key taxa was inconclusive, except to suggest increased loadings downstream for certain taxa in July, and to indicate substantial tributary contribution on occasion by both the Flora and Douglas Rivers. The extent to which the planktonic algal populations may vary from year to year can only be determined by further sampling. It would also be interesting to conduct a one-off sampling at an appropriate time to more clearly determine the origin of the organisms present in such a diverse population of algae.

Correlation between flow and other environmental variables with phytoplankton assemblages

The objective was to evaluate the relationship between phytoplankton composition and biovolume, with flow and other environmental variables in the Daly River and its tributaries. The unidirectional flow of rivers dominates the composition and biomass of phytoplankton. To maintain a population in a river, recruitment rates of phytoplankton need to exceed the

river's mean travel time; otherwise populations will decline. River flow also has a direct influence on turbulence, and hence the light climate phytoplankton are exposed to, whilst stratification can indirectly affect river nutrient dynamics. The biotic control of river phytoplankton, for example by zooplankton grazing, can only take place when the physical constraints of flow are reduced. These influences combine to make phytoplankton a potentially sensitive component of a river's ecosystem to flow.

The principal factors selecting phytoplankton in rivers are: (1) nutrient limitation (N,P, Si), (2) light limitation, (3) river discharge, and (4) river mixing dynamics. These factors combine to determine the total biomass of phytoplankton, and its species assemblage.

Nutrient limitation of phytoplankton biovolume is often less important than physical constraints. Concentrations of phytoplankton are low in the Daly River and its tributaries compared to the lower reaches of the Murray River, but similar or greater than smaller rivers in southern Australia. The addition of nutrients may have altered the phytoplankton assemblage, based on the relative abilities of species to utilise these nutrients. Filterable reactive phosphorus was found to be a significant correlate when the phytoplankton data set included diatoms, though notably not when diatoms were excluded from the data set. This probably reflects the significance of reactive phosphorus in explaining the assemblage of benthic diatoms.

Diatoms in the Daly River and its tributaries are unlikely to be limited by silica, an essential element for diatoms for their cell frustules. Concentrations >0.6 mg/L Si can limit the growth of some diatoms. Silica was a significant correlate for the analysis that excluded diatoms, but itself was correlated to conductivity, pH and gilvin. This correlation is not considered to have ecological significance, instead it is attributed to silica's correlation to other water quality variables of potential ecological significance.

Light is not likely to limit phytoplankton biovolume or influence its assemblage at any of the sites, a conclusion supported by the multi-variate analyses, which found no significant correlation between the euphotic depth and phytoplankton assemblage. The waters of the Daly River, when groundwater fed, are clear. Furthermore, incident radiation levels are relatively high at a latitude of 13°S. The river is directly exposed to sunlight between about 10 am and 3 pm when daytime incident radiation levels are greatest. In the early morning and late afternoon portions of the river were in shadow.

Gilvin was significantly correlated to the phytoplankton assemblages in both statistical analyses. Gilvin is a quantitative measure of dissolved organic substances (e.g. humic acids) that absorb light with wavelengths of greater than 400 nm. High gilvin values increase the absorption of light by humic substances and reduces light penetration. This was not the case in the Daly River and its tributaries. The correlation between gilvin and conductivity best explains gilvin's statistical significance. As with silica, it is unlikely to provide selective pressure on the river's phytoplankton species or limit its biovolume.

Conductivity and pH contributed to explaining the variability in phytoplankton assemblages. Phytoplankton cells tolerate a range of salinities and pH, specific to a species. When the salinity exceeds this range, the cells die, due to water movement into or out of the cell. If a cell cannot maintain its plasma pH, critical enzymes may not function. The salinity and pH tolerances of benthic diatoms is known for some temperate species, but poorly known for phytoplankton except for large salinity ranges (freshwater-brackish-marine) and pH ranges. The ionic chemistry of the Daly River and its tributaries may exert selective pressure on the assemblage of phytoplankton.

Both correlation analyses identified flow as a factor that explained the phytoplankton assemblage of the Daly River and its tributaries. Flow will affect river phytoplankton

indirectly through current speed, and hence the rate of removal of phytoplankton and also the occurrence of zones where water is retained for periods longer than the average travel time. These occur in the deep pools in Katherine Gorge and in the Dorisvale-Beeboom reach may have zones of long retention time. The growth of phytoplankton is different in these low retention zones, that are separated from the main flow by a boundary where water is exchanged with the river.

Discussion

The study has shown that the phytoplankton assemblage of the river are responsive to flow. The extent to which flow determines the assemblage over the historic range is unknown. A reduction in dry season flow, due to water allocation for consumptive uses, could affect the size and nutritional value of the phytoplankton assemblage. This may have broader ecological implications for zooplankton grazing, and the river's carbon (energy) dynamics. Phytoplankton biovolume is often reported to increase as river flow reduces, though there was no evidence of this in the 2000 dry season. This may occur, though, when river flows are lower.

The concentration of phytoplankton, measured as either chlorophyll a or biovolume, in the Daly River and its tributaries was limited by river flow, rather than light, nutrients or zooplankton grazing. However, under lower flows, due to either climatic or anthropogenic influences, phytoplankton concentrations may no longer become limited by flow, and instead become nutrient limited. Under such a scenario, where soluble nitrogen and phosphorus enter the river from the Daly River Basin, phytoplankton concentrations could be expected to increase.

Conclusions and recommendations

The assemblage of phytoplankton is responsive to flow in the Daly River and its tributaries, and ought to be a useful biological indicator in determining the significance of any anthropogenic impacts on the rivers' ecosystem. These, of course, are not limited to the consumptive use of water. Changes in land-use and catchment hydrology will also potentially impact the river's ecosystem.

We recommend that phytoplankton (and other biological indicators) be incorporated into a monitoring program, as part of an adaptive management strategy. There needs to be (1) collection of pre-impact data, (2) evaluation of the effect of consumptive water use on river flow and (3) identification of other anthropogenic impacts on the river's ecosystem. Assessment of the physical mechanisms that determine phytoplankton assemblages and the ecological implications for zooplankton grazing on phytoplankton assemblages would be useful as would the effect of the historic range of flows and river pools on phytoplankton assemblages and biovolumes and their utility for long term monitoring.

Diatom assemblages on river substrates

Introduction

Benthic diatoms are an abundant component of periphyton in rivers and streams, and important primary producers in many lotic food webs. Their ubiquitous distribution in the aquatic environment and responsiveness to water quality have made diatoms a popular

biological indicator of river health in Europe and North America, and increasingly in Australia. Diatoms grow on a wide range of substrates, including epilithon (rocks), epidendron (submerged wood), epipelon (fine sediment ie mud), epipsammon (sand), epiphyton (submerged aquatic plants including macroalgae) and epizoon (aquatic animals).

For selecting substrates for benthic diatom sample collection, the 'single substrate sampling method' was chosen to assess (1) availability of river substrates and (2) the similarity of diatom assemblages on river substrates. If diatom assemblages on different substrates were similar, this would increase the number of substrates available for sampling. Variability between substrates may be reduced by using a single substrate, enhancing the comparability between sites. The principal disadvantage of this sampling protocol is the dependency of site selection on substrate availability. This, however, may be partly overcome if two or more substrates can be shown to have similar diatom assemblages. Species richness of a single substrate may be lower than multi-substrate sampling. In addition to evaluating diatom assemblages on river substrates, the number of diatoms required to evaluate species richness was evaluated and is referred to as the counting effort.

Results and discussion

The selection criteria for a sample site resulted in all sites being located where either a road crossed or ended at a river. Causeways were located, not surprisingly, where the river was shallow with a stable bed, generally comprising cobbles and boulders. Otherwise, roads tended to end at sites of recreation value, such as the Crystal Falls, Kathleen Falls and Douglas Hot Springs. All the sites included epilithic substrata, and featured fast flowing water that seemed to favour the presence of macro-algae. Woody debris were also a common substrate, as the Daly River and its tributaries have not been de-snagged as have some southern Australian rivers. Owing to the weathered nature of the catchments, and high loads of sand carried by the rivers, epipsammic substrates were common. Macrophytes and soft sediment, however, occurred less frequently than other substrata.

The similarity of diatom assemblages was, in general, greater between replicate samples collected from the same substrate, than replicates collected from other substrates. Diatom assemblages between substrates varied due to sometimes significantly different relative abundances of commonly occurring species. There was no evidence of commonly occurring species being substrate specific.

Diatom assemblages between substrates also varied due to the occurrence of species unique to a substrate. These taxa, however, were rare (relative abundance <1%) but sometimes numerous. Their low relative abundance may be due to stochastic factors, rather a being evidence of a preferred substrate. Species richness also varied between substrates.

The species richness and assemblage of the Vallisneria leaf substrate was depauperate compared to other substrata. Invertebrate grazing of periphyton may have limited the colonisation and growth of diatoms. The leaves of Vallisneria offered a sheltered habitat for invertebrate grazers, compared to the other macrophytes sampled (Juncus and Chara). To identify all species in a sample, about a conservative number of 500 valves need to be counted.

Conclusions and recommendations

Epilithic substrates are the recommended preferred substrate for benthic diatoms, as they are often accessible by road and occur where the river is flowing fast. However, where this

substrate is not available, an epidendric substrate can be substituted. Both these substrata have hard surfaces, and differed little in their relative abundances of common taxa and species richness. Epidendric substrates are relatively common in the streams and rivers of the Daly River catchment. Epilithon are the recommended substrate for European rivers, though other substrates are used frequently. The diatom flora of macrophyte leaf surfaces can vary substantially from epilithon and epidendron, and not recommended for catchment-wide monitoring. This substrate is the least preferred substrate. Diatom communities on macrophytes can vary between species, and even on the same plant.

Relationship between benthic diatoms and water quality

Introduction

Diatoms provide a simple and time-efficient means of biomonitoring streams as they are abundant and are easily to collect. This facilitates regular sampling that can provide insights of seasonal variation and, where support is maintained over longer periods, of inter-annual variability. Diatoms have advantages over macroinvertebrates for biomonitoring and, after a period of being under utilized in Australia are increasingly being valued as a biomonitoring organism. Diatom data sets have been established in Australia to infer lake and reservoir salinity, pH and phosphorous. Stream diatoms have been applied to the AUSRIVAS model with limited success and have been used to demonstrate the impact of urbanization, regulation, nutrient and thermal pollution.

By virtue of their abundance and diversity, diatoms were considered to be one of the most appropriate indicators groups for a study of the impact of flow on the ecology on the Daly River system. A wide range of samples was collected from 18 sites and from a range of substrates. Epilithic samples were used to evaluate the relations between diatoms and water quality both over time and position in the catchment. These sub-studies are identified as the temporal and longitudinal studies respectively. A total of 252 species were identified, comprising both cosmopolitan and tropical taxa.

Discussion

The diatom assemblages are clearly related to the water chemistry of the waters of the Daly, and in particular, the Douglas River systems. The most influential parameters appear to be conductivity or TDS, ionic ratio, pH, turbidity, dissolved oxygen and nutrients. These factors are influenced by the relative contributions of surface and groundwater contribution. It is clear that nutrients play an important role in defining the diatom flora at a site. Where TP concentrations are generally lower in the Daly River, by contrast, the diatom flora responds to the abrupt changes in pH, conductivity and ionic chemistry.

Outside the flood period of the wet season, diversion of surface waters, abstraction of surface waters, pumping of groundwaters, and the release of return water from irrigation development are all likely to impact upon these key water quality parameters by reducing the contribution of one source over the other or by introducing elements in concentrations not typical of the Daly-Douglas system.

The establishment of this baseline data set has characterised the variability of the diatom flora longitudinally down these systems and identified the hinge points where the influence of groundwaters exceeds that of surface waters. Ongoing monitoring of the systems will provide further insights into the inter-annual variation of this balance and will strengthen the capacity

to demonstrate the significance of the impact of catchment development on the aquatic microflora.

Several of the more common taxa are reliably found on the middle and lower reaches of the rivers and so appear to be broadly tolerant of the chemical changes within. The abundance of many, in fact most, other taxa is highly variable and they constitute useful indicator taxa for future monitoring. While a comprehensive monitoring regime would provide greatest levels of confidence, ongoing sampling undertaking small counts from single epilithic diatom samples from the established sites may be a cost-efficient means of overseeing changes of the interaction between the water and the biota in the future.

The water chemistry and diatom data shows that the Daly and Douglas Rivers exhibit biologically critical trends from turbid, dilute, acid to circumneutral waters to those which are clear, alkaline and of elevated conductivities. Critical hinge-points exist above Ooloo Road Crossing on the Douglas and below Knotts Crossing on the Katherine-Daly where there is an abrupt shift from water dominated by sandstone aquifers water to one dominated by Daly River Basin aquifers. These shifts are clearly differentiated by the diatom flora and they represent an efficient means of tracking any longitudinal changes associated with catchment development. By virtue of their abundance and diversity, diatoms ought to be one of the more useful biomonitoring tools in determining the significance of any impact on the aquatic biota of the system.

Conclusions

Having established the link between a general diatom community pattern, water quality (particularly ionic composition) and the relative contributions of surface and groundwater, it is conceivable that diatoms will provide an adequate means of assessing the adequacy of future environmental flows to the system. This assessment would relate mostly to the maintenance of community assemblages or changes in indicator taxa. The relationship between one diatom assemblage and that of another biological group is presently unknown. So is the more critical question of the link between one of the most instructive and efficient biomonitoring indicator groups and changes to aquatic ecosystem functioning that is likely to be of key issues in determining environmental flows. The abundance and palatability of diatoms suggests that this ought to be a key area of future research so as to assess the degree to which changes identified in diatom assemblages translate into the functioning of the greater system.

Relationship between flow, *Spirogyra* growth and loss of habitat

Introduction

The relationship between the benthic alga *Spirogyra* and flow along a 17 km reach of the Daly River was investigated. *Spirogyra* is an obvious and widespread species that grows on the river bottom and banks attached to rock, gravel, snags and living plants. Being a plant it has obvious importance both as a food source for animals (grazers) and as a habitat for smaller organisms. Although the contribution of *Spirogyra* to the ecology of the river is unknown, its significance to river ecology may be deduced by its status as a primary producer and its abundance.

The relationship between *Spirogyra* and flow was assessed by (1) determining habitat preference on the riverbed and modelling the effect of flow reduction on loss of habitat; and

(2) determining the relationship between velocity and biomass, and modelling the effect of reduced flows on algal biomass. Both required the development of a two-dimensional hydrodynamic model of the study reach. Simulations on the effects of different water extraction regimes were undertaken to determine the effect this may have on reach biomass. These simulations utilised the flow-biomass relationship and the historical dry season low flow record for the study reach. Simulations involved 'extracting' water from the flow record to determine the effect this has on biomass variability when compared to the no extraction case.

Results and discussion

Dry season flow during the study was at historically high levels. The approach adopted in this study in measuring field data by establishing transects over a broad range of substrate, depth and velocity (approximately 250 quadrats measured per survey date) is expected to negate any effects of high flows during the study.

The growth cycle of *Spirogyra* on the riverbed and edge shows a period of rapid establishment at the commencement of dry season recessional flow followed by a period of sustained high biomass over 2-3 months (Figure 1). The decline in biomass between August and October coincides with rising water temperature. The interruption in the decline of edge and riverbed biomass in October follows two small flushes. It is likely that nutrients transported by these flushes stimulated the growth of *Spirogyra*. The removal of all biomass by November was due to the destructive nature of the first major flow event (200 cumecs).

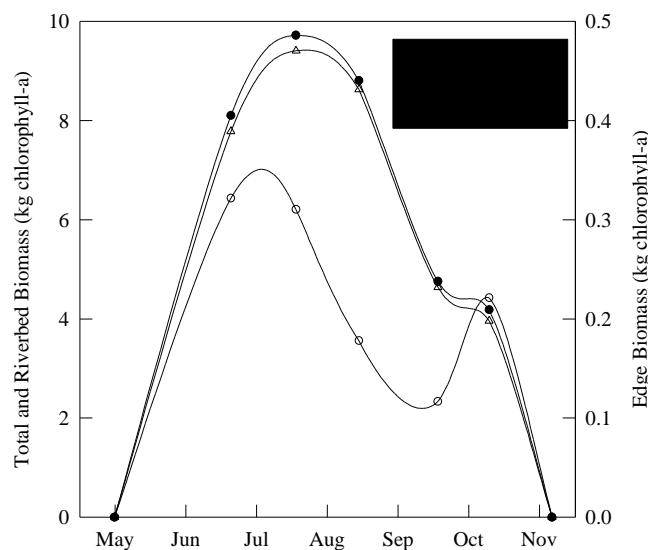


Figure 1 Seasonal changes in *Spirogyra* biomass as mass of chlorophyll-a in the study reach on the riverbed and edges (note different scales on y-axes)

Habitat preference

Spirogyra was not observed growing on sand (too unstable for attachment). This highlights the importance of gravel/rock substrates as a stable substrate allowing the development of extensive *Spirogyra* strands on the river bottom. Stable substrates along the edges of the river such as exposed roots, plants and rock allow the development of trailing stands of *Spirogyra*.

Although both the riverbed and edge provide suitable substrate for the growth of *Spirogyra*, the riverbed supports over 95% of the total biomass in the study reach. Because the bulk of the biomass was on the riverbed, this study focussed on this area of the river to establish a flow-biomass relationship. It should be acknowledged that the edges of the river provide important habitats for other plants and animals, and that these habitats may be lost through declining water levels as a result of water extraction. An investigation into this region of the river provides another measure of assessing a relationship between flow and habitat loss.

The proportion of gravel substrate exposed at 12.5 cumecs is 3%; at 10 cumecs 5%, at 7.5 cumecs 9%, and at 5 cumecs 13%. The increase in the area of exposed gravel <12.5 cumecs is of importance not only for the growth of *Spirogyra* but also for other organisms utilising this habitat. The drying of this substrate represents a loss of available habitat from the river and a corresponding loss of other biota.

Flow-biomass relationship

The relationship between algal biomass and flow (as shear velocity, calculated using bottom velocity) on gravel substrate was based on a derived measure of maximum potential biomass. In slow flowing areas high biomass was never observed. *Spirogyra* appears to require a minimum flow to enable dense stands to become established. In very high flow environments dense stands are also not observed, presumably due to the drag acting on filaments being sufficiently high to cause tearing or dislodgment. The relationship between maximum potential biomass and shear velocity is consistent with these observations. The optimal range for the growth of *Spirogyra* corresponds to shear velocities of 0.025-0.055 m/s, or a bottom velocity at 0.1 m of 0.17-0.44 m/s.

The establishment of a relationship between maximum potential biomass of *Spirogyra* and flow (as shear velocity) for gravel substrates enabled the calculation of river biomass when used in conjunction with a hydrodynamic model to simulate a range of discharge scenarios. This estimate of biomass may therefore be considered as the maximum biomass that may be produced in the study reach in a growing season.

Simulations on the effect of reducing flow through the 17 km reach shows a corresponding reduction in algal biomass, but not at a constant rate. The rate of decline in biomass with reducing discharge >12.5 cumecs (0.4 kg/cumec) was markedly less than the rate of biomass decline below this level (1.5 kg/cumec). This almost four-fold difference can be explained in terms of the relative changes in the area of gravel subject to the different shear velocity classes, the maximum potential biomass for each class, and the area of gravel exposed as river levels fall.

At discharges >12.5 cumecs the proportion of exposed gravel is small, accounting for 3% of the total gravel area (Figure 2). The main factor affecting total biomass in this range is the area of gravel exposed to shear velocities in the range 0.025-0.055 m/s. This range accounts for the greatest area of gravel beds and is associated with the highest biomass levels. Below 12.5 cumecs two factors contribute to the accelerated decline in algal biomass (Figure 3). Firstly, the area of gravel beds subjected to flows less favourable to algal growth is greater than the area of gravel subjected to more productive flows. This area is markedly greater at <5 cumecs. Secondly, there is a marked increase in the area of gravel exposed by falling water level. Therefore there is the additive impact of less favourable flows and habitat loss at <12.5 cumecs that results in an almost four-fold increase in the rate of loss of biomass compared to flows >12.5 cumecs.

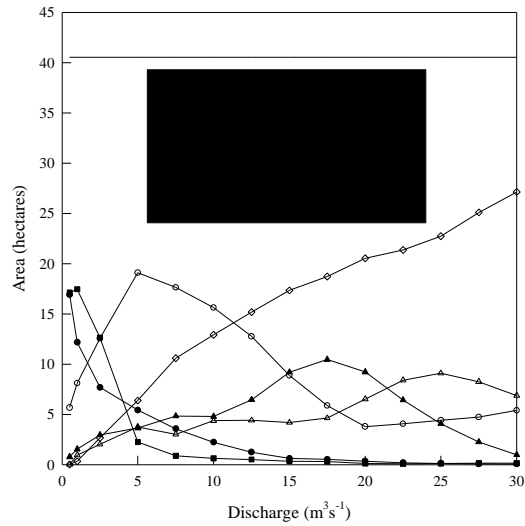


Figure 2 Calculated area of gravel substrate for shear velocity classes and exposed beds at different discharges. Shear velocity classes with no biomass refers to the total area of gravel where shear velocity is either too slow or fast for growth of *Spirogyra*

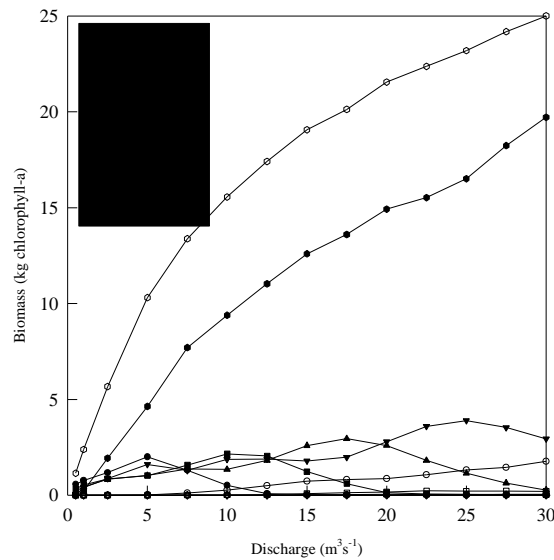


Figure 3 Estimated biomass of *Spirogyra* on gravel substrate subjected to different shear velocity classes (m/s).

Water extraction simulations

The relationship between flow and biomass was applied to the dry season historical low flow record at the study reach to determine the annual biomass frequency distribution for the 42 years for which flow records are available. The relation between flow and biomass in Figure 3 can be summarised as: $\text{Biomass} = (0.9969 \times \ln(Q) + 1.6243)^2$ ($r^2 = 0.99$) for the range 0.5-30 cumecs. This provides a comparative assessment of how water extraction may change the distribution of biomass levels from the expected natural state. Figures 4 and 5 show that a proportional extraction regime has less of an effect on the natural historical distribution of biomass as opposed to a fixed extraction rate.

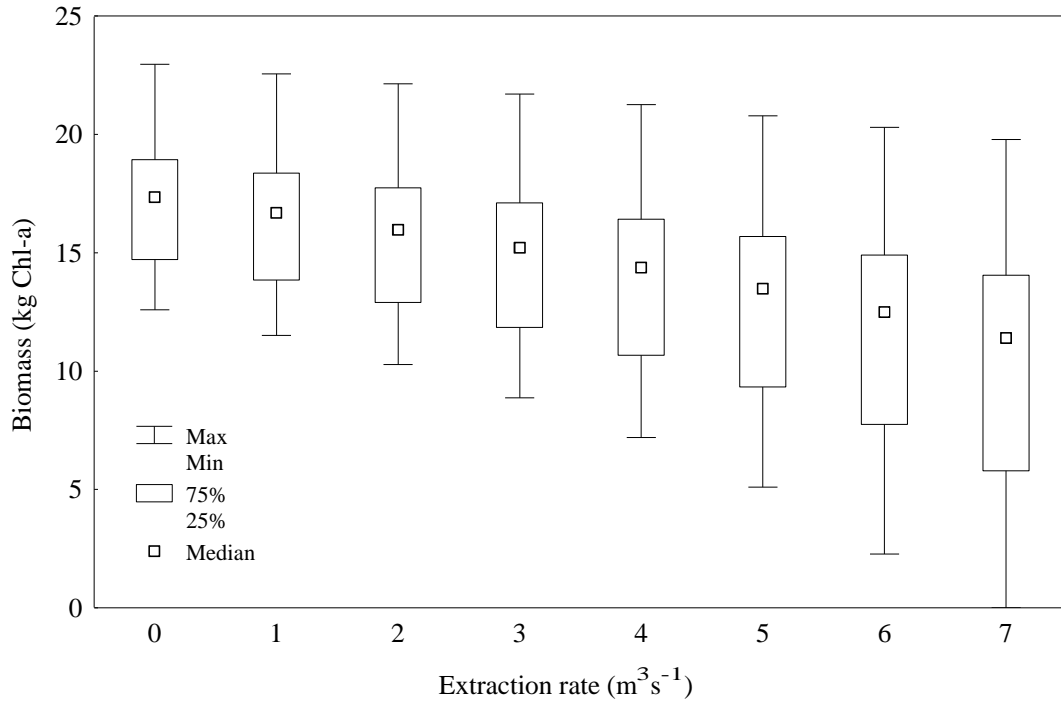


Figure 4 The effect of a fixed water extraction rate on the expected historical distribution of chlorophyll-a biomass in the study reach. The extraction rate of 0 m³ s⁻¹ represents biomass distribution based on the natural historical flow record.

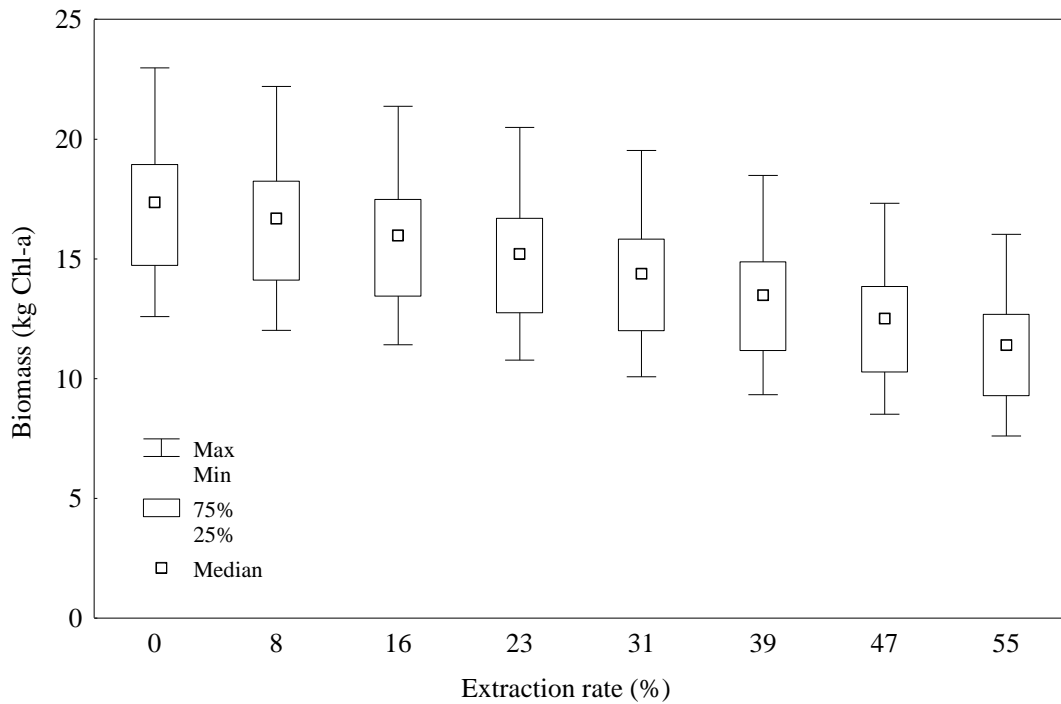


Figure 5 The effect of a proportional water extraction rate on the expected historical distribution of chlorophyll-a biomass in the study reach. The extraction rate of 0 m³ s⁻¹ represents biomass distribution based on the natural historical flow record.

Assumptions and unknowns with respect to the flow-biomass model are:

- accuracy of the hydrodynamic model for low flows is unknown.
- relationship between flow and velocity is based from a single above average dry season
- historical low flow record for the study reach is assumed representative of the longer-term
- substrate distribution (ie gravel) remains unchanged between high and low flow years
- Spirogyra is an important component of river ecology as a primary producer and habitat
- consequences of low flows on river ecology are unknown; assumed that low flows add stress to river organisms through loss of wetted area, changes in water quality and flow

Given these assumptions and unknowns a conservative approach in setting water extraction levels should be adopted in the first case. Two guiding rules are proposed for a conservative water allocation approach.

1. maintain the historical annual biomass frequency distribution of Spirogyra through a proportional water extraction regime
2. recognise that low flows place additional stress on the river and its biota

When presented as a frequency distribution, an extraction rate of 8% does not result in a new biomass distribution; ie upper and lower biomass classes are retained (Figure 6). At extraction rates >8% the annual biomass frequency distribution is changed to the extent that the upper biomass class is lost and a new minimum biomass class created. On the basis of the guiding rules proposed above this change in biomass distribution is unacceptable.

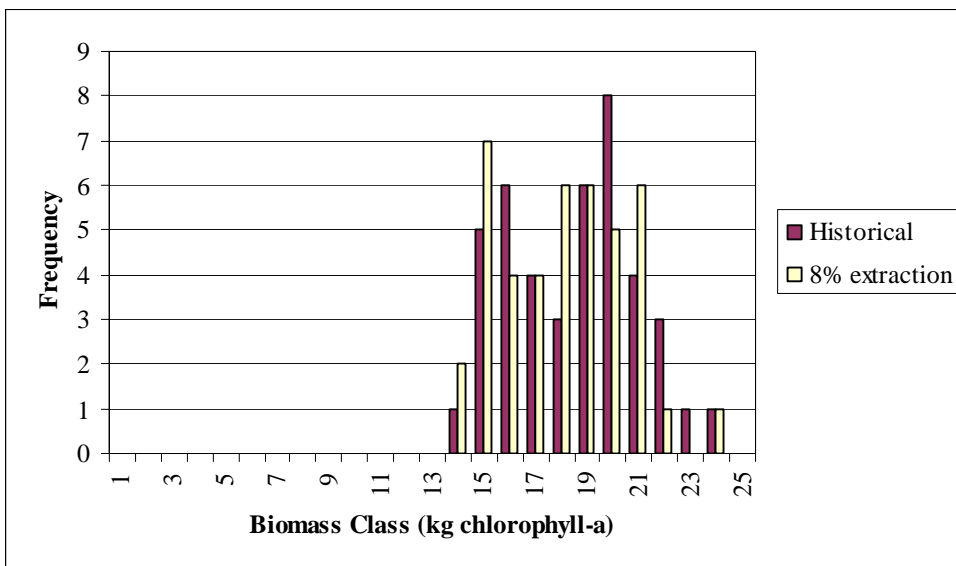


Figure 6. Comparison of biomass frequency distribution for an 8% proportional extraction rate with the expected historical distribution.

The proportional rate of extraction is similar with and without, a minimum flow threshold being set. However, a minimum threshold flow below which extraction is not allowed offers some protection to river ecology at the expense of surety of water. Presuming that extraction of water is most likely to be from aquifers, the issue of surety of supply needs to consider the relationships between previous years rainfall, movement of groundwater and effects on river flow. Distance between groundwater extraction point and river is also a factor that needs to be considered.

Conclusions and recommendations

Spirogyra growing in the study reach was only observed attached to gravel or rock substrates. The importance of Spirogyra to river ecology needs to be investigated although it can be deduced by its status as a primary producer and its widespread occurrence.

A relationship between flow and algal biomass was quantified by expressing algal biomass as maximum potential biomass. There was an optimal range of shear velocity that could sustain high levels of biomass (0.025-0.055 m/s). There was a reduction in biomass if shear velocity was either above or below this range.

There is a reduction in total algal biomass of the study reach (from 25 to 1 kg chlorophyll-a) with decreasing flows (from 30 to 0.5 cumecs, respectively). The rate of decline of total algal biomass with decreasing discharge is almost four times greater between 0.5-12.5 cumecs than between 12.5-30 cumecs. Above 12.5 cumecs the reduction in biomass is primarily due to the effects of reduced velocity. Below 12.5 cumecs it is due to reduced velocity and loss of habitat through exposure of gravel beds.

Gravel substrate in the study reach makes up 50% of the total area. The area of gravel lost through a reduction in water level from 30-12.5 cumecs is ~3%. The proportion of gravel area lost at 10 cumecs is 5%, at 7.5 cumecs 9%, and at 5 cumecs 13%.

A proportional extraction rate is preferred over a fixed extraction rate to maintain the historical biomass frequency distribution (ie natural variability). Based on simulations of the effects of water extraction on the annual biomass frequency distribution, and adopting a conservative approach, the proportional extraction rate should not exceed 8% of the minimum dry season flow at the study reach.

Recognise the importance of low flow years and develop a minimum threshold below which extraction is not permitted. As an example a minimum threshold of 10 cumecs will allow 9% of the minimum dry season flow to be extracted for 70% of years.

Final recommendations

Final recommendations for water allocation to the environment need to be based on a whole-of-ecosystem approach that:

- defines the nature of the anthropogenic impact on the river's hydrography and water quality
- brings together knowledge of the river's ecosystem needs to identify processes, habitats and biota vulnerable to altered flow regime (ie conceptual model)
- ranks ecological impacts and risk to the ecosystem's function and sustainability

Assuming the impact of consumptive use will be on dry season flows of the the Daly River and its tributaries, this project makes the following recommendations:

1. the altered dry season flow regime for the Daly River and its tributaries is maintained above historic minimum flows. For example, at Mt Nancar hydrographic station, this approximates 7 cumecs, though a more conservative flow could be set (e.g. 10 cumecs) in recognition that this represents an extreme.
2. inter-annual variation in dry season flows is mimiced, with a proportion allocated to the environment and the remainder made available for the consumptive uses. (This amount allocated to the environment is in addition to the minimum flow as stated above). The altered dry season flow regime will then still be maintained within the natural flow variation. The impact on the river's productivity, however, should be assessed as it is unlikely to be directly proportional to flow based on the river's wetted area and benthic algae biomass. On the basis of simulations on *Spirogyra* biomass it is recommended that proportional extraction should not exceed 8%.
3. that consideration be given to meeting consumptive water needs that exceed the amount available during the dry season, to be taken from wet season runoff and flows that have been stored in off-stream reservoirs (ie no streams or rivers are dammed).

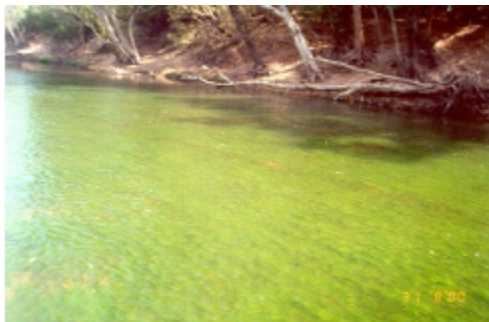


Plate 1 *Spirogyra* attached to different substrates. Clockwise from top. Extensive coverage over a gravel bed; attached to gravel but not sand; attached to surface of rock and crevices; and attached to *Vallisneria nana* and bedrock